Disaster Resilience and Green Growth

Series Editors: Anil Kumar Gupta · SVRK Prabhakar · Akhilesh Surjan

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Extremes in Atmospheric Processes and Phenomenon: Assessment, Impacts and Mitigation

Springer

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Over the years, the relationship between environment and disasters has received significant attention. This is largely due to the emerging recognition that environmental changes - climate change, land-use and natural resource degradation make communities more vulnerable to disaster impacts. There is a need to break this nexus through environment based and sustainability inclusive interventions. Science – technology and economic measures for disaster risk management, hence, need to adapt more integrated approaches for infrastructure and social resilience. Environmental and anthropogenic factors are key contributors to hazard, risk, and vulnerability and, therefore, should be an important part of determining risk-management solutions.

Green growth approaches have been developed by emphasizing sustainability inclusion and utilizing the benefits of science-technology interventions along policy-practice linkages with circular economy and resource efficiency. Such approaches recognize the perils of traditional material-oriented economy growth models that tend to exploit natural resources, contribute to climate change, and exacerbate disaster vulnerabilities, Green growth integrated approaches are rapidly becoming as preferred investment avenue for mitigating climate change and disaster risks and for enhancing resilience. This includes ecosystem-based and nature-based solutions with potential to contribute to the resilience of infrastructure, urban, rural and peri-urban systems, livelihoods, water, and health. They can lead to food security and can further promote people-centric approaches.

Some of the synergistic outcomes of green growth approaches include disaster risk reduction, climate change mitigation and adaptation, resilient livelihoods, cities, businesses and industry. The disaster risk reduction and resilience outcome of green growth approaches deserve special attention, both for the academic and policy communities. Scholars and professionals across the domains of DRR, CCA, and green growth are in need of publications that fulfill their knowledge needs concerning the disaster resilience outcomes of green growth approaches. Keeping the above background in view, the book series offers comprehensive coverage combining the domains of environment, natural resources, engineering, management and policy studies for addressing disaster risk and resilience in the green growth context in an integrated and holistic manner. The book series covers a range of themes that highlight the synergistic outcomes of green growth approaches.

The book series aims to bring out the latest research, approaches, and perspectives for disaster risk reduction along with highlighting the outcomes of green growth approaches and including Science-technology-research-policy-practice interface, from both developed and developing parts of the world under one umbrella. The series aims to involve renowned experts and academicians as volume-editors and authors from all the regions of the world. It is curated and developed by authoritative institutions and experts to serve global readership on this theme.

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Anil Kumar Gupta
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Foreword

Human society can be very tolerant of activities and phenomena which are highly undesirable if they develop gradually. One example is road traffic accidents which reap a huge toll of death and injury internationally, but are tolerated as part of everyday living, and are one of the risks of life which has to be accepted. One only has to look to air travel, which is far more highly regulated to ensure passenger safety, to see that things could be different and that such a toll is not inevitable. Outdoor air pollution causes around 30,000 premature deaths annually in my own country (the UK), and according to the Global Burden of Disease Study around four million worldwide, with a similar number of deaths arising from exposure to indoor sources. This is another risk of life which is tolerated because it has been there for longer than anyone can remember, and in the UK, documentation of urban air pollution problems extends back for many centuries although it was the nuisance, rather than the health risks which led to the earliest legislation. The current downward trend in air pollution in developed countries stems largely from a few extreme events. Probably, the best documented event is the 1952 London smog which killed 4000 (and most probably more) people over a period of a week of stagnant weather. Similar events in the Meuse Valley of Belgium and Donora, Pennsylvania, USA, were also key to raising awareness and stimulating change.

We now know that air pollution has effects far beyond those on human health, and extreme events serve to highlight the risks, although often the consequences are the result of long-term lower level exposures. Extreme air pollution events have been very important in the past and will continue to be in the future until all countries have achieved acceptable air quality, which will take many decades, especially as research advances continue to show adverse effects at ever lower concentrations.

I very much welcome the initiative by three talented scientists to develop this book and believe that a deep understanding of extreme events is one of the keys to safer air for us all.

Queen Elizabeth II Birmingham Centenary
Professor of Environmental Health,
School of Geography,
Earth and Environmental Sciences,
University of Birmingham
Birmingham, UK
July 2021

Roy M. Harrison

Preface

Extremes in atmospheric processes and phenomena often lead to change in air quality and can have harmful impacts on climatic processes as well as human lives. Atmospheric extreme events are generally very intense and may lead to short-lived as well as long-lived changes in the environment. In the recent years, extremes in atmosphere and air pollution-related emergencies like smog, biomass burning, dust storms, heat waves, etc. have increased and, therefore, there is an urgent need to focus the attention of governments, policy makers and scientists on such issues and to come up with sustainable solutions for present and future.

Extremes in Atmospheric Processes and Phenomenon: Assessment, Impacts and Mitigation encompasses a holistic comprehension on fundamental concepts of atmospheric processes, mechanisms, phenomena, air pollution episodes and extreme events, impacts and mitigation strategies. Chapters provide a holistic overview of atmospheric extreme events like dust storms, fog, smog, biomass burning, volcanic eruptions, heat waves etc. and also describe their impacts on environment, challenges and possible strategies to mitigate and control them.

This book covers a special approach towards disaster risk management methods, policies and governance to manage and mitigate atmospheric extreme events which can help reduce the havoc and damaging consequences from them. This book is expected to serve as valuable knowledge support system for scientists, policy makers, academicians, consultants and research scholars in the area of Environmental Science, Biological Science, Medical Science, Policy Planning, Disaster Management and Agriculture. It will also be a unique document for air quality professionals like meteorologists, atmospheric chemists, modellers and disaster management experts.

New Delhi, India

Pallavi Saxena
Anuradha Shukla
Anil Kumar Gupta

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Abbreviations

AD	Aerodynamic diameter
AERMOD	Atmospheric dispersion module
AMSL	Above mean sea level
AOD	Aerosol optical depth
APEC	Asia-Pacific Economic Cooperation
APTI	Air pollution tolerance index
AQI	Air quality index
BC	Black carbon
BOB	Bay of Bengal
BSOA	Biogenic secondary organic aerosol
BTEX	Benzene toluene ethylbenzene xylene
CAP	Comprehensive action plan
CC	Carbonate carbon
CCAC	Climate and clean air coalition
CCN	Cloud condensation nuclei
CEC	Cation exchange capacity
CEPI	Comprehensive environmental pollution index
CFCs	Chlorofluorocarbons
CLRTAP	Convention on long-range transboundary air pollution
CMIP	Coupled model intercomparison project
CNG	Compressed natural gas
CO	Carbon monoxide
CONUS	Continental United State
COPD	Chronic obstructive pulmonary disease
CPCB	Central Pollution Control Board
CRB	Crop residue burning
CWWG	Crop Weather Watch Group
DGR	Diameter growth rate
DI	Discomfort INDEX
DMI	Dipole moment index
DOC	Dissolved organic carbon
DS	Dust storm
DU	Dobson unit

EC	Elemental carbon
ECMWF	European Centre for Medium-Range Weather Forecasts
EDGAR	Emissions database for global atmospheric research
EIA	Environmental impact assessment
ENSO	El Nino Southern oscillation
ESP	Electrostatic precipitator
EU	European Union
FHWA	Federal Highway Administration
GCMS	Gas chromatography mass spectrometry
GDP	Gross Domestic product
GFED	Global fire emissions database
GHGs	Greenhouse gases
GIS	Geographical information system
GRAP	Graded response action plan
GTP	Global temperature change potential
GWP	Global warming potential
H_2SO_4	Sulphuric acid
HGR	Height growth rate
HHWSs	Heat-health warning systems
HNO_3	Nitric acid
HW	Heat waves
IARI	Indian Agricultural Research Institute
IAV	Inter annual variability
IAVCEI	International Association of Volcanology and Chemistry of the Earth’s Interior
ICAO	International Civil Aviation Organization
ICMR	Indian Council of Medical Research
IGP	Indo gangetic plain
IHME	Institute for Health Metrics and Evaluation
IMD	Indian Meteorological Department
IOD	Indian Ocean dipole
IPCC	Intergovernmental panel for climate change
IPM	Inhalable particulate matter
IPO	Interdecadal pacific oscillation
ISMR	Indian summer monsoon rainfall
ITCZ	Intertropical convergence zone
LIPs	Large igneous provinces
LLJ	Somali low-level jet
LPS	Low pressure system
LRTAP	Long-range transport of air pollutants
MH	Mascarene high
MIC	Methyl isocyanate
MJC	Madden Julian oscillation
MODIS	Moderate resolution imaging spectroradiometer
MoES	Ministry of earth sciences

NAAQS	National ambient air quality standards
NCAP	National clean air programme
NCDs	Non-communicable diseases
NCP	Northern China plain
NDMA	National Disaster Management Authority
NFHS	National family health survey
NHAP	National health adaptation plan
NIDM	National Institute of Disaster Management
NMVOCs	Non-methane volatile organic compounds
NOAA	National Oceanic Atmospheric Administration
NOx	Nitrogen oxides
O_3	Ozone
OC	Organic carbon
OH	Hydroxyl radical
OLR	Outgoing longwave radiation
OP	Oxidative potential
PAHs	Polycyclic aromatic hydrocarbons
PBL	Planetary boundary layer
PM	Particulate matter
PUC	Pollution under control
RCP	Representative concentration pathway
RH	Relative humidity
ROT	Runway occupancy time
RYL	Relative yield loss
SAM	South Asian monsoon
SDS	Sand and dust storms
SGVP	Smithsonian global volcanism program
SIA	Secondary inorganic aerosols
SLCPs	Short-lived climate pollutants
SO_2	Sulphur dioxide
SOA	Secondary organic aerosol
SPI	Standardized precipitation index
SSH	Sea surface height
SST	Sea surface temperature
TCO	Total columnar ozone
TEA	Triethylamine
TEJ	Tropical easterly jet
TMA	Trimethylamine
TRAP	Traffic-related air pollution
TRMM	Tropical rainfall measuring mission
UAVs	Unmanned aerial vehicles
UFP	Ultrafine particles
UHI	Urban Heat Island
UKMO	United Kingdom Met Office

UNCCD	United Nations convention to combat desertification
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations framework convention on climate change
USEPA	United States Environmental Protection Agency
VEI	Volcanic explosivity index
VFR	Visual flight rules
VHR	Very heavy rainfall
VOCs	Volatile organic compounds
WD	Western disturbance
WHO	World Health Organization
WMO	World Meteorological Organization
WSN	Wireless sensor network
WSOC	Water-soluble organic carbon

An Introduction to Extremes in Atmospheric Processes and Phenomena: Assessment, Impacts and Mitigation

1

Pallavi Saxena, Anuradha Shukla, and Anil K. Gupta

Abstract

Extremes in atmospheric phenomena and processes can strongly affect ambient air quality that has harmful impacts on human and climate health. High urbanization and industrialization are highly responsible for causing disturbances in different spheres of environment like atmosphere and its processes and phenomena. This will further impact human and climate health. Various episodic extreme events are reported in urban areas causing health impacts like respiratory disorders, cardiovascular diseases and damage to central nervous system that often lead to death. This chapter focuses on factors governing in atmosphere that resulted in air pollution, fundamental understanding about recent and historic air pollution episodes, emergencies and extremes and their impacts on living organisms. Moreover, possible mitigation strategies have also been discussed to reduce the occurrence of air pollution episodes and minimize the disturbance in atmospheric processes. It also summarizes the highlights of different chapters signifying various aspects of atmospheric processes, mechanisms, extremities, impacts and disaster risk mitigation strategies.

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Keywords

Atmosphere · Air quality · Extreme events · Mitigation · Disaster risk management

1.1 General Introduction

Extreme events in atmospheric processes and phenomena are majorly responsible for affecting the air quality and pose deleterious impact on plant, animal, human and material health. Extreme events can be heat waves, extreme precipitation, volcanic eruptions, smog, biomass burning, fireworks, dust storms and many more which are significantly important to impair the air quality and can show impacts in the long run on environment (Jacob and Winner 2009; Saxena and Sonwani 2019; Sonwani and Saxena, 2022). Extremities in atmosphere can occur due to drastic change in weather processes, disturbance in atmospheric processes and climate change that ultimately affect air quality. Pattern changes in duration, frequency and spatial level in weather extremes have been discussed by Intergovernmental Panel on Climate Change (IPCC 2007; Blanken et al. 2022). For instance, extremities in heat waves can cause high temperature; increased biogenic emissions and rapid chemical reactions can give rise to high production of ozone and fine particulate matter concentrations. Goel et al. (2021) reported that fine particulate matter-related health hazards like premature mortality, respiratory ailments and cardiovascular diseases may increase mostly in dense populated areas and can become more worsen if not controlled. Climate prediction models, emission inventories and population dynamics model are greatly acknowledged for assessing the possibility of health hazards in a particular area due to extremes in air pollution and atmospheric processes. Such assessment practices can be further improved if the relationship between air pollution events, atmospheric processes and phenomena is presented in a more understandable and efficient way (Saxena and Srivastava 2020; Sonwani et al. 2021).

In the recent era, extremes in atmosphere and air pollution-related emergencies (fog, smog, health-related, heat and cold wave) has become a major environmental hazard and a big reason to affect human health (Pant and Harrison 2013; Saxena et al. 2020; Tiwari and Saxena 2021). Outdoor air pollution has become one of the major threats to human health and was estimated to cause 3.9 million premature deaths each year (WHO Fact Sheet 2018). Bell et al. (2004) reported that 0.52% high-risk daily mortality was caused by ozone in megacities of the United States over the period of 1987–2000. Satellite-based observations have shown that worldwide population-weighted fine particulate matter ($PM_{2.5}$) has increased by 0.55 μgm^3, mostly covering an exponential increase in East and South Asia (3.2 and 2.9% per year). Moreover, projection models also estimate that contribution of megacities to worldwide mortality from outdoor air pollution will rise from 60 to 65% of the total from 2010 to 2050 (Lelieveld et al. 2015; Saxena and Sonwani 2019). The effects caused by air pollution can lead to various health hazards like chronic obstructive pulmonary disease, acute respiratory infections, bronchitis, etc (Sonwani and Saxena

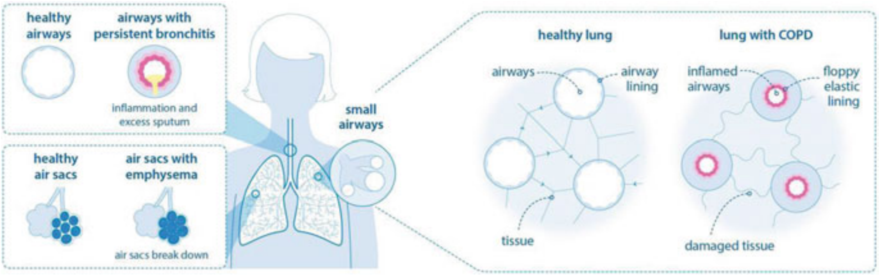

Fig. 1.1 Comparison of healthy and infected respiratory system due to inhalation of particulate matter in atmosphere (Source: www.blf.org.uk)

2016). Figure 1.1 shows the comparison of respiratory system of healthy and infected person due to inhalation of particulate matter in atmosphere. Populations living in developing countries and underdeveloped countries suffer from both indoor as well as outdoor air pollution (Pope III et al. 2009; Saxena et al. 2012).

Atmospheric processes and extremes like fog episodes also give rise to health hazards and huge impact on environment. Rise in aerosol concentrations in urban areas due to high urbanization and industrialization and high vehicular density catalyses fog events. Increase in relative humidity and aerosols are major factors responsible for poor visibility and causing rail, road and flight accidents (Saxena et al. 2020; Saxena and Kulshrestha 2015). In later run, particularly during winter season, extensively increased concentrations of NOx, SOx, oxidants and particulate matter along with favourable meteorological conditions like low boundary layer, low temperature, temperature inversions and low wind speed give rise to the condition "Smog" (Sonwani and Saxena 2021). Smog is very much prevalent and recorded since historic times like famous episodes of "London Smog" and "Los Angeles Smog". London Smog is one of the most deadly smog recorded so far that killed around 12,000 people due to emissions from thermal power plants (Tiwari and Saxena 2021). Presently, India witnesses smog events every winter almost every year and in 2016, Delhi's smog was declared as "The Great Delhi Smog". Schools were closed and people were advised to stay indoors during high pollution days (Bhalla et al. 2019). Smoke from rural kitchens, vehicular emission, industries, more numbers of vehicles, jeopardization of non-polluting public transports, dense population, low investment in public transport and insufficiency of public infrastructure, extensive construction activities, and crop residue burning issues from adjacent states such as Punjab, Haryana and Uttar Pradesh contribute together. During the months of post-monsoon and winter, approximately 500 million tons of crop residues are burned in Indo-Gangetic plains leading to mass emissions from biomass burning (Sharma et al. 2010; Saxena et al. 2021). According to another study, 72% of the total air pollution load in Delhi is from vehicular emissions as calculated using emission factor and activity-based approach suggested by Intergovernmental Panel on Climate Change (IPCC) (Sindhwani and Goyal 2014). Furthermore, during winters calm winds and low temperatures entrap dust particles and pollutants near the ground setting up smog layer. And then the festival of Diwali, due to fireworks, gives an incremental effect to the air pollution of Delhi. Another atmospheric extreme event is volcanic eruption. On the basis of type and region of eruption, volcanic events can become extreme events in particular regions of the Earth. Emission of tropospheric aerosols from quiescent volcano will have a lifetime of weeks; however, an explosive eruption injecting the aerosols in the stratosphere can scale up the lifetime from weeks to years. The resulting impact on radiative forcing will hence be much more significant. The extremity of an eruption impact is not only visible in the amount of material that is ejected but also by the distance the impact propagates. Even smaller eruptions can have a long-range impact under favourable meteorological conditions. Recently in 2018, Manaro Voui volcano on Ambae island of South Pacific injected a record amount of 400,000 tons of SO_2 in the UTLS region, which was thrice the amount of SO_2 released from all volcanoes in the previous year (NASA Report 2018). The impacts ranged from destruction of homes, burying of crops, blackening of the sky by volcanic ash, acidifying the drinking water and forcing the entire population of the island to evacuate. Likewise, there are various extreme events which occurred due to disturbance in seasonal cycles and atmospheric phenomena that ultimately causes ecological imbalance and severe changes in air quality.

Atmospheric extremes and air pollution episodes are considered as a form of disaster and therefore disaster risk management plan is very important to mitigate such events. Disaster management authorities that can strategize pre-disaster, immediate post-disaster and recovery steps taken during a disaster are a necessity. Disasters involving extreme air pollution are causing an immediate public health crisis leading to an increased pressure on stakeholders and agencies to provide solutions to protect impacted communities during any such emergencies (Chandrappa and Kulshrestha 2016). During any disaster, the air quality management is dependent on the local community preparedness and external aid.

1.2 Summary of Chapters

A number of points discussed above have clearly depicted that extremities in atmospheric processes, phenomena and resulted degradation in air quality are important issues that need to be given attention and should be taken into serious consideration. This book “Extremes in Atmospheric Processes and Phenomena: Assessment, Impacts and Mitigation” covers a general overview of factors governing in atmosphere to lead to air pollution, description about recent and hazardous air pollution episodes, emergencies and extremes in atmospheric sciences, impact studies on living organisms and atmosphere related to emergencies and possible remedies/mitigation strategies which may also include green growth strategies for management. Chapter 2 provides a compact overview of atmospheric phenomena and their mechanism; and how they will play a significant role as both positive and negative effects on human livelihoods and human well-being. Moreover, it also provides the effects of human activities on the mechanism of atmospheric phenomena. Chapter 3 deals with the major atmospheric pollutants (sulphur **d**ioxide, oxides of nitrogen, ground level ozone, suspended particulate matter, fluorides and peroxyacyl nitrates), their impacts on atmosphere (global warming, stratospheric ozone depletion, acid rain, etc.) and threats to the biota health. This chapter has given a fundamental understanding about air pollution, air pollutants, reasons of their impacts on atmosphere and living organisms health. Chapter 4 focuses on South Asian monsoon extremes, intra-seasonal variations and modulation by remote forcing and their future trends in global warming scenario. Moreover, it also summarizes that how good quality observational data sets can help future climate management strategies for land-based water resources, groundwater, agricultural best practices, food security, disaster early warning and preparedness. Chapter 5 presents a brief review on the contribution of fog in changing air quality, its extremities and risks to environment and society. It also focuses on fog types and distribution, physio-chemical characterization, factors for its formation and evolution and extremities of this fog pollution phenomenon on environment and society. Chapter 6 deals with the concept to understand nature and phenomena of dust and sandstorms (SDS) processes, current and past trends of SDS impacts, as well as understanding impact of SDS hazard on environment and human health as well as extremities and their correlation with climate change. Chapter 7 focuses primarily on heat waves (HW) addressing with details their definition, generation, future projection and synergy with the urban heat island (UHI) effect and air pollution in cities, as well as their harsh impacts on several sectors and the approaches for mitigating these effects. A part of this chapter is also devoted to cold waves, while a case study concerning the inter-play between extreme temperatures, thermal comfort and air pollution during a significant HW episode that occurred in Greece is presented. Chapter 8 deals with the status of excessive biomass burning emissions over the Indo-Gangetic Plain (IGP), and their impacts. It also describes the sources of biomass burning with depiction of intense biomass burning, illustrates extreme biomass burning episodes and provides a description of the elevated levels of trace gases and aerosols generated as a result of biomass burning, followed by their impacts on environment. Chapter 9 gives an overview of the challenges behind the increasing trend of smog events across Northern India. It also seeks to deliver an understanding of the question of why the northern part of our country is becoming the pollution centre of the world and intends to link the plausible causes and impacts for the rising extreme events of smog. Chapter 10 focuses on different types of volcanoes and their atmospheric impacts. It also aims to simplify and summarize the information available regarding volcanic eruptions from an atmospheric and climate perspective and ends with the case study of the most famous volcano the Mt. Pinatubo of 1991. Chapter 11 deals with the extremities caused due to emission of high concentrations of air pollutants like trace gases and particulate matter during fireworks and how they affect the air quality by taking the support of a case study of Vishu festival celebrated in Kannur, a Coastal city of Southern India. Chapter 12 focuses on an overview of the history of air pollution episodes and their impacts, key driving mechanisms, followed by an outlook including some perspectives on the control measures. Chapter 13 outlines various disaster mitigation and adaptation strategies. Importance of science and decision support systems, data availability and sharing, early warning systems, timely information dissemination and post-disaster management are also highlighted. Chapter 14 aims to examine and assess the various components of air pollution, their effects on human health and way forward to deal with air pollution as a disaster and public health emergency with existing policies and programmes. The identified framework will be useful to all stakeholders and decision makers as a roadmap while designing the future air pollution mitigation policies from a disaster management point of view. Chapter 15 aims to discuss common technologies for air pollution control and measurement. The discussion about commonly used technologies for air pollution management and their cost-effectiveness has been highlighted in this chapter. Chapter 16 talks about air pollution and its extremes, how anthropogenic actions have lead air pollution to a disaster and how the air pollution and its extremes can be mitigated through ecological and natural-based solution as green growth strategies. The aim of the chapter is to use the approach of nature-based solutions that uses ecological and environment-friendly methods in urban planning and management to mitigating air pollution. Chapter 17 reviews all the existing international and national policies that outline measures to curtail and abate ambient air pollution in chronic and episodic events as well as targeting natural and anthropogenic sources. It also gives details of the international policies that have been implemented to address the transboundary pollution with global implications and also the policies adopted in India in response to abatement of deteriorating air quality at the state and national level. This book ends up with Chapter 18 that discusses different approaches with national and international examples to understand the effectiveness of participatory model in relation to atmospheric processes and extremities. Although participation of different stakeholders in decision making process and in managing the extremities is not straightforward process. It is discussed that role of training and decision on appropriate level of involvement of people is also important for further improvement and governance of extremities in atmospheric processes and phenomena.

1.3 Conclusions

It is important to build significant relationship between extremes in atmospheric processes, phenomena and resulted air quality degradation. This is a vital step toward analysing the pattern of air quality extremes in changing climate. For instance, high concentrations of ozone and fine particulate matter are common air pollutants responsible for causing extremes in atmosphere and major factors behind air pollution episodes. Therefore, more systematic studies should be conducted to understand the factors behind the disturbances held in various atmospheric processes and that ultimately lead to extremes in weather and climate. Such extremities are further responsible for health hazards and often leads to epidemic outbreaks too. Moreover, the extreme events like heat waves, cold waves, dust storms, smog, biomass burning, etc. can cause deleterious impacts on plants, animals, human and even material health. High mortality and premature deaths are reported every year on worldwide basis and stringent disaster risk management methods and green technologies can help to reduce and mitigate extreme events in atmosphere and related air pollution episodes. Thus, the different chapters in this book explain about factors governing in atmosphere to lead to air pollution, description about recent and hazardous air pollution episodes, emergencies and extremes in atmospheric sciences, impact studies on living organisms and atmosphere related to emergencies and possible remedies/mitigation strategies which may also include green growth strategies for management.

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Atmospheric Phenomena: Origin, Mechanism, and Impacts

2

Vanisa Surapipith and Pornpan Uttamang

Abstract

Haze, fogs, wind-blown dust, and tornadoes are well-known examples of atmospheric phenomena. These atmospheric occurrences are normally observed around the world; however, some phenomena may be frequently observed over specific regions than others. For example, the United States (the U.S.) has the most experience in tornado strikes than any nation worldwide. The U.S. receives approximately 1200 tornadoes per year while this phenomenon annually occurs over New Zealand with about 20 tornadoes (the National Severe Storms Laboratory (NSSL), Severe weather 101—Tornadoes, 2021). When the strengths and intensities of these phenomena are raised, they become more and more severe; eventually, they turn to be natural hazards that threaten properties, economy, environment, and lives. In May 2011, Joplin, a destructive tornado, hit the city of Joplin, Missouri, USA that caused 161 fatalities and more than 1000 injuries; about 553 business structures and 7500 residential structures were destroyed. Economic loss of the city of Joplin after the devastating Joplin tornado stroke was estimated to be $2.8 billion (Houston et al., PLoS Curr 7:ecurrents.dis.18ca227647291525ce3415bec1406aa5, 2015; the National Institute of Standards and Technology (NIST), Joplin Missouri Tornado 2011, 2021).

The aim of this chapter is to demonstrate important atmospheric phenomena, in particular, hydrometeor and lithometeor, and their mechanism, since these atmospheric phenomena play a significant role in human livelihoods and human well-being with both positive and negative effects. On the other hand,

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human activities such as urbanization, industrialization, and intensive agriculture may accelerate the formation of these natural events and strengthen their intensities that may ultimately result in an increase in more frequent and more severe natural hazards. Therefore, in this chapter, effects of human activities on the mechanism of atmospheric phenomena are addressed and discussed. In the last session, we focus on the impacts of hydrometeors and lithometeor on human society in order to emphasize human-environment interactions, to raise awareness of environmental protection to societies which atmospheric phenomena should be integrated into environmental management. After all, the chapter illustrates how the environmental mechanisms enhanced by human activities are having tremendous impact on the human society ourselves.

Keywords

Atmospheric phenomena · Atmospheric phenomena mechanism · Hydrometeor · Lithometeor · Effects of atmospheric phenomena

2.1 Introduction

"Atmospheric Phenomenon" is an observable physical occurrence in the atmosphere which opposed to dynamic or synoptic phenomena (American meteorological society (AMS) 2012a). Dynamic meteorology is usually referred to a meteorology study that focuses on fluid mechanism and thermodynamics of atmosphere since the atmosphere is considered as a continuous fluid medium (Holton 2004). Synoptic phenomena are atmospheric occurrences that occur in a range scale of 500–10,000 km such as cyclones (Jacobson 2005; AMS 2012b). Therefore, the atmospheric phenomena include all hydrometeors, lithometeors, igneous meteors (for example, lightning), and luminous meteors or optical meteors (for example, rainbow); however, local-scale or large-scale occurrences of winds, pressure, temperature, and clouds are excluded (AMS 2012a, c, d).

Among the atmospheric phenomena mentioned above hydrometeors and lithometeors are two major atmospheric phenomena with so far greatest impacts on human society. Hydrometeors are various forms of water in the atmosphere that produced through condensation and deposition (AMS 2012c); while lithometeors are small particles that can be wet or dry particles suspended in the atmosphere (AMS 2012d).

Significantly at present, intensity of the atmospheric phenomena is changing, and this is affecting the society. Learning about the origin including mechanism of the formation and process is therefore highly important. Understanding on the transformation of the hydrometeors and lithometeors till they reach the receptors, whether human or the environment, will provide the possibility to prepare and adapt to any negative impacts of the phenomena. As found through the literature reviews, for example, vast area from Eastern Asia to Middle-central Europe recently experienced the impacts of carbonaceous lithometeors, so-called radiation-absorbing aerosols, on enhancing the melt of snow cover and ice sheet, and cause the retreat of glaciers, as observed by decadal space-based active and passive measurements (Wang et al. 2020a, b; Sonwani and Saxena 2021). The study showed that the Pan Third Pole was mainly affected by natural dust, polluted dust, and elevated smoke causing detrimental environmental and climate change. Moreover, in Indo Gangetic Plain (IGP) annually there occur persistent fog events during the winter time (Saxena et al. 2020; Saxena and Kulshrestha 2016). The fog-affected area extends throughout the IGP ranging from Pakistan, in the west, to Bangladesh, in the east, covering about 3000 km in length and 400 km wide taking the plain area of Northern India and southern Nepal (Gautam et al. 2007; Saxena and Kulshrestha 2015). Studies based on meteorological data over two decades indicated the increased number of foggy days during winter (Jenamani 2007; Shrestha et al. 2018; Syed et al. 2012), while the IGP is one of the world's densely populated regions with the significant fertile land for agricultural activities and numerous operational industries which generate pollutants emitted into the atmosphere mixing with the fog. It was found by Izhar et al. (2019) that the mechanism of fog formation involved both the long-range and regional contributions, indicated by the presence of inorganic species like nitrate and sulfate versus dissolved organic carbon (DOC) as contents in the fog water droplets. The observed sulfate concentration in the IGP fog water highlighted the aqueous processing of gaseous SO_2 into fog water droplets. The clustering analysis results showed that locally driven air masses were enriched with the DOC, which is essentially influenced by biogenic emissions from the intensive agricultural land, cooking and heating activities, brick kilns, and resuspension of unpaved roads in the region.

In this chapter, we are focusing on the formation of hydrometeors and lithometeors in the atmosphere. The effects of biomass burning, urbanization, and industrialization on the hydrometeors and lithometeors formations are discussed to point out the impacts of human activities on enhancing frequencies and severities of these atmospheric phenomena. Finally, hydrometeors and lithometeor are discussed as natural hazard events that threaten human society, economy, and health in order to emphasize why it is important to care about the environment and natural phenomena.

2.2 Atmospheric Phenomena and Mechanism

As mentioned earlier, atmospheric phenomenon is an observable physical natural event including hydrometeors, lithometeors, igneous meteors, and luminous meteors. Hydrometeors basically can be classified into many types, but well-known hydrometeors are clouds, fog, rain, snow, hail, dew, rime, glaze, blowing snow, and blowing spray. The term hydrometeors encompasses water and ice particles suspended, or falling, in the air as well as those formed at the surface, such as dew. A precipitation particle is a type of hydrometeor. More details of their formation mechanism are explained in this section.

2.2.1 Hydrometeor

"Hydrometeors" refers to water in liquid or solid phases suspended or falling through the atmosphere (World Meteorological Organization (WMO) 2017a). Water particles that are blown from the Earth's surface are also included in the term hydrometeors (AMS 2012c). Hydrometeors can be classified into five categories including:

- *Suspended particles*: liquid or solid suspended water particles in the atmosphere.
- *Precipitation*: liquid or solid falling water particles.
- *Wind-blown particles from the Earth's surfaces*: sea sprays.
- *Deposits of particles*: dews, frozen dews, and frost.
- *Spouts*: rotating columns of air that contain water droplets.

In general, snow or water on the ground are not included as hydrometeor (WMO 2017a); therefore, in the Hydrometeors section, we put more focus on the formation of suspended particles, precipitation, and spouts.

2.2.1.1 Suspended Particle

"Fog" and *"mist"* are well-known examples of suspended particle. They are water particles that can be in liquid phase or solid phase (ice crystal particles) or both that suspend in the atmospheric boundary layer. These suspended particles are the results of condensation process (Gultepe et al. 2007; Ahrens and Henson 2014) which is the process that atmospheric water vapor is changed to liquid or solid water particles. Except relative humidity, condensation nuclei are one of the most important factors that drive condensation processes in the atmosphere (Pui et al. 2014). Condensation nuclei are extreme light and tiny particles in the atmosphere where their surfaces serve as water vapor condensation surfaces. Condensation nuclei can be dust, smoke, sea salt particles, and sulfate particles with various particle sizes (range from less than 0.1 μm to greater than 1 μm in radius) and number concentrations (range from 10,000 to less than 1 particle per cubic centimeter air) (Ackerman and Knox 2003; Ahrens and Henson 2014). The most common condensation nuclei mode considered by number of particles per cubic centimeter air is "Aitkin condensation nuclei". Aitkin condensation nuclei are particles with radius less than 0.1 μm and the number concentration of this particle mode typically ranges from 1000 to 10,000 particles per cubic centimeter air. Particles within the radius range of 0.1–1.0 μm are considered as "large condensation nuclei" whose number concentrations normally range from 1 to 1000 particles a cubic centimeter of air. "Giant condensation nuclei" are referred to particles with mean radius larger than 1.0 μm (Ahrens and Henson 2014).

The condensation nuclei can be characterized into two groups (Fig. 2.1). Hygroscopic particles or water-seeking particles are particles that allowed water vapor to condense on their surfaces; even the atmospheric humidity (RH) is less than 100%, a condensation process can take place. Hydrophobic particles or water-repelling, on the other hand, are particles that resist water vapor condensation on the particle surfaces. Without hygroscopic particles, very high atmospheric relative humidity

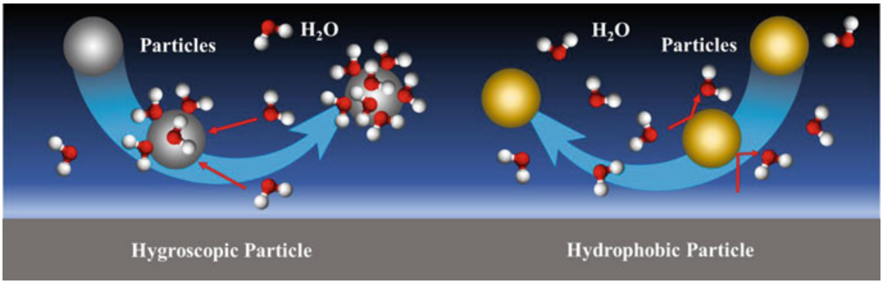

Fig. 2.1 Hygroscopic nuclei and hydrophobic nuclei (modified from: University of Arizona 2018a)

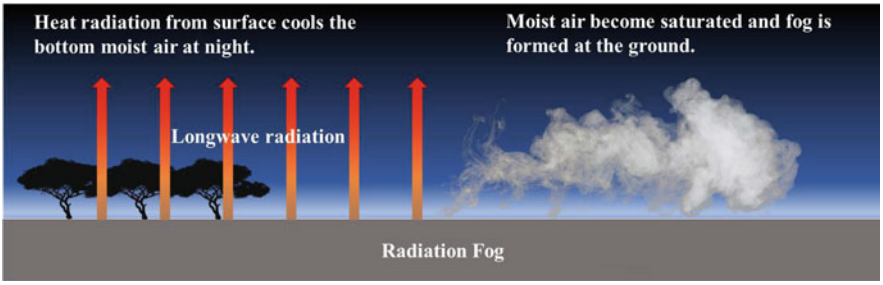

Fig. 2.2 The formation of radiation fog (modified from: Midwestern Regional Climate Center 2021)

(may greater than 100%) may be required in order to induce condensation (Ahrens and Henson 2014).

When the hygroscopic nuclei have water condensation on their surfaces and generate small droplets, fog and mist occur. Even fog and mist have a similar formation process, the major difference between them is horizontal visibility reductions. In general, fog reduces horizontal visibility in the range of less than 1 km, but mist has horizontal visibility range from 1 to 5 km (WMO 1966). "*Heavy fog*" might be used when the horizontal visibility is less than about 200 m (Van Oldenborgh et al. 2010).

Fog can be characterized into several types depending on fog formation processes and place of occurrences; however, in this chapter, we are more focused on types of fog based on the formation processes.

"Radiation fogs" are formed through the radiation cooling process of the Earth's surface (Fig. 2.2). This type of fog usually is formed during nighttime with cloudless. This condition promotes the escape of longwave radiation emitted by earth to space (Aguado and Burt 2007). Due to the nighttime radiational cooling process, moist air masses become saturated and radiation fogs are formed. Since radiation fogs are generated near the ground, it is also known as "ground fog" (Ahrens and Henson 2014).

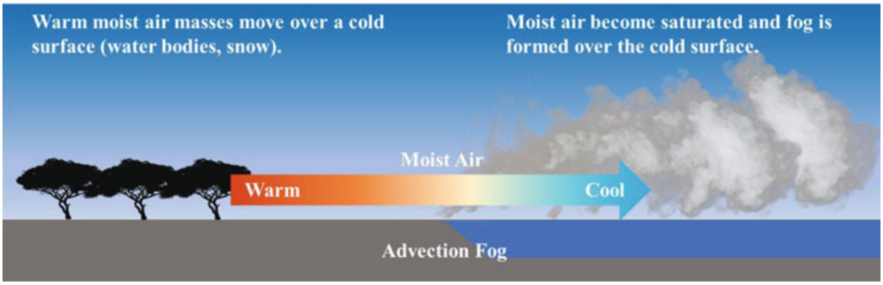

Fig. 2.3 The formation of advection fog (modified from: Midwestern Regional Climate Center 2021)

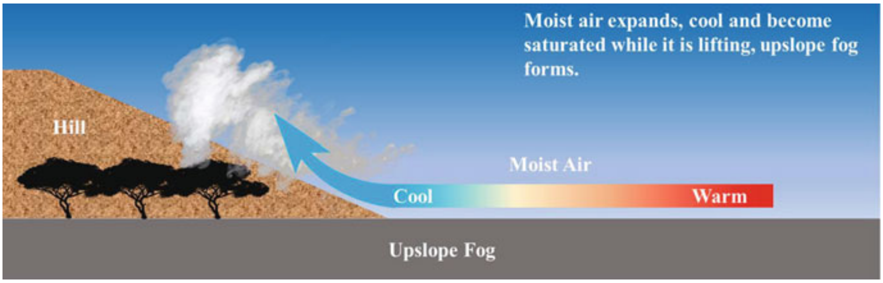

Fig. 2.4 The formation of upslope fog (modified from: Northern Vermont University n.d.)

"Advection fogs" are formed when moist air travels over a cooler surface. The moist air is being cooled due to the heat transfer process from the moist air to the surface. When the moist air temperature reaches its dew point, advection fog is formed (Aguado and Burt 2007; Ahrens and Henson 2014). Advection fogs can be found near coastal areas when warmer air over the sea moves toward the cooler land (Bergot and Guedalia 1994; Ahrens and Henson 2014). Figure 2.3 illustrates schematics diagrams of radiation fog and advection fog formations.

"*Upslope fog*" is a type of fog that is formed through the adiabatic cooling process of air. Upslope fog is formed when warm and moist air travels along an elevated slope such as hill or mountain. While the air is rising, its temperature drops owing to its expansion, then upslope fog occurs (Fig. 2.4) (Ackerman and Knox 2003; Aguado and Burt 2007; Ahrens and Henson 2014).

By now, one should be apparent that the formation of suspended particles (i.e., fog and mist) is closely related to relative humidity conditions in which suspended particles can grow faster under high relative humidity levels and number concentration of condensation nuclei. Another important factor is windspeed (Luan et al. 2018; Deng et al. 2008; Wang et al. 2019). Light windspeeds (about 5 km h^{-1}) promote condensation and fog formation, but stronger windspeeds (greater than 5 km h^{-1}) stir warm air downward to the surface, which resist cooling processes in the atmosphere (Aguado and Burt 2007; Ahrens and Henson 2014).

Human activities also accelerate the formation of suspended particles and their lifetime. Increases in local emissions and regional transport lead to increases in the suspended particulate levels (Wang et al. 2019; Sonwani et al. 2021). Changes in the characteristic of urban and rural areas can show direct and indirect impacts on suspended particles lifetime (Saxena and Sonwani 2019a). Generally, the lifetime of suspended particles is strongly influenced by canopy layer, vegetation, land use, and soil (Saxena and Sonwani 2019b). For example, fog is unlikely to occur in urban areas because the air has low relative humidity and high temperature owing to the high proportion of impermeable objects that prevent evaporation. However, the number concentration of aerosols over polluted areas are higher than these over rural areas. These aerosols can bind more water vapor, results in thicker and longer life fog once it forms in urbans (Tiwari et al. 2011; Stolaki et al. 2015; Van Oldenborgh et al. 2010). In China, increases in energy consumption, industrialization, and urbanization are considered as the major sources of increases in suspended particles, haze, and $PM_{2.5}$ concentrations, resulting in the visibility reduction in China with the rate of 2.1 km per decade (Che et al. 2009). Recent studies showed that amines emitted from vehicles, waste treatment plants, agriculture, animal farming, ocean, biomass burning, vegetation, and soil play an important role in secondary organic aerosol (SOA) formation in the atmosphere (Malloy et al. 2009; Murphy et al. 2007; Price et al. 2014, 2016; Tang et al. 2013; Yu et al. 2012). Amines can form salt particles via chemical reaction with a presence of gaseous nitric acid (HNO_3) and gaseous sulfuric acid (H_2SO_4) (Murphy et al. 2007). Besides salt particles, tertiary amines with no hydrogen atoms (H) on the nitrogen atom (N), such as trimethylamine (TMA) and triethylamine (TEA), have significantly contributed to non-salt SOA formation; which in general, they are more stable salt particles (Price et al. 2014, 2016; Tang et al. 2013; Murphy et al. 2007).

2.2.1.2 Precipitation

Precipitation is liquid or solid water particles that are falling from the atmosphere or cloud bases to the ground. "*Rain*", *"freezing rain", "sleet",* and *"snow"* are examples of precipitation. Rain is defined as liquid water falling drops that have diameter equal to or greater than 0.5 mm. Smaller drops are considered as drizzle (Ahrens and Henson 2014). If water droplets contact with thin cold air layer over the surface, water droplets become supercooled and freezing rain occurs. Similar to freezing rain with a thicker cold air layer over the surface, water droplets become frozen and turn back into tiny ice pellets which are called sleet. If the atmospheric temperature is below freezing from the cloud base to the surface, snow falls (Ackerman and Knox 2003; Ahrens and Henson 2014; NOAA 2013). Figure 2.5 shows photos of freezing rain, sleet, and snow, and Fig. 2.6 illustrates the formation of rain, freezing rain, sleet, and snow.

There are two important processes involved in the precipitation formation including droplet growth processes and precipitation forms (University of California, Irvine (UCI) 2020). Since water droplets have to be large enough to overcome the updraft and fall to the Earth's surface, growth processes are necessary. Droplets can

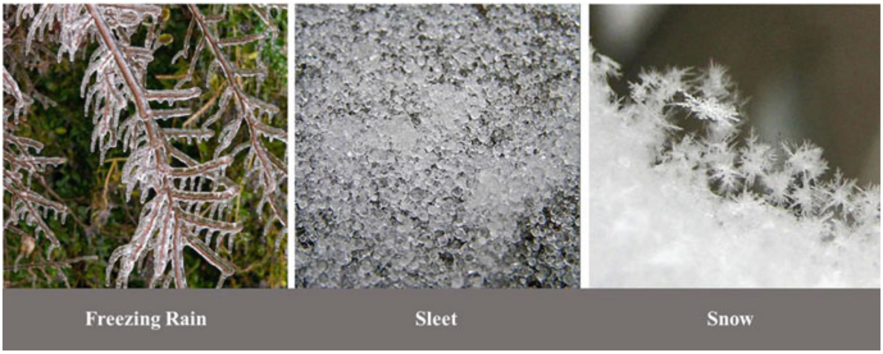

Fig. 2.5 Photo of freezing rain, sleet, and snow (NOAA 2015)

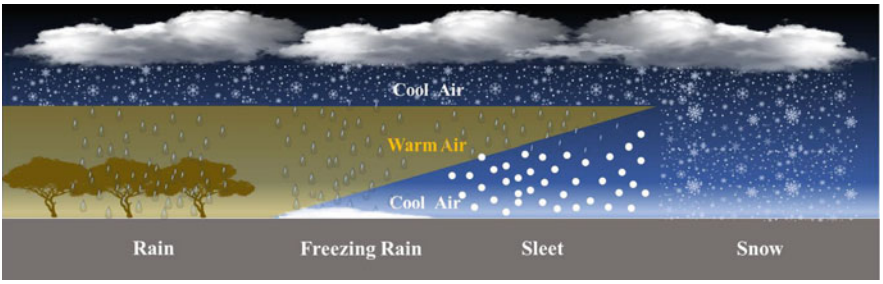

Fig. 2.6 Rain, freezing rain, sleet, and snow formation (modified from: NOAA 2013)

enhance their sizes through several processes, such as condensation, collision-coalescences, and ice-crystal (Bergeron) processes.

Among these growth processes, the collision-coalescences process plays an important role in increasing the size of water droplets in warm clouds in tropical regions (Ackerman and Knox 2003; Ahrens and Henson 2014). By droplet-droplet collision, collision-coalescences process can generate large water droplets with fast speed (Ackerman and Knox 2003). Condensation process is a slow process that takes time to create large water droplets. Ice-crystal process only occurs in cold clouds with ice particles that serve as ice-forming nuclei for water vapor deposition (Ackerman and Knox 2003; Ahrens and Henson 2014).

Effects of human activity on precipitation formations have been reported in several studies. Over polluted areas, precipitation may be suppressed. A study of Givati and Rosenfeld (2004) revealed a strong evidence of precipitation downwind of pollution sources was suppressed by 15–25% resulted in water losses in those areas ranging from 15 to 25% compared with the annual average precipitation in California, the USA, and in Israel. A similar effect of air pollution on precipitation formation was shown by Jirak and Cotton (2006). Their study showed that upslope precipitation over western Denver and Colorado Springs, Colorado, USA had a decreasing trend (about 30% compared to upwind urban sites) during the twentieth century; while the concentration of pollutants increased. Air pollution can suppress precipitation formation by creating a narrow spectrum of small droplet size that limits the collision-coalescence process. A study of Borys et al. (2003) showed that anthropogenic aerosols created tiny cloud droplets that retarded snow particle growth process, resulting in a decrease in snow fall over the northern Rocky Mountains of Colorado, Colorado, USA.

2.2.1.3 Spout

Spout is identified as a phenomenon consisting of rotating columns of air extending from the base of a cumuliform cloud. The rotating air columns consist of water droplets from the sea or dust particles over land (AMS 2012e). A "*Tornadoes*" over the sea (Fig. 2.7) is a good example of a waterspout. Generally, tornadoes form from thunderstorms with an unstable atmospheric condition or form with supercell thunderstorm (called supercell tornadoes). Tornadogenesis or tornado formation can be classified into three steps (Danielson et al. 2003):

- Mesocyclone formation
- Wall cloud formation
- Tornado formation

A mesocyclone is a large air vortex that occurs from a slow and horizontal rotation of a large segment of the cloud (Aguado and Burt 2007). The rotational speed of the mesocyclone increases when it is reshaped to be slim and extended vertically toward the Earth's surface. During this transitional stage, a wall cloud may be observed below the cloud base of the mesocyclone. Since the mesocyclone is a low-pressure area, then air moves rapidly toward the mesocyclone and increases the acceleration. If the circulation of the mesocyclone reaches the Earth's surface, a tornado is formed (Ahrens and Henson 2014; Danielson et al. 2003).

Fig. 2.7 Waterspouts in the Florida Keys (NOAA 2018). **Photographer**: Dr. Joseph Golden

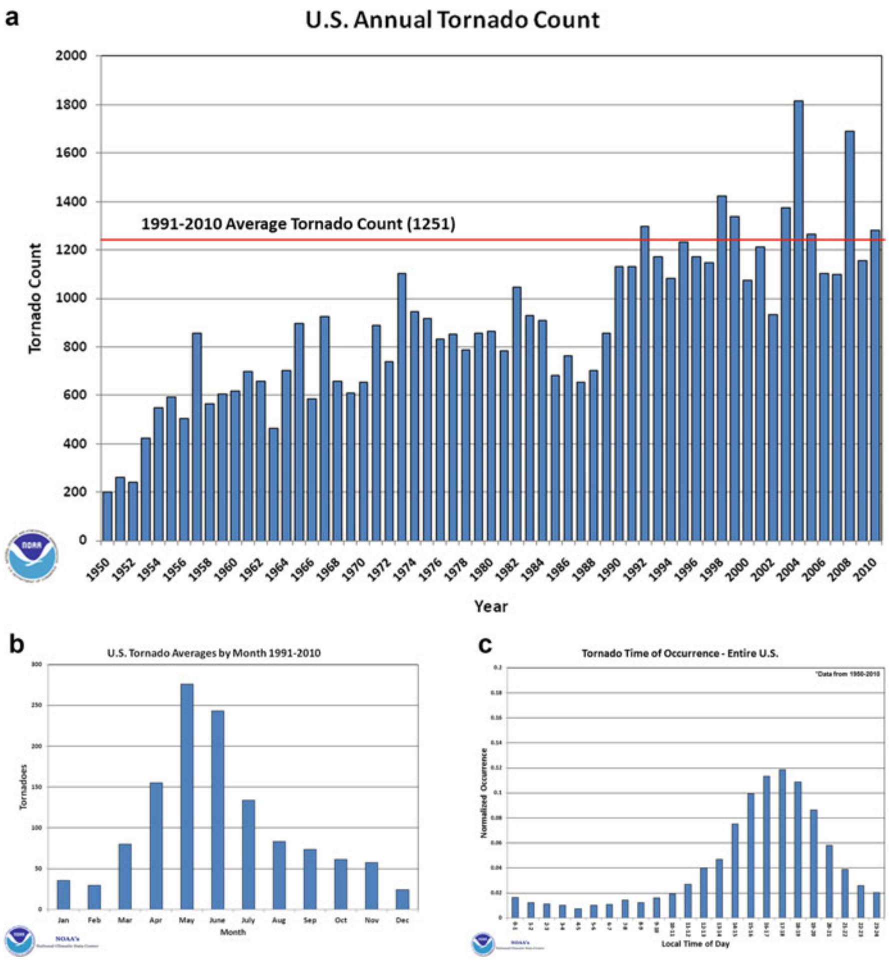

Fig. 2.8 Temporal distribution of Tornado count over the U.S. (**a**) from 1990 to 2019, (**b**) monthly average, and (**c**) daily average (NOAA 2019)

Tornado may occur more frequently over some Earth's regions, such as the U.S., than other regions. Regarding NOAA tornado's report, the number of tornadoes that occurred over the U.S. was increasing from 1995 to 2019 (Fig. 2.8a) with the annual average tornado count from 1950 to 2010 being about 1251 tornadoes (NOAA 2019). Tornadoes can occur at any month of the year and any time of the day, but most of them usually occur during May and June (Fig. 2.8b) and they can be found in the afternoon and evening more than in the morning (Fig. 2.8c).

Possible linkages between urbanization and tornadoes were reported in several studies. Molina and Allen (2020) revealed that, in regards to climate change, severe thunderstorms might occur more frequently in the future over Continental United States (CONUS). The study showed that moisture content and moisture flux had been increasing continuously since 1980s. The increases in moisture factors would lead to lower convective bases and larger vertical instability and eventually resulted in high frequency of severe thunderstorms. Saide et al. (2015) studied the effects of biomass burning smoke on the increases in tornado severity over the U.S. The study showed that by accompanying biomass burning smoke, more severe tornadoes were more likely developed over the Southeast and central U.S. During the smoke events, lower cloud bases and stronger low-level wind shear were conducted by smoke and soot resulted in stronger tornado intensity.

2.2.2 Lithometeor

"Lithometeors" are similar to hydrometeors, but lithometeors are suspended of dry particles and non-aqueous particles (AMS 2012d; WMO 2017b). Well-known examples of lithometeors are haze and lifting or blowing dust (Fig. 2.9) (WMO 2017b).

2.2.2.1 Haze

"Haze" refers to a layer of tiny dust or salt particles with diameter of about or less than 0.1 μm that are suspended in the atmosphere and it occurs when relative humidity is low. Horizontal visibility can be reduced by haze to less than 10 km through the light scattering process (Zhu and Wan 2019).

Haze can be categorized into two categories including dry haze and wet haze. Particles of dry haze are extremely small; thus, they can scatter short wavelengths of light (AMS 2012f). Due to their light-scattering ability, haze reveals bluish colors when one views against a dark background. When haze is viewed against a lighter background, it appears yellowish tint colors (AMS 2012e; Ahrens and Henson 2014). Wet haze usually occurs during nighttime to early morning due to an increase in relative humidity. When the atmosphere relative humidity reaches about 75%, water vapors collect on the dry haze particles, the size of the particles increases, and

Fig. 2.9 A hazy morning during a $PM_{2.5}$ episode across Mae Salong Mountain, Chiang Rai, Thailand and a dust devil at Arizona desert, Arizona, USA (NASA 2007)

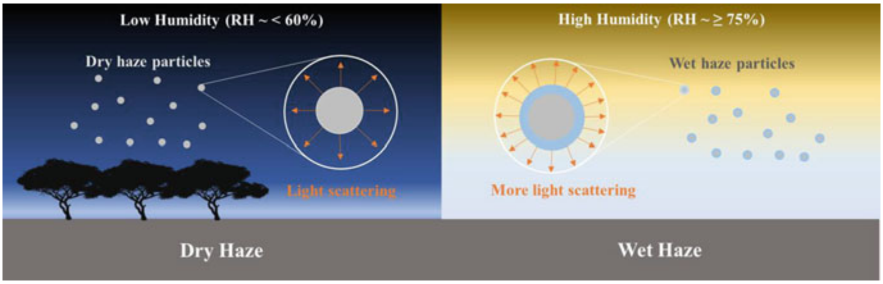

Fig. 2.10 The formation of dry haze with low relative humidity and wet haze with higher relative humidity (modified from: University of Arizona 2018b)

wet haze forms. Since the size of wet haze particles is larger than the dry haze, light is more scattered by wet haze (University of Arizona (UA) 2018). Figure 2.10 illustrates the formation of dry haze and wet haze.

Effects of human activities on haze formation are reported in many studies. Zhu and Wan (2019) reported that serious haze events that occurred in Harbin were associated with the local straw burning that generated a large amount of particles. Increasing fuel consumption also enhances the severity of haze events. Li et al. (2017) reported that more severe haze phenomena that occurred in China were a result of increases in national fossil fuel consumption that led to enhance $PM_{2.5}$ sulfate levels. Ye et al. (2011) investigated the effects of ammonia on haze formation in Shanghai, China which the study showed that ammonia from the agriculture sector might be a major source of $PM_{2.5}$ nitrate particles ($(NH_4)_2SO_4$) in Shanghai.

More pronounced impacts of haze are found in South and Southeast Asia. Very recently, Saxena et al. (2021) confirm that the haze event in conjunction with crop residue burning (CRB) over northern India has been a major air quality and human health issue. They found that CRB activities in Haryana had been affecting the air quality of Delhi, the capital region of India, with a considerable increase in pollutant concentrations during the transition from pre-burning to burning period. PM10 and PM2.5concentrations exceeded National Ambient Air Quality Standard (NAAQS) limits by 2–3 times. Clearly meteorological conditions influence pollutant concentrations during both seasons, while the conditions were exacerbated by dust storms (rabi) in the upwind city called Dusshera, as well as the firework during Diwali celebrations in kharif season.

In the Southeast Asian region, Chantara et al. (2012) describe how haze has also become an important environmental issue in the past decade, due to its impacts on both the economy and human health. They found through the daily samples of PM2.5 collected during the dry season (March–April) in the years 2017 and 2018 in Chiang Mai and Nan Provinces in Northern Thailand that the forest fires during the dry season, and agricultural residue burning regularly impacted the levels of PM2.5 concentrations. Comparisons made during La Niña years (which are usually less affected by open burning), i.e., in 2012 indicated a drop in PM2.5 values could be influenced by the implementation of the zero-burning policy that was enforced for a period of about 60 days in an attempt to control open burning practices in upper

Northern Thailand. Interestingly, nevertheless, the zero-burning policy has also contributed to prolonging the smoke haze situation from a 2-month period (mid February till mid April) to a 3-month-long period (mid February till mid May). Moreover, there are health risks from the inhalation of PM2.5 bound PAHs found in the study. Therefore, not only fine particulate matters are concerned, but their chemical compositions, particularly the levels of carcinogenic compounds that are bound to the PMs, are also posing significantly adverse health effects to the exposed population (Saxena and Sonwani 2019c).

2.2.2.2 Blowing Dust

"*Dust devil*" is a small column of air in a cylindrical shape that contains dust or sand. The size of dust devils ranges from 1 to 1000 m tall and less than 50 m in horizontal diameter at ground level. In general, dust devils are considered as a small-scale phenomenon (Luan et al. 2017). Dust devils usually occur under weak wind and sunny conditions when the hot air mass over ground level rises and generates a thermal convection whirlwind with a low-pressure core. This whirlwind has to have sufficient strength to lift and carry dust, sand, or particles (Fig. 2.11) (Luan et al. 2017; Onishchenko et al. 2019; Rafkin et al. 2016). Since dust devils are small-scale with short lifetime, normally, they are not dangerous.

2.3 Impacts of Hydrometeors and Lithometeors on Human Society

Fogs, mists, precipitation, tornadoes, and dust devils are natural phenomena; however, they may have negative impacts on human society. From the previous section, it should be apparent that visibility reduction is a major effect of suspended particles and haze on environment.

This visibility reduction influences on transportation, travel business that eventually lead to economic losses (Gultepe et al. 2007). Anaman and Looi (2000) estimated economic loss due to haze episodes that occurred over Brunei Darussalam during 1997–1998. The study showed that, by using ordinary least squares, the number of tourists to Brunei Darussalam decreased about 3.75% (compared with the tourist number in 1999) and direct economic loss was about B$1 million due to haze

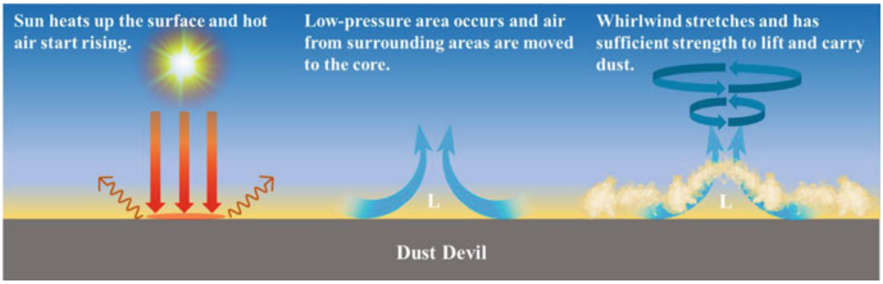

Fig. 2.11 The formation of dust devils (modified from: Gabbert 2019)

pollutions. More recent study showed a similar negative impact of haze events on tourism industry. A study of Wang et al. (2020a, b) revealed that the number of tourist arrivals to Beijing, China decreased about 5.22 million tourists owing to moderate to severe haze events, resulting in 8.95 billion yuan in Beijing's economic loss during 2016–2018. Even the number of foreign tourists decreased owing to haze events, the haze events have no significant impact on domestic tourists (Sun et al. 2019).

Negative impacts of suspended particle and haze on human health have been reported in many studies. Adverse health effects of fine particulate matters are lung irritation, respiratory diseases, cardiovascular diseases, cardiopulmonary disorders, morbidity, and mortality (Saxena and Srivastava 2020). Human respiratory system can be susceptible from fine particle's components such as free radicals, metal, and organic compounds, resulting in an inflammation of respiratory system, cell and DNA damages, impairment of human immune system, cardiac autonomic nervous system, and antioxidant system (Feng et al. 2016; Xing et al. 2016). Hanafi et al. (2019) investigated the negative effects of haze event on human health and economic losses in Pasir Gudang and Larkin, Malaysia based on observations during 2014–2016. Their study revealed that the number of morbidity cases for children (age $\leq$ 12 years old) and adults (age $\geq$ 13 years old) increased during haze episodes compared with those during non-haze events, resulting in economic losses of roughly RM83,233 and RM107,486 per year in Pasir Gudang and Lakin, respectively. In China, particulate matter is suspected as a major cause of respiratory diseases, lung disease, and premature death (Hou et al. 2019; Matus et al. 2012; Zhu and Wan 2019). A study of Matus et al. (2012) showed that high haze pollution was a substantial China's economic burden due to health damages which decreased gross domestic product in 1995 US$64 billion.

Fine particulate matter also shows negative impacts on agricultural sectors. Very high concentrations of fine particulate matter reduce wheat and corn yields. Corn yield decreases by 0.5% per unit area while $PM_{2.5}$ level increases about 1% (Zhou et al. 2017).

Thick haze plays an important role in controlling climate and pollution dispersion. Incoming solar radiation is attenuated due to the thick haze, resulting in lower surface temperature, lower heat flux, and shallow boundary layer that limit pollution dispersion. Conversely, precipitation may increase owing to more nuclei under hazy condition that can bind more water vapor (Kokkonen et al. 2019).

Tornado threats over the U.S. are obvious examples of the effects of spout on human society. Tornadoes are one of the major natural disasters in the U.S. that cause the third highest number of deaths (after floods and lightning) and it is the top three causes of economic losses owning to natural damage (after floods and hurricanes) (Boruff et al. 2003). During April 25–28, 2011, an extreme severe tornado event occurred over the U.S. About 300 tornadoes hit the U.S. from the Midwest through the Mid-Atlantic that caused about $9 billion economic loss and nearly 360 fatalities during the event (NOAA 2021; Simmons et al. 2012). Patterns of neighborhood change and relocation are associated with natural hazards. Raker (2020) studied demographic changes after natural disasters (i.e., severe thunderstorms and tornadoes) across the U.S. The study implied that after natural disasters, financially advantaged residences reconstructed the built environment rather than relocated which financially disadvantaged residences did (Raker 2020).

2.4 Conclusion

Learning about origin, mechanism, and impact of atmospheric phenomena is the first key to know how to make prediction and anticipate the effect of the phenomena. The learned society may be able to avoid loss in lives and negative consequences of experiencing the phenomena. Hydrometeors including suspended particle, precipitation and spout, and lithometeors such as haze and lifting or blowing dust are atmospheric phenomena that their formation mechanisms are significantly affected by human activities. There are strong evidence that the increases in pollutant emissions due to fossil fuel consumption and biomass burning accelerate the formation of these atmospheric phenomena and strengthen their severity; eventually; they will show negative impacts on human society such as property damages, economic losses, and the toll of death and injuries. Research on finding the origin of the mechanism and impact of the atmospheric phenomena required more support, particularly in the many parts of Asia, where less resources are available. Joint research collaboration and knowledge transfer for building the capacity of the less-developed country to monitor and collect data are crucial for the analysis on trends of the atmospheric changes. Without such effort, the society may not survive as a whole, despite the advance in technology serving other conveniences. In this respect, systematic study on the issue is highly encouraged.

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Air Pollution and Its Associated Impacts on Atmosphere and Biota Health

3

Shishir Singh and Rakesh Kumar

Abstract

Unregulated humans' activities have over-exploited the earth's natural resources, disturbed its terrestrial and aquatic ecosystems, and released vast amounts of pollutants into the environment. Air pollution is typically the presence of one or more contaminants in the atmosphere and in such quantity that is injurious to animals, plants, humans, and all other man-made and natural resources. World Health Organization (WHO) estimates that every 9 out of 10 people are exposed to high levels of air pollutants. World over air pollution is responsible for the death of about seven million people annually. A large proportion of this affected population (about 91%) resides in the developing economies in the South-East Asia and Western Pacific regions. The low- to middle-income groups are the ones who are most affected by air pollutants. Scientific studies have reported that a marginal increase of 10 μg/m^3 of ambient PM_{10} levels in Asian cities could lead to a surge in the mortality rate by 0.6%, which is significantly higher than the trends estimated for Western cities. The atmospheric CO_2 concentrations have already crossed the 410 ppm mark, which has never been recorded in human history. Air pollution operates on variable time scales and at various levels, i.e., local, regional, and global; and also produce impacts such as greenhouse effect and global warming; stratospheric; ozone depletion; atmospheric deposition, and acid rain; suppression of rainfall; atmospheric visibility reduction, etc. The severity of the impacts also varies from one organism to another and from one ecosystem to another ecosystem. Impacts on biota health are generally measured

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in terms of their influence on the morphological, biochemical, and physiological status and the responses generated thereof. Plants exposed to air pollutants may exhibit (1) direct or visible effects, which are often linked with short-term exposures to high concentrations of air pollutants or (2) indirect or invisible from long-term exposure to pollutants. Several national and international regulatory frameworks have been established to control and manage air pollutants. Despite intergovernmental and local efforts, air pollution has continued to rise across the major urban centers of the world, especially in developing economies like India and China. Scientific understanding and timely policy interventions are crucial in combatting the problem of air pollution emissions from the developed and developing world and consequently reducing their impacts on the living and non-living world. In this chapter, we have attempted to deliberate upon the major atmospheric pollutants (sulfur dioxide, oxides of nitrogen, ground level ozone, suspended particulate matter, fluorides, and peroxyacyl nitrates), their impacts on the atmosphere (global warming, stratospheric ozone depletion, acid rain, etc.), and threats to the biota health.

Keywords

Air pollution · Plants · Human health · Air quality · Atmosphere

3.1 Introduction

Earth and its atmosphere have been incessantly evolving since its inception. The primitive Earth had a toxic atmosphere with no traces of molecular oxygen and was too hostile to support any organic life. Early photosynthetic organisms were stromatolites that looked much similar to modern-day cyanobacteria that emerged around 3.2–3.5 billion years ago (Blankenship 2010). The gradual emergence and expansion of photosynthetic organisms over this Earth's surface paced the evolution of its atmosphere from an oxygen deficit to the present-day levels of around 21% (Allègre and Schneider 1994). The present-day atmosphere is an outcome of the earth's evolutionary history of 4.5 billion years; living organisms have played a crucial role in shaping the Earth and its atmosphere (Knoll 2015). Historical records suggest that over the ages various lifeforms have dwelled in a unique synergy with the Earth's atmosphere until the large-scale human interventions made since the dawn of the industrial revolution. Intensified and unregulated human actions have not only looted the Earth of its natural resources but also resulted in widespread land-use changes, emission of pollutants, and large-scale disturbances in the terrestrial and aquatic ecosystems. The atmospheric CO_2 concentrations have already touched 410 parts per million (ppm) marks at Mauna Loa Observatory, Hawaii (NOAA) (https://www.co2.earth/). Last time, the Earth's atmosphere possessed such high concentrations of CO_2 which was around three million years ago, when human had not even existed on this planet, and the average earth' surface temperature was as high as 2–3 °C relative to pre-industrial levels, while the average sea level (AMSL) was 15–25 m higher than at present (Lindsey 2020; Sonwani and Saxena, 2022).

Typically, air pollution is defined as the presence of one or more contaminants (chemicals, particulate matter, or biological materials) in the atmosphere at such concentrations and for such duration, that it is injurious, or tends to be injurious, to natural flora and fauna including humans (Katulski et al. 2011; Saxena and Sonwani, 2019a; Saxena and Srivastava, 2020; Saxena et al. 2021a); results in deterioration of surface or groundwater quality, soil productivity; damages terrestrial or aquatic ecosystems, and or materials (Manisalidis et al. 2020). In the last few decades, the urban and industrial clusters in developing economies like India and China have emerged as the new epicenters of atmospheric pollution, firstly from unplanned and unregulated economic development and secondly due to poor implementation of the regulatory framework (Chung et al. 2011). Besides, in the rural regions, the burning of traditional biomass-based fuel for heating and cooking has remained the primary source of pollution in indoor environments. According to WHO, world over around 90% of people were exposed to high levels of atmospheric pollutants in 2016. The air pollution alone kills an alarming 7 million people annually, out of which a whopping 4.2 million premature deaths are caused by outdoor air pollutants (Sonwani et al. 2021a). A large proportion of this burden, estimated to be around 91%, is shared by third world countries mainly in South-East Asia and Western Pacific regions (WHO 2020). Chung et al. (2011) reported that a marginal increase of 10 $\mu g/m^3$ of ambient PM_{10} levels in some Asian cities would increase the mortality rates by 0.6%, which is much higher relative to the Western cities. In financial terms, premature deaths due to air pollution cost about $5 trillion in welfare losses worldwide (The World Bank 2016; Sonwani et al. 2021b).

Air pollutants have been in existence for centuries. The first such complaint of air pollution from coal-burning was recorded in the thirteenth century in London (Katulski et al. 2011). Two major types of air pollution episodes were identified in the twentieth century: (1) London smog or “Reducing smog” and (2) the photochemical smog also called a “Los Angeles Type Smog”. The former is formed as a consequence of the combustion of coal under strong inversion conditions, while the latter is formed from photochemical interactions of hydrocarbons and oxides of nitrogen (emitted from sources like automobiles, incinerators, municipal dumps, etc.) in the presence of ultraviolet light from the sun (Jacobson and Jacobson 2002). The worst pollution episode of London type smog occurred in 1952, which resulted in an estimated 4000 excess deaths than the normal (Brimblecombe 1987a, b). Asian region in recent decades has emerged as a new pollution epicenter of the twenty-first century. India alone accounts for 14 of the 20 worst polluted cities in the world in terms of atmospheric $PM_{2.5}$ levels (IQAIR 2019). Recently, India has made a drastic shift in its policy toward regulating air pollution. India has committed to shifting its 40% of electricity generation to non-fossil fuels under the Paris agreement (2015). Besides, in 2019, India launched its first National Clean Air Programme (NCAP), which aims to reduce 20–30% $PM_{2.5}$ and PM_{10} levels across 102 cities in India by 2024 relative to 2017 levels (Government of India 2019). Lately, the Covid-19 shutdown in the country brought a short-term drop in air pollution levels. But as the lockdown restrictions have eased, the clear skies have disappeared again. The cities like New Delhi have already crept into the category of “severe” level of air pollution. Burning of agricultural residue is one of the major reasons for air pollution in Northern India and several other regions of South Asia too. There is a sharp dip in the air quality in the National capital New Delhi during winter. The latest reports suggest that this year, the share of crop stubble burning to New Delhi's $PM_{2.5}$ load has gone beyond 36% (SAFAR-India 2020). Huge economic losses are incurred by the airline companies due to dense foggy conditions prevailing over New Delhi in winter every year. In parts of Indonesia and Malaysia, burning of peatland and forests for land clearing for lucrative oil palm plantations also resulted in deterioration of air quality causing a choking smog which blankets not only parts of Indonesia but also spreads to Malaysia, Singapore, and southern Thailand.

3.2 Air Pollutants: Types and Sources

The majority of the air pollutants in the atmosphere are short-lived and quickly removed by wet or dry deposition generally in the vicinity of their sources. Some of them are having longer residence times (half-life of a pollutant) in the atmosphere. Many of these pollutants undergo transformation or "aging" forming new secondary species and transported via local as well as long-transport pathways. More than 3000 air pollutants have been identified which are otherwise not present in the natural environments (Gheorghe and Ion 2011). The places from where these pollutants originate are called "Sources", and the places they disappear are called "Sinks". There are a wide variety of sinks such as forests and other vegetation, soil, material structures, water bodies, etc. The removal mechanism of a pollutant from the atmosphere into the sink is called "Scavenging", while the time of its stay in the atmosphere is called its half-life. The half-life of a pollutant is defined as the time it takes for the disappearance or scavenging of half of a pollutant emitted into the atmosphere from its source. Atmospheric conditions and topography to a greater extent influence the local as well as the regional concentrations of a pollutant (Watson et al. 1988). For example, urban zones located in the valleys where atmospheric inversions take place generally have high pollutants owing to lower atmospheric mixing heights. Such places are more likely to experience a high frequency of severe smog episodes. Several gases like CO_2, CFCs, and N_2O have longer half-life times and tend to accumulate in the atmosphere over the years reaching concentrations high enough to substantially alter the natural composition of the air. The chlorofluorocarbons (CFCs) are chemically very inert and don't undergo any chemical degradation in the troposphere. In the stratosphere, high energetic ultraviolet (UV radiation) photolyze the CFC molecules, thereof releasing free chlorine atoms. Excess of free chlorine atoms disturbs the steady-state of ozone concentration in the stratosphere, triggering the destruction of stratospheric ozone, ultimately permitting harmful UV to penetrate the earth's surface (Vallero 2014; Saxena and Sonwani, 2019b).

Air pollutants can be distinguished by their chemical composition, persistence, transformation reactions, sources and sinks, and transportation mechanisms and effects on plants and animals including humans (Kampa and Castanas 2008).

Pollutants emitted directly from their sources are categorized as the primary pollutants, whereas those formed by transformation reactions with atmospheric gases or by other pollutants are termed as secondary air pollutants (Bernstein et al. 2004). The concentrations of a secondary atmospheric pollutant may decrease if a reduction in the emissions of precursors could be achieved (Gaba and Iordache 2011). Air pollutants are also classified into (1) criteria pollutants and (2) hazardous air pollutants. Both the categories of pollutants are hazardous. Regulatory authorities conduct regular monitoring for the criteria pollutants to maintain the state of ambient air quality of a region (Katulski et al. 2011). The majority of the countries including India have devised their National Ambient Air Quality Standards (NAAQS) for air pollutants of utmost concern. Under the Clean Air Act (Environmental Protection Agency 2008), United States Environmental Protection has devised NAAQS for six pollutant criteria air pollutants namely: SO_2, NO_2, CO, tropospheric O_3, suspended particulate matter, and lead (Saxena and Sonwani, 2019c).

3.3 Air Pollution and Its Impacts on the Atmosphere

Air pollutants operate at local, regional, and global levels and produce different impacts on each level (Manisalidis et al. 2020). For example, the presence of tropospheric ozone is known to augment Earths' greenhouse effect, while ozone in the stratosphere produces overall cooling effects. Some of the impacts of air pollutants on the atmosphere are discussed as:

3.3.1 Greenhouse Effect and Global Warming

Earths' atmosphere is dynamic and continually in motion. The vertical and horizontal mass movements in the atmosphere are driven by differential vertical and horizontal heating of Earth by incoming solar radiations. The state of the atmosphere measured in terms of variations in temperature, precipitation, wind direction and speed, relative humidity, the extent of cloud cover, and solar flux measures in hours, days, or weeks defines its weather (Tinsley and Yu 2003). These parameters, when observed within the geographical context and over longer durations (years, decades, centuries, thousands of years), define climate (Paruelo et al. 1998). In general, the climate is defined as the average weather conditions over a minimum period of 30 years. Air pollutants to a larger extent impact the global climate, likewise, the changing climate can impact air quality. The black carbon, a particulate product of incomplete combustion, is a strong radiative agent. This contributes to the warming of the Earth, while the particulate sulfates reflect the incoming solar radiation and exhibit a cooling effect on the Earth's atmosphere (Pöschl 2005).

The atmosphere allows the visible short-wave radiation from the sun to pass through it while inhibits the flow of long-wave infrared radiation back into space, a phenomenon which is known as the "Greenhouse Effect". The greenhouse effect helps the earth to maintain its average surface temperature at ~ +15 °C (Schneider

1989). Without the natural greenhouse effect, the average temperature on Earth is estimated to have been colder by approximately 30 °C, cold enough to sustain any of the present-day ecosystems. CO_2 and water vapors are the major gases that regulate the greenhouse effect on Earth. Other important greenhouse gases (GHGs) present in trace amounts in the atmosphere are CH_4, N_2O, tropospheric O_3, CFCs, PFCs, and SF6 (Lee 1973). Accumulation of GHGs since the onset of the industrial revolution and change in earth's albedo from land-use activities have significantly raised the global average temperatures and consequently bringing in the anthropogenic-induced climate change (Ramanathan et al. 2001: Schmidt et al. 2006). As of 1750, the GHGs like CO_2, CH_4, and N_2O have shown a respective increase of 40%, 150%, and 20% as observed till 2011. United Nations Framework Convention on Climate Change (UNFCCC) refers to climate change to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable periods. The alteration in the energy budget of the earth by atmospheric pollutants is measured in terms of radiative or climate forcing (Pachauri and Reisinger 2007) defined as any variation forced on the energy balance of the Earth (Murphy et al. 2009) and expressed in terms of watts per square meter (Wm^{-2}). The causal substances responsible for radiative forcing are known as radiative forcing agents. Earth is warmed by positive forcing agents and cooled by negative forcing agents. Greenhouse gases are positive radiative forcing agents whose presence in the atmosphere reduces the earth's ability as a whole to re-radiate sunlight into space, as a consequence of which the earth absorbs more thermal energy and warms (Zhao et al. 2019). Climate change has posed danger for all countries, however, the nations with limited adaptive capability are at the greater risks of climate-induced extreme events. Many regions in India due to their fragility are highly vulnerable to climatic impacts. Several kinds of research have been carried in India to make future climatic projections as well as to assess the vulnerability of different regions of the country toward climate change and other associated risks. In their study on Karnataka, Kumar et al. (2016a, b) have estimated that around 70% of the cultivated area of the State has been facing extreme to a high level of vulnerability from the climate-associated impacts. In another study from the Himalayan state of Arunachal Pradesh, Maiti et al. (2017) have highlighted that 7 out of 12 district studies show high social vulnerability toward changing climate. Sam et al. (2020) also emphasized that the formulation of local adaptive measures in India could potentially reduce the risk of climate-induced extreme events. Researchers have associated the probability and severity of heatwaves in India with global warming (van Oldenborgh et al. 2018). Uprety and Saxena, 2021 have predicted that the average temperatures in India would increase by 2.5–4.4 °C by end of the century w.r.t. to the current scenario, whereas the annual rainfall has been projected to show an average increase by 15–24%. Gupta and Jain (2018) have estimated that in the future the droughts in the Indian sub-continent would get more severe and frequent. Likewise, Chevuturi et al. (2018) have reported that the Leh region of India had shown a warming trend and reduced precipitation which could be associated with the reducing number of days with higher precipitation amounts over the region.

Worldwide, anthropogenic activities have produced an increase of 45% in the atmospheric concentrations of CO_2 from 280 ppm to present-day levels of 411 ppm (Shieber 2019). Such high concentrations of CO_2 have never been witnessed in human history; last time, the earth's atmosphere had these much high CO_2 concentrations which were around three million years ago, when the average earth' surface was as high as 2–3 °C relative to pre-industrial levels, and average sea level was 15–25 m higher than at present. The cumulative impact of human activities on the global average temperature rise has been approximated to around 1.0 °C relative to the pre-industrial levels of 1750. At the present pace, the GHG emissions would result in warming up to 1.5 °C between 2030 and 2052 (IPCC 2018). United Nations Framework Convention on Climate Change (UNFCCC) has taken steps from time to time to develop a global consensus to check the GHGs emissions by various countries. Under UNFCCC's Paris agreement (2015), keen efforts have been made by the global community to restrengthen the commitment for the regulation of GHGs emissions, limit the global temperature rise in this century well below 2 °C above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 °C (UNFCCC 2015). IPCC which provides important scientific inputs for framing international policies toward climate change recently has also released a special report in 2018 to evaluate the global response concerning advancement made toward limiting the temperature rise in this century up to 1.5 °C above pre-industrial levels (IPCC 2018).

3.3.2 Stratospheric Ozone Depletion

The stratospheric ozone layer or "Good" ozone is a region of the atmosphere between 10 and 50 km where 90% of the atmospheric ozone is contained. Stratospheric ozone (O_3) absorbs harmful ultraviolet (UV) radiations from the solar flux, which could otherwise harm life on the earth's surface. The total atmospheric O_3 mass is estimated to be around three billion metric tons, which constitutes only 0.00006% of the atmospheric mass of all gases combined. The highest O_3 concentrations nearly equal to ~15 ppm is found at roughly 32 km above the earth's surface. Total columnar ozone (TCO) is represented as a Dobson Unit (DU). One Dobson Unit is defined as the number of molecules of O_3 required to create a pure O_3 layer of 0.01 mm thickness at a temperature of 0 °C and sea level (1 atm pressure) (Godish et al. 2014). Natural O_3 formation and degradation begin by high-intensity, shortwave solar ultraviolet radiation (<242 nm) in the stratosphere, as seen in the equations below:

$$O_2 + h\upsilon \rightarrow O + O \tag{3.1}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{3.2}$$

$$O + O_3 \rightarrow 2O_2 \tag{3.3}$$

$$O_3 + h\upsilon \rightarrow O_2 + O(^1D) \tag{3.4}$$

where hυ is a UV photon and M is a molecule that absorbs energy. These reactions are known as the Chapman Cycle. In the stratosphere, ozone production and degradation involve molecular-oxygen (O_2), atomic oxygen (O), and O_3 reactions (Rowland 2009).

Ultraviolet radiations coming from the sun are classified into UV-A, UV-B, and UV-C radiations. Stratospheric ozone absorbs almost 99% of UV wavelengths below 320 nm. UV-C light (100–290 nm) has a relatively smaller wavelength and is extremely harmful to the living biota on the earth's surface. Most of it is absorbed by O_3 and O_2 molecules in the stratosphere. The UV-B (290–320 nm) are highly energetic UV radiations and harmful for living biota, roughly 95% of all UV-B is absorbed by the stratospheric ozone. UV-A (320–400 nm) has the longest wavelength and is the least harmful UV radiations (Rowland 2009). Earth's surface receives a high influx of UV-A radiation and low to moderate influx of UV-B radiations depending upon the state of stratospheric O_3 (Cutchis 1974). Scientific deliberations on stratospheric O_3 depletion started in the late 1960s. In 1974, Sherwood Rowland and Mario Molinas suggested that chlorofluorocarbons (CFCs) in the stratosphere undergo photolytic break down releasing Cl atoms, which in turn chemically degrade the stratospheric O_3. Later evidence suggested that O_3 layers could also be affected by the increased release of nitrous oxide (N_2O) from the denitrification of ammonium and nitrate fertilizer (Rowland 2009). The stratospheric ozone hole was first discovered by a team of scientists, Farman, Gardiner, and Shanklin working in Antarctica; their findings were published in the "Nature" journal in 1985. The decline in the polar ozone was far more than the anticipated figures (Farman et al. 1985). More information from satellite data suggested that the ozone depletion extended beyond the experimental sites, covering most of the Antarctic region. Technically, the ozone hole is defined as a geographical region having an ozone concentration of the air column lower than 220 DU (Newman et al. 2004). In the 1980s, several deliberations between scientists and policymakers resulted in the framing of landmark international regulatory provisions aimed at phasing out and prohibiting the use of long-lived Cl and Br halocarbons (Godish et al. 2014). Montreal Protocol of 1987, and subsequent amendments made therein, placed an international ban on the manufacture and distribution of CFCs, halons, and other ozone-depleting substances (ODS) with effect from 1989. It is expected that stratospheric O_3 would eventually recover to its pre-industrial levels, though it would take years for its complete recovery since CFCs and halons have a longer residence time in the atmosphere (Wilmouth et al. 2018).

In the lower troposphere, surface O_3 has a crucial role in increasing the oxidizing ability of the atmosphere but also has detrimental effects on plant and animal health including humans (Saxena et al. 2019). In India, surface ozone observations were carried out by various groups in different regions and their findings were highly useful to explain the regional air quality. South-East Asia is an anthropogenically active region and model simulations predicted major environmental consequences due to increased ozone values only in India, China, etc.

3.3.3 Atmospheric Deposition and Acid Rain

Atmospheric gases and particulates emitted from different sources are transported from air to water and soil through atmospheric deposition. This transfer process may be harmful or beneficial in terms of the impact of deposition on various sources. For instance, ozone deposition has detrimental effects on vegetation, while the deposition of nitrogenous compounds may be beneficial or detrimental. Nitrogen deposition can bring in additional nutrients for the plants, though the excessive deposition may cause eutrophication of water bodies (Smith et al. 1999). The acidification of precipitation, also termed as "Acid Rain", is also an example of the detrimental effects of atmospheric deposition. During their atmospheric transport and deposition, gases and particles undergo different physical and chemical transformations. These transformations affect significantly the fate and behavior of different chemicals undergoing deposition (Pacyna 2008). Besides, atmospheric deposition has potential consequences of increasing glacier melting by the darkening of the surfaces of snow and ice; decreases the photosynthesis process on the surface of the leaves; acidification of water bodies; changes in the soil's properties, etc. (Menon et al. 2007).

Atmospheric depositions on the terrestrial and aquatic ecosystems may happen through (1) dry deposition and (2) wet deposition. Primary and secondary particulates are removed by the gravitational force from the atmosphere over time without precipitation, this process is termed as "dry deposition" (Lovett and Kinsman 1990). Dry deposition primarily depends on the size, concentration, and reactivity of the particle deposited and the surface being affected (Lindberg et al. 1982). Particles with a size of >0.8 mm are considered to be easy to settle whereas those with a diameter of <0.08 mm may remain suspended for a longer duration in the atmosphere and therefore transported over to longer distances (Ruijrok et al. 1995). Dry deposition primarily delivers particulates of crustal origin predominantly rich in Ca^{2+}, Mg^{2+}, K^{+}, and total phosphorous to the earth's surface. On the other hand, wet deposition is assisted by wet weather events (e.g., rain, snow, and hail) and dominantly deposits Na^{+}, total nitrogen, NO_3^{-}, and fine particulates to the earth' surface (Morales-Baquero et al. 2013). In countries like India, where dry conditions prevail in a larger part of the year, dry deposition is an important process of removal of atmospheric pollutants (Sharma et al. 2008). Wet deposition predominates in the higher precipitation regime zones (Balestrini et al. 2000). Dry deposition is an important feature in the local removal of micropollutants in the industrialized regions too (Gambaro et al. 2009). Studies have shown that dust load deposited from dry deposition has profound effects that impact on the lake, marine sediments, leaf surfaces, forest canopy, crop productivity, etc. (Gao et al. 2019). The aerosol deposition over snow or ice affects its reflective efficiency and increases the heat absorption and melting of Himalayan glaciers and polar ice (Hansen and Nazarenko 2004; Yasunari et al. 2013). Wet deposition, on the contrary, is completely related to wet weather events (e.g., rain, snow, and hail). Wet deposition is responsible for the removal of the majority of aerosols from the atmosphere. Wet deposition can be classified as (1) in the cloud scavenging, where condensation occurs around one or more aerosols which are used as a core (nucleation) and (2) scavenging beneath the cloud, where the particles are impacted in the air column beneath the cloud. Both of these may occur individually or together, depending on the aerosol concentration in and below the cloud when precipitation is taking place (Roux et al. 2016).

Acid rain refers to low pH precipitation events. Natural rain is slightly acidic, having a pH of 5.7 due to the formation of carbonic acid formed from the dissolution of atmospheric CO_2 following Henry's law governing the dissolution of gases. The acidity of rain is caused by the dissolution of atmospheric SO_2 and NO_2, which undergo reactions with water molecules in the atmosphere to produce acidic compounds, i.e., H_2SO_4 and HNO_3 (Magaino 1997). Acid rain is highly harmful to terrestrial plants, aquatic biota, crops, and materials. Such precipitation events are threats to the terrestrial and aquatic ecosystems, the local and regional geology is important in neutralizing the acidity. Soils and surface water having lower amounts of Ca and Mg carbonates exhibit lower buffering capacities and are most prone to damages from acid deposition. Acidity lowers the cation exchange capacity of the fertile soils, it also results in leaching away of an important nutrient, thus restricting their availability to the plants. On the other hand, the availability of toxic ions like Al^{3+} and Fe^{2+} increases in the soil solution (Aerts and Bobbink 1999). The acidic deposition has resulted in the chronic acidification of many lakes and streams in North America and the Scandinavian peninsular region (Godish et al. 2014). Beier et al. (2017) reported that the chronic acidification of the Adirondack region's (USA) forests, lakes, and streams affected the potential economic and cultural benefits they provide to society. Liu et al. (2018) observed that the Chinese fir sapling height growth rate (HGR) and basal diameter growth rate (DGR) decreased as acid rain pH decreased. In a similar study, Du et al. (2017) observed that acid rain-reduced leaf chlorophyll content on average by 6.7% per pH unit across the recorded plant species. Sosa-Echeverría et al. (2019) also emphasized that external emission sources play a decisive role in acid rain within Mexico City. In India, Roy et al. (2016) reported that 55 and 65% of the rainwater samples during monsoon seasons of 2013 and 2014 over Falta and Darjeeling, West Bengal (India) were acidic. In similar observations, Garg et al. (2000) reported that acidic rain events occurred throughout the year, with a frequency of 64% and 87% during monsoon and non-monsoon seasons, respectively, in Guwahati during June 2016–June 2017.

3.3.4 Suppression of Rainfall

Air pollutants produce diminishing effects on the intensity of rainfall. This could be a serious public issue especially for the water-scarce and densely populated regions of the world. Long-term precipitation data of 50 years collected from several mountain ranges in the western United States have suggested a gradual decrease in the rainfall by around 10–25% (Schiermeier 2007) during the observation period. Cloud is formed of tiny cloud droplets typically of a 10 μm radius. These droplets coalesce together to form precipitation-sized raindrops of radius 1000 μm (= 1 mm), thus the mass of typical raindrops is equivalent to one million cloud droplets.

The coagulation of tiny cloud droplets into raindrops is governed by their size, at least some of the cloud droplets in a cloud mass should have a size of radius >15 μm for the effective formation of precipitation in that cloud (Rosenfeld 1999, 2000). Hydrophilic aerosol particles are good cloud condensation nuclei (CCN). Water vapor easily condenses on the surface of such particles resulting in the formation of clouds under supersaturated conditions (Che et al. 2016). Whereas, the pollution aerosols act as small CCN, which produces a large number of smaller-sized cloud droplets. This leads to the suppression in the formation of precipitation-sized rain droplets within the cloud mass and prolongs the clouds' life, warm rain process, and ice precipitation (Rosenfeld 2000; Borys et al. 2003; Rosenfeld et al. 2008). Besides, the sulfate aerosols are also known to suppress the precipitation from the clouds. Borys et al. (2003) have reported that an addition of 1 μg m^{-3} of sulfate aerosols leads to the reduction of snowfall rate by 50% in the Colorado Rocky Mountains (USA). Thus, there is enough experimental evidence to suggest that anthropogenic aerosols can disturb the hydrological balance over a landmass by interfering with the cloud formation and precipitation.

3.3.5 Visibility Reduction

Visibility is considered as a primary air quality index. Visibility reduction results from the absorption and dispersal of sunlight by suspended particulate matter as well as from the atmospheric gases (Hyslop 2009). Visibility is also limited by natural factors such as rain, snow, fog, aeolian dust, sea spray, hazes, etc. The first case of Arctic haze was reported in the 1950s. Industrial pollution of SO_2, elementary carbon (EC), HCs, metals, other gases, and particulate matter are the main cause of the Arctic haze. As the occurrence of Arctic haze was identified and researched over decades, observation of the Asian brown clouds was made in 1999 (Graff Zivin and Neidell 2013). The brown haze of about 3 km high covers the majority of the tropical Indian Ocean, South East, and East Asia. Studies have revealed high concentrations of sulfates, nitrates, organics, carbon (C), fly ash, and other pollutants as the major components of such haze (Chen et al. 2012).

Indo-Gangetic plains (IGP), in particular, are the hotspots of Asian brown haze or clouds. Large-scale agricultural, industrial, and other commercial activities in this region generate a wide variety of atmospheric pollutants resulting in the formation of brown haze. The winter in North India is frequented by low visibility from fog formation. Indian capital city, New Delhi, and nearby regions, experience a high frequency of smog episodes during winter due to pollutants from the burning of crop stubble in the surrounding states of Punjab, Haryana, and Uttar Pradesh during the winter season (Kumar et al. 2016a, b) along with high relative humidity (RH), sufficient sunlight, and reduced vertical mixing (Chen et al. 2018). Smog episodes have been associated with serious health ailments, besides low visibility often disrupts railways, flights, and road transport services yearning economic losses. Visibility reduction is not only detrimental to ambient air quality (Gu et al. 2017) but can also diminish solar flux reaching the earth's surface. Volcanic emissions from the eruption of Mount Pinatubo, the Philippines in June 1991 released an estimated 20 million sulfur dioxide in the atmosphere. Sulfate aerosol emissions of this magnitude reduce the solar flux reaching the earth's surface lowering the tropospheric temperatures.

3.4 Impacts on Biota Health

Atmospheric pollution significantly affects human health, terrestrial and aquatic ecosystems, local and regional climate, and consequently society and economy (Correia et al. 2013; Fang et al. 2013; Rao et al. 2017). The Geneva Convention held in 1979 on Long-range Transboundary Air Pollution emphasized the protection of humans and the natural ecosystem from the deleterious effects of atmospheric pollutants. The convention has endorsed the reduction of eight air pollutants: SO_x, NO_x, persistent organic pollutants, non-methane volatile organic compounds, tropospheric ozone, heavy metals, particulate matters (PM_{10}, $PM_{2.5}$), and black carbon (De Marco et al. 2019). The effects of air pollutants on lower and higher organisms are measured in terms of their influence on the morphological, biochemical, and physiological status and responses thereof. In plants, the penetrations of pollutants mainly occur via leaves (Fig. 3.1). Small penetration of pollutants may happen through the stems and trunk (Seyyednejad et al. 2011). Air pollution effects may be classified into (1) direct or visible and (2) indirect or invisible injury (Gheorghe and Ion 2011). Visible injury is often linked with short-term exposures to high concentrations of air pollutants. The damaged portions of the leaf surface can offer easy entry for plant pathogens. Besides the visible injury in the form of discoloration, scabs, etc. can reduce the market values especially of the crops, for instance, visible injury can reduce the market value for tobacco, spinach, and horticultural crops. Invisible injury results from long-term exposure to pollutants. It impacts various physiological or biochemical processes in plants that can ultimately damage their growth and development, reduce nutritional quality, and yield (Liu and Ding 2008).

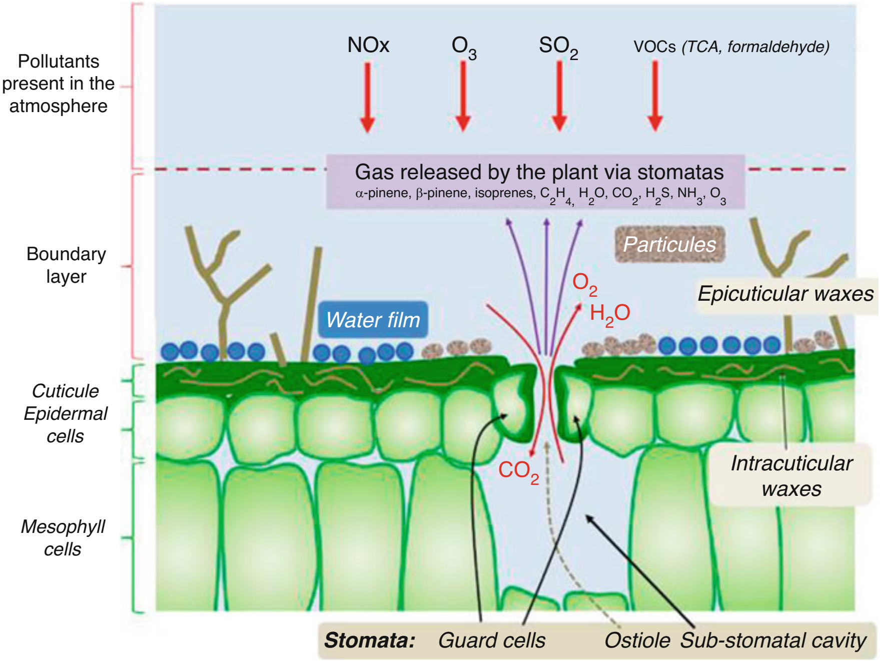

Fig. 3.1 Schematic representation of the environment of leaf surfaces. [adapted from Garrec 2020]

3.4.1 Sulphur Dioxide (SO_2)

Sulfur dioxide (SO_2) is a common atmospheric pollutant that affects plants, animals, men, and materials. SO_2 has a solubility of 228 g/L in the water at 0 °C. SO_2 is an important precursor for the formation of secondary atmospheric pollutants and acid rain. As of 2019, India contributes to the largest anthropogenic emissions of SO_2 in the world, which roughly equals to $>15\%$ of global emissions of SO_2 from anthropogenic sources (Kapil 2019). Under high humidity conditions, SO_2 is oxidized to SO_3 which forms sulfuric acid (H_2SO_4) when hydrated. SO_2 is taken up by the plants predominantly through the stomata. The uptake is dependent both on the stomatal conductance (Mudd 2012) as well as the prevailing environmental conditions such as the amount of light, temperature, relative humidity, wind speed, etc. Under the low light and water deficit condition, stomata remain closed and exhibit a lower degree of susceptibility to the SO_2 injury.

Nonvascular plants like lichens and bryophytes having low chlorophyll contents and no cuticle present are relatively more susceptible to SO_2 injury under high exposures. SO_2 has been the major culprit responsible for the dramatic decline in several bryophytes and lichens species in urban and industrialized regions of the world. Under high SO_2 polluted atmospheres, lichens become compact and sterile with a much smaller colony size. Among the plants, the most common type of acute injury due to SO_2 pollution is interveinal chlorosis. Some common species susceptible to SO_2 injury are oats (*Avena sativa*), cucumber (*Cucumis sativus*), and spinach (*Spinacia oleracea*), while celery (*Apium graveolens*), maize (*Zea may*), and citrus species (Mudd 1975) are known to exhibit resistance toward SO_2 injury. India is the largest emitter of sulfur dioxide in the world. Several studies have been conducted in India to evaluate its effects on plants and animals. Farooq et al. (1985) reported the depletion of starch and accumulation of free sugars in tissues in 2-month-old chilbil *Holoptelea integrifolia* exposed to SO_2 in experimental chambers. Similarly, Agrawal and Verma (1997) have also observed that SO_2 exposure leads to a reduction in total chlorophyll, ascorbic acid, starch, and protein contents in the 30-day-old two cultivars of wheat (Malviya 206 and Malviya 234). In another study, Verma and Agrawal (1996) observed that SO_2 fumigation to soybean (*Glycine max*) plants resulted in severe effects on photosynthetic pigments, ascorbic acid and protein contents, biomass, and productivity. A study by Dwivedi and Tripathi (2008) revealed a positive correlation between ambient air sulfur dioxide and sulfate contents in leaves of Ficus religiosa. The nonvascular plants show the acute direct impacts of SO_2 at much lower concentration relative to vascular plants, thus bryophytes and lichens often determine critical level set for ambient atmospheric SO_2 concentration in the natural environment. Experiments by Majernik and Mansfield (1970) revealed that exposure of SO_2 to fully hydrated 5-week-old broad bean (*V. faba*) leaves at 40% relative humidity and 18 °C, promoted stomatal opening, thereby promoting greater diffusion of sulfur dioxide into the leaves. Similar experiments by Unsworth et al. (1972) using ^{14}C technique in the lichen species *Cladonia alpestris, C. deformis, Stereocaulon paschle*, and *Umbilocaria muhlenbergii* suggested that exposure to SO_2 at low pH resulted in a reduction of carbon fixation by lichen species. Similarly, studies have shown that exposure to SO_2 increased the rate of respiration in lichens and bryophytes.

3.4.2 Oxides of Nitrogen

Nitrogen in molecular form (N_2) is the most abundant gas in the atmosphere. Lesser amounts of nitrogen exist as nitrous oxide (N_2O), nitrogen dioxide NO_2, nitric oxide (NO), ammonia (NH_3), and several other oxides of nitrogen. Nitrogen dioxide acute injury signs appears in plants when the latter is exposed to a threshold concentration of 2 ppm of NO_2 for a duration of 4-h. This rarely happens at its natural ambient background concentrations of NO_2. Natural sources of oxides of nitrogen include atmospheric lighting, the decay of organic matter, and forest fires. While human activities such as the burning of fossil fuels in factories, automotive, and other high-temperature processes are its primary sources, which often emits more than its natural sources. The usage of catalytic converters in the locomotive exhaust can prevent emissions of nitrogen oxides to a larger extent (Forcetto and Daemme 2017). Many oxides of nitrogen are important precursors resulting in the formation of secondary pollutants including smog, acid rain, ground-level ozone, and formation of particulates (Brown et al. 2006; Yung et al. 2007; Ghazali et al. 2010).

Exposure of NO_2 in plants beyond tolerable threshold levels triggers complex physiological responses and changes in antioxidant enzyme activity. The use of tolerant species which could catabolize the atmospheric NO_2 is considered a viable ecological method to reduce its air concentrations. A recent experiment conducted by Sheng and Zhu (2019) revealed that NO_2 exposure in garden plants (6 μL/L NO_2 in glass chambers and subsequently transferred to a natural environment for a 30-day recovery) affected the leaf chlorophyll content and induced biochemical defense responses. Mansfield et al. (1982) also suggested that SO_2 interferes with the induction of the nitrite reductase, an enzyme responsible for the reduction of NO_2 to NH_3, which possibly the main mechanism by which NO_2 toxicity is regulated by the plant cells. Besides, atmospheric nitrogen deposition results in soil degradation thus indirectly affecting the soil biota. Acidic deposition of oxidized and reduced nitrogenous compounds is characterized by loss of buffer capacity of the soils and reduces their cation exchange capacity (CEC). Lowering of the CEC of the soils leads to the increased loss of the Ca^{2+} and Mg^{2+} and other micronutrients to the soil solution, and increased availability of harmful metals like Al^{3+} and Fe^{2+} (Aerts and Bobbink 1999). Besides, the lower pH triggers the inhibition of nitrification, resulting in an increase of ammonium to nitrate ratios. Because of their high sensitivity to atmospheric NO_2, lichens can be used as potential cost-effective bioindicators of NO_2 pollution in the air (Conti 2008).

Lichen distribution, colony size, and concentration of elemental nitrogen in thalli have been used for biomonitoring nitrogen distribution and deposition patterns (Johansson et al. 2012) in many parts of the world. Owing to their unique biology, and lack of a cuticle layer to regulate the atmospheric absorption and the leaching of nutrients, lichens dynamically concentrate such nutrients in proportion to their atmospheric abundances. Increased nitrogen deposition favors the growth and abundances of eutrophic nitrogen-loving lichen species over oligotrophic species, growing in nutrient-deficient environments (Root et al. 2015). Bignal et al. (2007) reported the ecological impacts of nitrogen oxides from vehicular sources on vegetation at two experimental sites in England. Their findings suggested that NO_2 emissions from vehicular emissions exerted a strong influence on vegetation within the first 50–100 m from the road. In India, Pandey and Agrawal (1994) reported that exposure of SO_2 and NO_2 (0.1 ppm SO_2 + 0.2 ppm NO_2 for 4 h daily for 50 days) to 45-day-old Tomato plants (*Lycopersicon esculentum*) produced reduced root growth and low root:shoot ratio.

3.4.3 Ground Level Ozone

Ground level or tropospheric ozone is a secondary air pollutant unlike good ozone in the stratosphere. It is produced in the troposphere by a series of complex photochemical reactions from its precursor gases, i.e., NO_x and VOCs (Brown et al. 2006; Ghazali et al. 2010). The emissions of precursors of O_3 have decreased or remained constant in the last few decades especially in developed countries. But in the developing countries China and India, due to rapid industrial development and

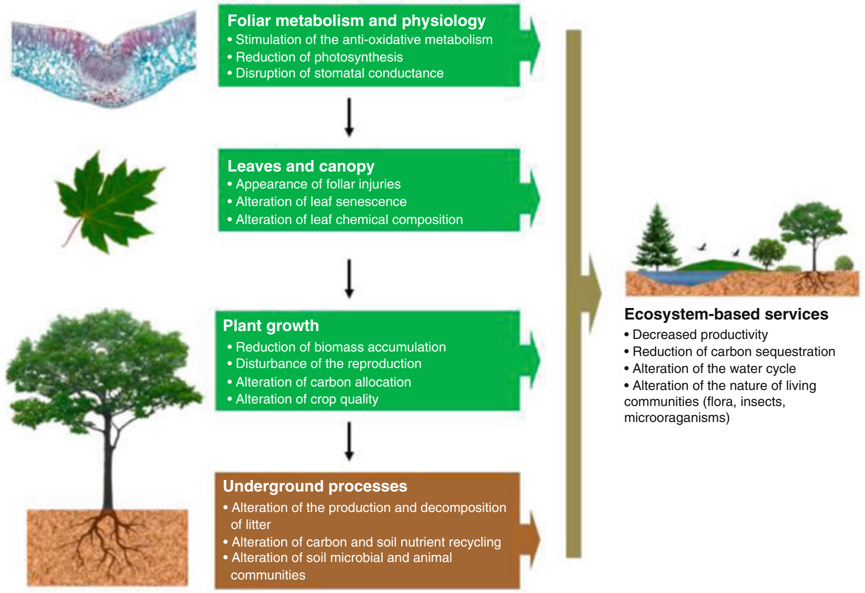

Fig. 3.2 Effects of ozone on vegetation: from plant cells to ecosystems. [Source: © J.P. Garrec]

urbanization, emissions of such gases have been continuously increasing (IPCC 2007; Ohara et al. 2007). Other than precursors, meteorological parameters like solar irradiations and temperature influence atmospheric ozone concentration.

Ozone is highly phytotoxic, its adverse effects on plants were first identified in the 1950s (Ashmore 2005), which can affect many plant species growing in the wild as well as the cultivated ones (Runeckles et al. 1992; Saxena et al. 2021b). Common symptoms of ozone injury include a decrease of photosynthetic pigments, visible leaf injury, and decline of photosynthetic activity in plants exposed to higher doses of atmospheric ozone (Krupa and Manning 1988; Soldatini et al. 1998; Guidi et al. 1998; Saitanis and Karandinos 2001). The acute visible injury in plants (Fig. 3.2) could decrease the economic value of species such as horticulture crops whose market value highly depends on their visible appearance (Fumagalli et al. 2001). For instance, in North Athens, an ozone episode of 1998 caused such severe reddening and necrosis on *Chicorium endivum* and *Lactuca sativa* devalued the market price of that local crops (Velissariou 1999). Many examples of ozone injury to the crops have been reported from India (Bambawale 1986), Taiwan (Sheu and Liu 2003). Proietti et al. (2016) reported a decrease in Gross Primary Production (GPP) ranging from 0.4 to 30%, in European forest from ozone exposure during 2000–2010. Heck and Dunning (1967) have also observed that plants are grown under shorter photoperiods and lower light intensities are more sensitive to ozone stress relative to those grown under longer photoperiods and lower light intensities or shorter photoperiods and higher light intensities. Further work by Hoshika et al.

(2013) suggests that ozone exposure and water stress together delayed the time of the closing signal in snap bean. Gas chamber experiments by Alonso et al. (2001) also suggested that cumulative effects of ozone and drought decreased antioxidant enzyme activities in *Pinus halepensis* exposed to 40 nL L^{-1} concentrations of ozone. Studies have revealed that ozone exposure resulted in reduced chlorophyll contents of leaves, many workers have used plant's chlorophyll content as a reliable indicator of ozone injury (Agrawal et al. 1993; Welfare et al. 1996; Della Torre et al. 1998). In India, Sarkar and Agrawal (2012) observed that the growth parameters such as pollen viability and grain yield were reduced under elevated O_3 stress exposure to two high-yielding rice cultivars (*Oryza sativa L. cvs Malviya dhan 36* and *Shivani*). Bhatia et al. (2011) reported that ozone exposure to rice (Oryza sativa L.) has been associated with a decrease in methane and nitrous oxide (GHGs) emissions. In similar observations, Singh et al. (2018) reported that elevated ozone exposure of 30 ppb above ambient levels to 14 widely grown Indian cultivars exposed to 30 ppb elevated O_3 resulted in foliar injury and severely affected grain yield. Mina et al. (2010) have also observed the effects of O_3 exposure on different growth stages of Potato (*Solanum tuberosum*).

3.4.4 Suspended Particulate Matter

Suspended particulate matter includes the solid and liquid particles suspended into the air. These particulates vary in their shape, size, and composition and originate from diverse natural and anthropogenic sources (El Morabet 2019). Based on their size which is measured in terms of their aerodynamic diameter (dp), suspended particulate matters are classified into three commonly used size categories as (1) coarse particulates (dp = 2.5–10 μm), (2) fine particulates (dp $\leq$ 2.5 μm), and (3) ultrafine particulates (dp $\leq$ 0.1 μm) (Seinfeld and Pandis 2016). The aerodynamic diameter of a particle is defined as the diameter of a unit density spherical particle, having the same settling velocity as that of the particle under consideration. Coarser particulates are generally of crustal in origin, i.e., derived from aeolian action on dry soil, road dust sediments, combustion particles, municipal and solid waste debris, etc. Whereas, the fine and ultrafine particulates are originated directly from the combustion processes, the nucleation of the small particulates, and/or gas to particle conversion mechanisms.

Many studies have revealed that in the urban environments the PM_{10} and $PM_{2.5}$ atmospheric concentrations are closely linked to vehicular emissions and other combustion processes (Prajapati and Tripathi 2007; Kumar and Yadav 2016; Kumar et al. 2016a, b). World over, countries including India have established the legal framework to regulate the ambient concentration of suspended particulates especially $PM_{2.5}$ (dp $\leq$ 2.5 μm) and PM_{10} (dp $\leq$ 10 μm). Ultrafine particles can penetrate the systemic circulation and exhibit high levels of toxicity relative to coarse and fine mode particles. Moreover, the larger surface area of the fine particles increases their potential to adsorb high content of hazardous substances including heavy metals (Bernstein et al. 2004). Deposition of particulates on the leaf surface may obstruct the amount of sunlight, result in the plant by increasing leaf surface temperature (Rahul and Jain 2014), and, the effect on plant physiology and biochemistry (Rai 2016). Particulates with diameter lesser than the stomatal aperture can directly enter the sub-stomatal cavity, may result in stomata clogging (Vijaywargiya and Pandey 2003), which in turn could decrease the rate of carbon dioxide exchange (Darley 1966), carbon assimilation, transpiration (Singh and Rao 1982), and therefore net photosynthesis (Singh and Sthapak 1999). Studies have reported an increase in the number of epidermal cells and stomata, necrotic lesions, and death of epidermal cells in plant species exposed to particulate pollution (Jafri et al. 1979; Borka 1981; Shanmughavel 1997; Pal et al. 2000).

Plant leaves provide a large surface area for impingement, absorption, and accumulation of air pollutants. Vegetation cover can be used as an important means for filtering out suspended particulates in the air, especially in the high traffic density locations and industrial zones (Freer-Smith et al. 1997) for enhancement of urban air quality (Beckett et al. 1998; Freer-Smith et al. 2005). The capacity to filter atmospheric pollutant may vary from one species to other (Liu and Ding 2008). Sett (2017) suggested that cuticular and epidermal traits of the leaves in response to the dust pollution could be used as the bioindicator of the pollution levels.

3.4.5 Fluorides

Fluoride compounds have severe impacts on the animals and terrestrial and aquatic ecosystems (Weinstein and Davison 2004; Divan et al. 2008; Walna et al. 2013). Natural sources of fluoride emissions into the atmosphere are rock weathering, volcanic eruptions, or the marine environment (Barnard and Nordstrom 1982), while the principal anthropogenic sources are fertilizer production and application, household detergents, aluminum smelters, cement industries, ceramic and pottery works and glass manufacture (Cape et al. 2003). Common examples of fluoride pollutants are SiF_6, HF, CF_4, and F_2 in the gaseous phase and CaF_2, NH_3F, Ca_3AlF_6, AlF_6, NaF, and Na_2SiF_6 in the particulate phase. Hydrogen fluoride (HF), is the most hazardous fluoride pollutant. Fluorine emitted from anthropogenic sources in the gaseous phase is hydrolyzed under moist conditions to form HF. Hydrogen fluoride undergoes a rapid chemical reaction with silicates to form volatile SiF_6. HF also reacts with many materials forming nonvolatile, stable fluoride compounds (Kirk and Lester 1986). The distribution and deposition of its compounds are primarily governed by the magnitude of their emissions from the source, chemical reactivity of the fluoride compounds (Hara et al. 1998), size of the particulates, and meteorological conditions (Gasic et al. 2010; Scheringer 2009).

Damage to plants from fluoride compounds can happen at concentrations about 1000 times lower than those causing any visible effects on human health (Manins et al. 2001). Atmospheric HF can result in visible injury in plants at concentrations as low as 0.3 μm^{-3} (Cape et al. 2003). Fluoride contamination affects photosynthesis and other physiological processes in plants. It enters into the transpiration stream of plants through stomata or roots (Feng et al. 2003) and accumulates in leaf margins.

Symptoms of fluorine damage includes tip necrosis in confers that spreads to the base, while in broadleaf plants include marginal and tip necrosis that spread inward (Krupa 2001; Sharma and Kaur 2018). The vegetation contaminated by fluoride deposition if eaten by domestic animals may produce serious effects since these animals are typically vulnerable to fluoride (Shupe 1969). Studies have shown that roughly 96% of the ingested fluoride accumulates as mineral crystals in the teeth and bones in the bodies of animals (Zipkin 1972). Irrigation from fluoride contaminated water has been linked to a gradual decrease in the germination pattern of *Oryza sativa* L. Mondal (2017). In India, groundwater contamination of fluoride is a major environmental issue. Many studies have been conducted in India to document the effects of fluoride on plants (Mondal 2017; Sharma and Kaur 2018; Khound and Bharali 2018; Usham et al. 2018).

3.4.6 Peroxyacyl Nitrates

Peroxyacetic nitric anhydride ($CH_3COO_2NO_2$), also known as peroxyacetyl nitrate, is a powerful respiratory and eye irritant. Peroxyacetyl nitrate (PAN) is an important reservoir species of NO_x in the atmosphere, consequently leads to the formation of ozone and hydroxyl radicals in the lower troposphere (Singh and Hanst 1981). PAN has a longer residence time in the atmosphere and can be further transported and distributed to remote locations away from their source of origin (Mudd 1975; Teklemariam and Sparks 2004; Fischer et al. 2014). The presence of non-methane volatile organic compounds (NMVOCs) and NOx is a prerequisite for the formation of PAN, both these precursors can be made available from natural as well as anthropogenic sources (Roberts 2007; Fischer et al. 2014). The burning of fossil fuels is the major source of NOx production, with additional inputs from biomass burning, natural lighting, and soils.

In plants like bean leaves (*Phaseolis vulgaris* L.), PAN could induce the oxidization of sulfhydryl groups on enzymes required for the photophosphorylation, thus producing inhibitory effects on the cyclic photophosphorylation of chloroplasts (Koukol et al. 1967). Plants are susceptible to PAN pollution and show visible injury at much lower concentrations. Studies by Temple and Taylor (1983) have shown that PAN exposure of 14 nmol mol^{-1} to petunia and tomato plants for 4-h duration initiated acute injury symptoms (Taylor 1969). In the susceptible plant species like lettuce and beet, the foliar injury was initiated at a threshold concentration of 15 nmol mol^{-1} and for 4-h exposure, while severe injury resulted from 25–-30 nmol mol^{-1} concentration of PAN for 4-h exposure.

Besides major air pollutants, there are many minor pollutants such as hydrogen sulfide (H_2S), carbon monoxide (CO), vapors of metals like mercury, arsenic, cadmium, etc.; heavy metals bound in particulates; bromine (Br_2) and iodine (I_2); soot dust; chlorides of sodium, potassium and calcium, sodium sulfate dust; pesticides, insecticides, and herbicides which were known to significantly affect the biota health.

3.5 Impacts of Air Pollutants on Human Health

Humans are exposed to air pollutants directly via inhalation, ingestions, and through dermal contact or indirectly from ingestion of contaminated water, soil, or through the food chain. According to WHO, world over around 90% of the people were exposed to high levels of atmospheric pollutants in 2016. The air pollution alone kills an alarming 7 million people annually, out of which a whopping 4.2 million premature deaths are caused by outdoor air pollutants. A large proportion of this burden, estimated to be around 91%, is shared by third world countries mainly in South-East Asia and Western Pacific regions (WHO 2020). Short-term exposure to air pollutants exposure to humans may induce symptoms ranging from acute to severe breathing problems, wheezing, eyes burning, skin irritation, higher rates of hospitalization, whereas, the long-term exposure is closely associated with more complicated health issues leading to cardiovascular diseases, chronic asthma, effects on the nervous system, reduced activity of the immune system, cardiovascular mortality, carcinogenicity, etc. (Manisalidis et al. 2020). Traffic-related air pollution (TRAP) is the predominant source of air pollution in urban areas throughout the world. In rural regions, especially those in the developing countries, indoor domestic emissions from coal and biomass burning are the major pollution source (Laumbach and Kipen 2012). The occurrence of sporadic events like the Bhopal gas tragedy in 1984 in the Indian state of Madhya Pradesh that claimed around 2000 from the release of methyl isocyanate (MIC) from pesticide plant is another serious concern of air pollution exposure to humans, especially in the occupational environments. Many urban regions of India and China in recent decades have emerged as the new hotspots of the world, where a large proportion of the world's population lives and is exposed to the dangers of air pollution.

The majority of the air pollution-related health issues include respiratory and allergic diseases such as asthma, chronic obstructive pulmonary disease (COPD), pneumonia, skin irritation, and tuberculosis (Laumbach and Kipen 2012). Nations across the world including India have devised their National Ambient Air Quality Standards (NAAQS) to regulate the ambient concentrations for air pollutants of utmost concern. USEPA has identified six pollutant criteria air pollutants, i.e., SO_2, NO_2, CO, tropospheric O_3, suspended particulate matter, and lead for regular monitoring to maintain the ambient air quality of different regions. NO_2 is a respiratory irritant, as it penetrates deep in the lung. Its inhalation may induce respiratory diseases, coughing, wheezing, dyspnea, bronchospasm, and even pulmonary edema at higher ambient concentrations. It may affect the T-lymphocytes in the body as their concentrations exceed 2.0 ppm. Likewise, the SO_2 is a sensory irritant and penetrates deep into the lung converted into bisulfite and interacting with sensory receptors, causing bronchoconstriction. Its inhalation, particularly in the industrialized and high traffic density locations, induces respiratory irritation, bronchitis, mucus production, and bronchospasm, (Manisalidis et al. 2020). Air pollutants act as unspecific irritants and immunomodulators; studies by revealed that high pollution levels especially NO_x and PM_{10} are positively correlated with increased risk of asthma among asthmatics in Taiwan. Chronic exposure to such pollutants could further enhance the risk of lung cancer-sensitive individuals. In India, Singh et al. (2000) have observed severe respiratory symptoms and reduced forced expiratory volume among the Traffic Police personals of Jaipur City, Rajasthan due to high exposure of air pollutants. Ambient concentrations of $PM_{2.5}$ and PM_{10} are reported to exhibit adverse health effects on humans such as heart disease, stroke, blood pressure, and cardiovascular diseases (Brook et al. 2010; Lee et al. 2014). Bourdrel et al. (2017) in their review work on cardiovascular effects of air pollution found that a 10 $\mu g/m^3$ increase in long-term exposure to $PM_{2.5}$ was associated with an 11% increase in cardiovascular mortality. Exposure to carbon monoxide affects the oxygen-carrying capacity of the blood resulting in impaired concentration, slow reflexes, confusion, and in extreme cases deaths. In India, Suresh and Das, 2003 reported that the levels of various antioxidants in the RBC lysate such as catalase, superoxide dismutase, and glutathione peroxidase were found to be low in a traffic policeman in the city of Hyderabad.

Besides, exposure to air pollutants in particular heavy metals and dioxins adversely affects the central nervous system, and is closely associated with cognitive dysfunction, Alzheimer's disease and Parkinson's disease, structural brain effects, and white matter injury (Genc et al. 2012; Babadjouni et al. 2017). Dioxins are known to decrease nerve conduction velocity and impair the mental development of children (Thömke et al. 1999; Walkowiak et al. 2001). Exposure of As, Pb, and Hg has been linked to symptoms such as memory disturbances, anger, fatigue, sleep disorders, blurred vision, slurred speech, and hand tremors (Ewan and Pamphlett 1996; Ratnaike 2003). Maternal exposure to air pollutants affects the developing fetus (Schell et al. 2006). Maternal exposure to lead increases the risks of spontaneous abortion and reduced fetal growth, congenital malformations (Bellinger 2005). Dioxins can be transferred to the developing fetus from the mother via the placenta, they act as endocrine disruptors and affect the growth and development of the central nervous system of the fetus (Wang et al. 2004). Oxygen supply to the fetus is maintained from the mother's blood. Breathing polluted air during pregnancy can result in premature birth, low birth weight impaired lung development, increased later respiratory morbidity, early alterations in immune development, and can increase the baby's risk of contracting illnesses (Proietti et al. 2013; Korten et al. 2017; La Marca and Gava 2018). Besides, the prenatal exposure of PAHs affects the child's behavior and neurodevelopment, a decrease of IQ, increase of attention-deficit hyperactivity disorder, a decrease of brain-derived neurotrophic factor, and reduction of left hemisphere white matter (Sram et al. 2017). Furthermore, epidemiological evidence suggests that periods of elevated air pollution affect the semen quality and damage sperm DNA (Dejmek et al. 2000; Rubes et al. 2005).

Besides the above-mentioned health implications, many of the air pollutants are known to be potential carcinogens that can either initiate and/or promote carcinogenesis by a diverse number of mechanisms such as DNA adducts and DNA protein cross-links formation, epigenetic alterations, regenerative cell proliferation, oxidative stress, inhibition of DNA repair, and altered cell cycle regulation. Common air carcinogens are formaldehyde, benzene, PAHs, ETS (environmental tobacco smoke), etc.

3.6 Conclusions

Effects of air pollution on plant and animal biota and natural and man-made materials are manifested directly as well as indirectly. The severity of the impacts of pollutants is variable and differs from one ecosystem to another and one organism to another. Emissions of such pollutants also strongly interfere with the atmospheric processes at local, regional, or global scales. Common atmospheric impacts of air pollutants are greenhouse effect and global warming; stratospheric; ozone depletion; atmospheric deposition, and acid rain; suppression of rainfall; atmospheric visibility reduction, etc. Developing economies are at higher risks of their owing to higher abatement costs associated with it. Even a marginal increase of 10 μg/m^3 of ambient PM_{10} levels in Asian cities could lead to a surge in the mortality rate by 0.6%, which is significantly higher than the trends estimated for Western cities. Plants are highly susceptible to direct damages caused by contacting the air pollutants and indirectly from the changing state of the atmosphere, e.g., global warming, acid rain, stratospheric ozone depletion, etc. At the intergovernmental level several efforts have been made to regulate the air pollutants, e.g., the Geneva Convention on Long-range transboundary air pollution (1979) to regulate SO_x, NO_x, persistent organic pollutants, non-methane volatile organic compounds, tropospheric ozone, heavy metals, particulate matters, and black carbon; Montreal protocol to regulate ozone-depleting substances; the Paris agreement for control of GHGs, etc. Despite these efforts, control of air pollutants is still a far-off dream for policymakers, especially in developing economies like India and China, which are now the new pollution epicenters of the world. Therefore, timely policy interventions based on scientific facts must be made to regulate the air pollutants world over and minimize their impacts on living biota and atmospheric processes.

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South Asian Monsoon Extremes and Climate Change

4

Mamta Yadav

Abstract

South Asian monsoon (SAM) is an important segment of the tropical monsoon system that mainly lies in the range of the seasonal oscillations of the intertropical convergence zone (ITCZ). About 70% of total rainfall in South Asia occurs during monsoon months each year, between June and September. Even within season, rainfall pattern is highly variable. The South Asian developing countries are mainly agro-based economies and livelihood of rural population is mainly dependent on natural resources which revive through the monsoon. The South Asian monsoon has influence on global atmospheric circulation and its future behavioural patterns will have serious implications for the entire world. Monsoon seasonal rainfall has temporal and spatial variability. There is no significant trend in Monsoon rainfall over past 100 years over the entire South Asian region. Ocean–atmosphere coupling in terms of ENSO and IOD has significant correlation with performance of monsoon over Indian subcontinent. IOD and ENSO are playing complementary to each other and maintaining good monsoon during recent decades. Along with year-to-year variability there exists intra-seasonal variations which are more markedly noticeable nowadays. These are in the form of prolong dry days with no rain or little rain and prolong wet days with rather good to very heavy rain forming a cycle of active and break spells. Extremes occur during active and break spells of monsoon. The extreme rainfall events mainly occur during synoptic scale weather systems like lows and depressions. Extreme events like flood, drought and more landslides are high impacting events that need proper strategies to overcome the adversities. The present study focuses on monsoon extremes, intra-seasonal variations and modulation by remote

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forcing and their future trends in global warming scenario. The global ocean–atmosphere coupling and its linkage with South Asian monsoon is on chance and how it will be progressing in future.

Keywords

South Asian monsoon · Rainfall · Extreme event · Atmosphere · Natural hazards

4.1 Introduction

South Asian monsoon is basically summer monsoon on Indian subcontinent and is large-scale manifestation of ocean–atmosphere coupling (Hernandez et al. 2015; Ramaswamy 1965). The monsoon rainfall is mainly driving agricultural production supporting food security and steering economy of South Asia. The word monsoon is basically having its origin from Arabic language. Monsoon is a season during which reversal of wind direction takes place over a large geographic area. South Asia, Africa, Australia and Central America's Pacific coast are the main monsoonal regions of the world and mainly characterized by wind reversal during winter to summer or summer to winter transition mainly (Buckley et al. 2014). These are extended on tropical region 25°S to 35°N, 30°W to 170°E. Indian monsoon region is main central region of the South Asia. Wind reversal during seasonal transition can be understood by global pressure and wind patterns in January and July. The Siberian High of northern Asia and polar highs are main features of the winter (January) circulation in northern hemisphere with two intense low-pressure centres (the Aleutian low and the Icelandic low) situated over the North Pacific and North Atlantic, respectively, while in the summer months, the sub-tropical high-pressure areas of Northern Hemisphere shift westward and have more intensity than winter months (Sonwani and Saxena 2021). These strong high-pressure areas regulate the summer circulation over the oceanic regions and supply warm moist air on to the continents that are situated to the west of these highs leading to precipitation over parts of eastern North America and Southeast Asia. The changes in pressure patterns reverse wind from north-easterly in winter to south-westerly in summer (Fig. 4.1).

Monsoon can also be considered as atmospheric response of variable sun radiation governed by seasonal movement of sun. The movement of sun between Tropic of Cancer in Northern Hemisphere and Tropic of Capricorn leads to differential heating on different land and oceanic masses and generates significant temperature gradient which is opposite in direction compared to winter season (Lau and Li 1984; Webster 1987; Meehl 1992). This temperature gradient is basically responsible for the generation of low-pressure areas and faster wind movement towards these low-pressure areas through wind convergence along with vertical lifting of air masses and formation of clouds.

Moreover, if we look at general circulation patterns of atmosphere, we find alternate low- and high-pressure belts in both hemispheres. The equator is low-pressure belt where low-level surface north-easterly winds converge over a

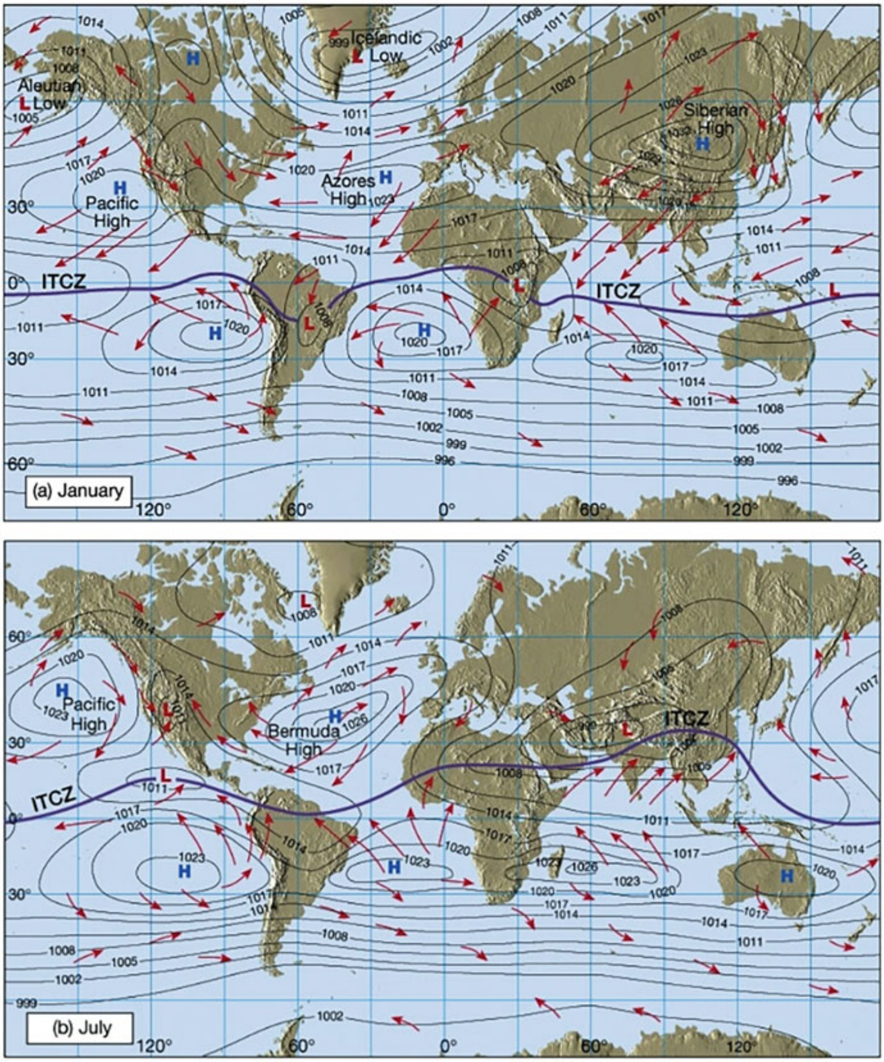

Fig. 4.1 Average surface pressure and associated global circulation (Source: The Atmosphere-An introduction to Meteorology, Book, Eleventh Edition, Authors: F. K. Lutgens, E.J. Tarbuck Illustrated by Dennis Tasa) source : The Atmosphere, 8th edition, Lutgens and Tarbuck, 8th edition, 2001

broad area forming inter-tropical convergence zone ITCZ. In monsoon season, it travels across lower latitudes of the Northern Hemisphere and in winter season shifts towards Southern Hemisphere low latitudes main (Gadgil 2018). The average position of ITCZ is a few degrees north of the equator due to extensive land masses of the Northern Hemisphere as compared to Southern Hemisphere creating maximum heating zone in Northern Hemisphere and equatorial trough remains in this maximum heating zone. The position and movement of this convergence zone is linked with movement of sun and formation of new low-pressure areas further north of its position. Monsoon can also be defined as gradual movement of ITCZ towards north and south with movement of sun. The movement of ITCZ is a characteristic feature of South Asian monsoon (Turner and Annamalai 2012).

South Asian developing countries maintain increase in growth rate from past few years except covid 19 pandemic crises. These countries have large domestic market and agro-based economy well maintained by regular robust monsoon. The growth of agriculture sector, work-based requirement and demand in domestic market are directly linked with performance of monsoon. The monsoon rainfall and its intra-seasonal variations are deeply affecting life of 1.89 billion people. The well-noticed variations in dry and wet spells and high impact extreme events like floods, droughts, severe thunderstorms and landslides during monsoon season carry atmospheric response to anthropogenic activities which can be quantified through meteorological and other related observations needed to understand climate change and associated risk. The prediction of onset and withdrawal of monsoon and also dry and wet periods is of key importance. The good quality observational data sets can help future climate management strategies for land-based water resources, ground water, agricultural best practices, food security, disaster early warning and preparedness, and infrastructural needs. The synoptic meteorology seems very important in this regard. Assessment of large-scale semi-permanent features based on observed data and how the synoptic features have modulated under various ocean–atmosphere forcing in recent climate change scenario are also addressed in this chapter.

4.2 Semi-permanent Features of Monsoon

4.2.1 Heat Low

The low-pressure area develops over Pakistan and North West India, also called “heat low”, indicating thermal heating conducive for its formation. The Hindukush mountains regionally play important role in its formation. Its location and intensity are significant for monsoon advancement process. Intensity of heat low is correlated to rainfall activity (Ramage 1971). The negative pressure departure in heat low region and positive pressure departure in peninsula are favourable for monsoon progress. Heat low formation starts from May and get established by June near to its normal position. Some variations occur in spatial position and strength of heat low during monsoon season but mostly it remains at its normal position and gradual weakening starts from September and vanish in first fortnight of October. The observed minimum values of the heat low were 992 hpa to 994 hpa during June and July and 996 hpa to 1000 hpa in August and September for the year 2016.

4.2.2 Monsoon Trough

The seasonal trough line, starting from heat low over Pakistan and adjoining areas, extending in southeast direction and passing through West Bengal's Gangetic region and reaching up to eastern part of West Bengal and Orissa known as Head Bay. The low-pressure line generally runs from Ganganagar to eastern West Bengal coming through Allahabad, having westerly to south-westerly winds in the south of the low-pressure line and easterlies to the north of the low-pressure line. The position of the low-pressure line oscillates on day-to-day basis and affects the monsoon rains. When the trough is near to the foothills of Himalayas termed as "break in monsoon" as there is decrease in rainfall activity over most parts of the country, though the Himalayan mountain region get good and heavy falls leading to occasional overflow of rivers creating floods. The migration towards south direction of trough from its mean position, i.e. the central parts of the country, under the influence of monsoon depressions forms in the northern Bay of Bengal and generally moves in westerly and west north-westerly direction across Indian land mass, giving widespread rainfall with some heavy to very heavy rain spells over the central India and some parts of peninsula. The oscillations of monsoon trough about its mean position govern active and break phases of monsoon. The total number of days in these positions is crucial for seasonal rainfall. In September month, western end of monsoon trough shifts near to foothills of Himalayas and eastern end remains south of its normal position and during last 15 days it almost vanishes.

4.2.3 Tibetan Anticyclone

Elevated Tibetan plateau by regular sun heating starts transferring its heat to upper winds acting as a heat source and plays significant role in global circulation and South Asian monsoon or Indian monsoon. The heating of the plateau just reverses the meridional temperature gradient throughout the troposphere. This reversal is the main factor which brings changes in seasonal circulation over East Asia, with poleward shift of the subtropical jet. At 500 hPa it is situated to the east of Long 80° E with axis near about 28° N. It is more intense at 300 hPa and extents between70 E and 110 E. The rainfall and its distribution are linked with east west well-oriented Tibetan anticyclone. The location of anticyclone changes during the monsoon and corresponding changes occurs in rainfall also. It has been observed that when it shifts towards west from its mean location rainfall activities get enhanced over western Himalayan region. Shifting of anticyclone towards west or southwest of its mean position enhances rainfall in northern India and shift towards north or northeast of mean position decreases rainfall over northern regions.

4.2.4 Tropical Easterly Jet (TEJ)

Strong concentrated easterly winds in the form of jet are seen in upper air wind charts located south of subtropical ridge over Asia. It is having centre over Chennai city latitude and prominent at upper tropospheric level, i.e. 100 hpa, mainly during the month of July. The Tropical Easterly Jet (TEJ) starts from eastern coastal areas of Vietnam and runs up African west coast. The jet gains strength over the region of South China Sea and southern Indian region, and after crossing this it starts weakening. A broad latitudinal spread of jet winds during monsoon months has been observed through wind charts and maximum wind velocity of 126 knots at upper tropospheric level around 154 hPa pressure level was recorded at Guwahati in radiosonde data. These easterlies of jet provide steering to LPSs formed in Bay of Bengal for westward movement. The jet is likely to weaken resulting in reduced wind shear favourable for more cyclonic storms (Brahmananda Rao et al. 2008).

4.2.5 Mascarene High (MH)

The strength of cross-equatorial flow is maintained by intensity and location of this high. It is a part of high-pressure belt located at subtropical latitudes in southern hemispheric Indian Ocean centred at 30° S/50° E, termed as Mascarene High. This high pressure generally forms close to the Madagascar island off the coast. The waves coming from extra tropics cause small duration fluctuations in its intensity (Sikka and Gray 1981). The increase in intensity of Mascarene High accelerates the moist wind current crossing equator at lower levels and forms a jet stream type of flow also known as low-level jet and identified as wind field associated with monsoon strength over regions of Arabian Sea. On similar lines decrease in intensity of this high weaken the cross-equatorial flow and monsoon current. The parameters like temperature over sea surface (SST), heat energy content of ocean and sea surface height (SSH) are on increasing trend over its region as evident from observations of recent 20 years. The warming of sea surface aids in curtailing the pressure at sea level resulting in feeble or weak gradient of pressure between the Mascarene high and the pressure over land and oceanic regions of Northern Hemisphere (Vidya et al. 2020).

4.2.6 Somali Low-Level Jet (LLJ)

Inter-hemispheric lower-level strong wind flow as a jet stream having location of core near 850 hpa appears flowing from Mauritius across Kenya, also called Find later jet or low-level jet. The lower-level strong winds with highest speed around 40–60 kts identified at core of the wind field over SE Arabian Sea and adjoining Peninsular India is a part of this Somalian or Find later jet. The frequent westerly waves of extra tropical origin modulates its intensity. Strong cross-equatorial low-level jet (LLJ) increases rainfall activity around entire west coast of India. The wind speed at core, depth of westerlies, zonal water vapour flux, horizontal wind shear and cyclonic vorticity show an increase near to the heavy rainfall days and a decrease afterwards (Xavier et al. 2017). The fluctuations of LLJ or Somali jet can be assessed through Somali jet speed index (Boos and Emanuel 2009). The LLJ intensity changes within 20- to 90-day period, in relation with the northward-advancement of active and break phases of the monsoon (Swathi et al. 2020).

4.3 Phases of Monsoon

4.3.1 Onset of Monsoon

The monsoon over south Asian land reaches initially at Andaman and Nicobar Islands around 20 May normally and starts moving towards Indian land; strong wind flow from Southern Hemisphere to Northern Hemisphere mainly cross the equator as strong concentrated wind flow, termed as low-level jet (LLJ) or Somali jet or Find later jet, and establishment of tropical easterly jet at upper level (100 hpa) is the main feature of wind charts during the onset phase. Onset date of monsoon over Andaman and Nicobar Island is based on actual observations, model forecast and convection in satellite imageries. The Zonal winds of 8 mps at 925 hpa and westerly wind up to 600 hpa and Outgoing Longwave Radiation (OLR) equal to or less than 210 watt/m^2 with fairly widespread or widespread rain over islands are realized in actual observation. Monitoring all such parameters for few days the onset date over Andaman and Nicobar can be declared (Debnath et al. 2019). The India Meteorological Department every year announces onset of monsoon over Kerala state considering three parameters: precipitation, wind speed and wind velocity, and vertical depth forming, i.e. wind field and outgoing longwave radiation mainly. The temperature gradient in the upper atmosphere, i.e. 700 hpa and 500 hpa, get reversed during onset (Ananthakrishnan and Thiruvengadathan 1966). The kinetic energy at low level, total kinetic energy generation in vertical direction and total available tropospheric moisture over Arabian Sea may also be used as possible predictors for onset date over Kerala (Raju et al. 2005). Normal date of monsoon arrival over Kerala is considered to be 1 June with a deviation of 7–8 days prior or later. Sea surface temperature gradient (SST) over Indian and Pacific Ocean have linear correlation with onset date on decadal time scale (Preenu et al. 2017).

4.3.2 Monsoon Advance

The progress of monsoon varies from year to year. Monsoon advances by two branches, one is Arabian Sea branch and the other is Bay of Bengal (BOB) branch. The Arabian Sea branch soon after onset over Kerala moves northward along the west coast and covers Gujarat region near June 15. Whole Peninsula and Central India get monsoon rainfall through this branch. The BoB branch moves northward and enters regions of Bangladesh, Assam and adjacent north eastern states. The

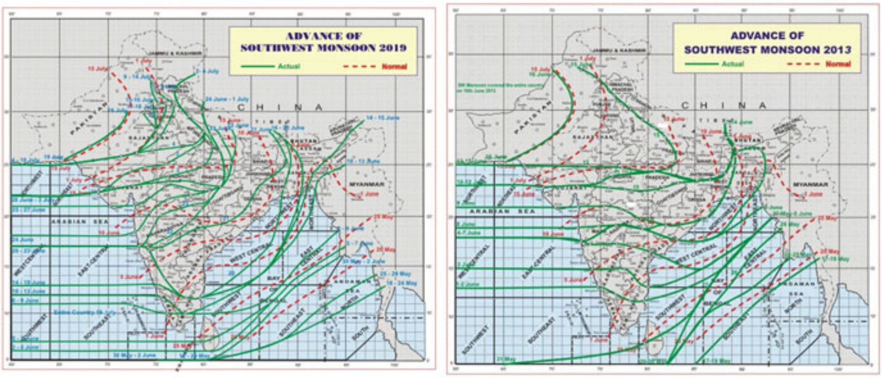

Fig. 4.2 (**a**) Monsoon onset and progress 2019; (**b**) Monsoon onset and progress 2013 (Fast Advancement) Source: India Meteorological Department; https://www.imdpune.gov.in/Weather/weatherforecast.html)

height and orientation of the hills of Assam, Meghalaya and Myanmar create obstruction, resulting in deflection of BoB branch in west direction under the Himalayas range. The BoB branch reaches over the Gangetic plains of north India in the form of south-easterly/easterly winds. The branches meet over north India around longitude 80° E. Monsoon takes 15–35 days to cover the entire country as observed during 2010–2020. Monsoon progressed fast in 2013 and taken only 16 days to cover the whole country.

Formation of low-pressure systems (LPS) in Indian Ocean region may facilitate timely onset of monsoon over Kerala or it may cause delay in monsoon advancement over Arabian Sea. In this context, the location of formation of system, its intensity and track are of much importance. The LPSs in BOB and Arabian Sea disturb the south-westerly wind flow coming from Southern Hemisphere crossing the equator. Sometimes the flow gets intensified favouring fast monsoon advancement over country and sometimes flow get decreased giving a temporary halt to the advancement of monsoon. The advancement of monsoon is not a continuous process during some periods northern limit of monsoon remain stagnant for 5–6 days or even up to 10–12 days and termed as hiatus in monsoon. The normal dates of monsoon progress (onset and withdrawal) have been revised by India Meteorological Department based on 1961–2019 data. The progress of the monsoon is sometimes fast and sometimes slow (Fig. 4.2).

4.3.3 Withdrawal of SW Monsoon

The withdrawal of monsoon starts from north western part of country in the month of September. During past decade 2010–2020, the withdrawal generally commenced from third week of September and took 15–30 days or even more for the entire country. The important meteorological aspects to be looked into for the withdrawal;

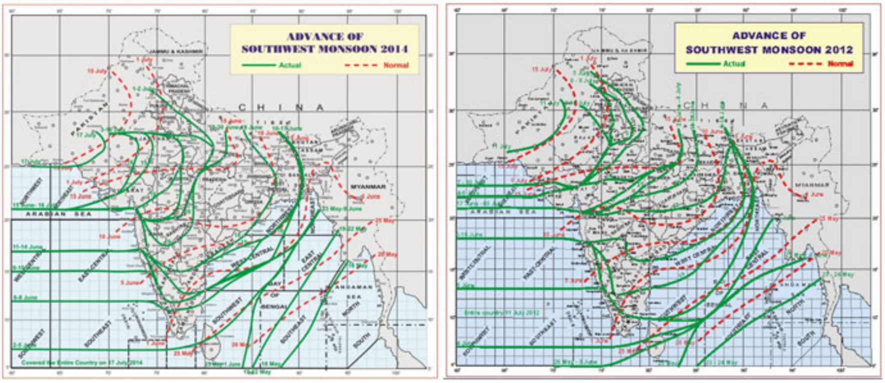

Fig. 4.3 (**a**) Monsoon withdrawal 2014; (**b**) Monsoon withdrawal (Fast) (Source: India Meteorological Department; https://www.imdpune.gov.in/Weather/weatherforecast.html)

no rainfall for consecutive 5 days and development of anti-cyclonic circulation which can be seen at 925 hPa or 850 hPa levels in upper air charts, i.e. reversal of vorticity field in the lower troposphere and dominance of northerly or north-westerly winds in over northwest India, shift of ITCZ in south and rapid reduction in available moisture in middle and upper atmosphere may be observed through satellite water vapour imageries and radio-sonde data. During past decade, most of the monsoon withdrawal commenced in late October month, so monsoon withdrawal dates has been revised based on operation dates data 1971–2019 (Fig. 4.3).

4.4 Intra-seasonal Variations/Active and Break Spells

Indian monsoonal system is a segment of large-scale circulation patterns associated with monsoon over Asian countries and having different temporal variability on daily, seasonal, annual and decadal time scale. In general term, active spells mean period of good rainfall days and weak/break spells are days of little rain or no rain. The long period of active spell or a greater number of days of good rainfall impacts monsoon rainfall of the country and with widespread spatial coverage fulfil agricultural needs and water requirements of the country. Similarly, long period or more days with no rain, i.e. breaks, impacts the total precipitation in monsoon (Gadgil and Joseph 2003) and adversely affect crop growth and management practices. The timing of occurrence of break spells is also very much crucial for agriculture and if coincides with period of crop maturity it will affect crop yield. Long and frequent break spells may lead to drought situation.

A break situation arises by shifting of low-pressure trough near to Himalayan foothills as defined by (Ramamurthy 1969). In this situation more rainfall in Himalayan region and rainfall activities get reduced in other parts of country. The position of monsoon trough is very critical for determining active and break spells.

When monsoon trough migrates towards south of its mean position good rainfall received over central and other coastal states of the country making monsoon active.

Earlier surface pressure and wind patterns were used for identification of breaks over the Indian region. A break could be identified by disappearance of easterly winds from sea level and 850 hpa charts at least for 2 days (Blanford 1886; Goswami and Mohan 2001) zonal winds at 850 hPa over the Bay of Bengal, used for "active" and "break" situation. The high frequency of active spells leads to strong monsoon and more number of break spells leads to weak monsoon. The variations with in the season ultimately decide the seasonal mean. The intra-seasonal variations are dominated by small time scale processes very chaotic in nature.

The positive OLR anomalies over western portion or segment of monsoon trough, i.e. northwest and central India is an indicative of break and the average OLR should exceed 10 Wm^{-2}, (Krishnan et al. 2000). Daily rainfall anomalies over Indian core region 73–82°E, 18–28°N were also used to define the active and break (Mandke et al. 2007). Low-pressure systems from and move over Indian subcontinent during active phase of monsoon and these systems generally follow the monsoon trough and clustering of clouds takes place around that trough line (Goswami et al. 2003). The gridded data sets prepared and used for classifying active and break spells using standard rainfall anomaly over a region (Rajeevan et al. 2006, 2010).

Indian Summer monsoon rainfall (ISMR) have significant negative correlation with break days and significant positive correlation with active days but the relationship of ISMR with break days is stronger than those of active days. Active and breaks operate on 10–12 days' time scale.

Revival of active spell after break spell is mainly governed by oscillations of monsoon trough. When a weather system of low-pressure develops in Bay of Bengal (BoB) under influence of cyclonic upper air winds, it pulls down the monsoon trough towards south. Monsoon trough again migrates to its mean position or further south of its normal position giving lot of rains in various states. The spatial coverage, intensity and period of rain depends on intensity of low-pressure system, its track and strength of moist winds and support from geographic features like mountain range or big water bodies. The LPS move Northward initially or North-westward along the monsoon trough (Goswami 1987; Sikka 1977). Some LPS formed in Bay of Bengal (BOB) entered Arabian Sea water after crossing Indian land while some LPS of BOB move Northward and then recurve to North-eastward towards Bangladesh and Myanmar. These systems following different tracks give widespread rain and make monsoon active again.

The second way of revival is through northward propagation of tropical convergence one. The deep convective clouds get oriented in east west direction in Indian subcontinent region linked with tropical convergence zone (TCZ) during active spell (Sikka and Gadgil 1980). The life period of active spell is small as compared to break spells, so after the dissipation of deep convective clouds associated with TCZ, there should be northward propagation of freshly formed convective clouds from the equatorial Indian Ocean, so TCZ has two arms—one on Indian land mass and the other on ocean. When land arm is active, the oceanic arm is in formative or beginning stage, and when land arm gets dissipated, the oceanic arm gets developed with convective clouds and starts propagating towards northern latitudes with winds and starts rain leading to revival from a break phase.

4.5 Extremities in South Asian Monsoon

The rainfall extremes are high magnitude rain particularly above threshold value for a day or more number of days leading to large runoff on ground. South Asian nations receive rainfall via southwest monsoon. In Asian continent, monsoon extreme event frequency has been increased (Yao et al. 2008; Shrestha et al. 2017). The change and rise in of extreme also assisting probability of the event to an increase noticed over various regions of countries situated in South Asia (Christensen et al. 2007). Some opposite trends of decreasing precipitation over a time period of 30 years from 1976 to 2005 and large regional variations of high intensity rainfall events have been observed addressing impact of regional variability over Pakistan (Salma et al. 2012).

The monsoon season extreme rainfall events (rainfall >124.4 mm in a day) over Indian region have spatial variability over selected regions like entire west coast, some parts of central and northeast India. The significant rising trend of frequency of extreme rainfall over the Indian monsoon region season and significant increasing trend during June and July months during period 1951–2005.The increased fraction of extreme rainfall events to the total seasonal is compensated by a significant decreasing trend in rainfall (rainfall $R \leq 64.4$ mm in a day) events (Pattanaik and Rajeevan 2010). Most prominent extremes are caused by synoptic scale weather systems, mainly the low-pressure systems, leading to floods and landslide. The low-pressure system may intensify to depression or occasionally to a cyclone surrounded by convective clouds mass and give heavy rains. The rainfall activities in south west sector of the LPS (Godbole 1977; Sikka 1977). These systems remain active for 3–5 days and cover area more than 1000 km^2. A cyclonic system of the intensity characterized for low has associated wind speed not more than 8.5 ms^{-1} and next stage of intensity, i.e. depression wind speed, ranges from 8.5 to 16.5 ms^{-1}. The low-level meridional wind shear linked with the ITCZ assists the processes involved in genesis of lows. Whole area of North Indian Ocean is known for formation of lows but comparatively more number of lows form in Bay of Bengal (BoB) because of high SST of oceanic water and the effective mixed layer not very deep and trough also passes through various sectors of BOB during monsoon season. The low-pressure systems generally follow monsoon trough (Goswami 1987) and their movement towards West and North West direction explained through change of Coriolis force across latitudes on movement track, i.e. beta-effect. Research studies (Dash et al. 2004; Pattanaik 2007; Prajeesh et al. 2013) are indicating decrease in frequency of depression from past few years although the total number of LPSs remained constant. The observed decrease in number of depression stage cyclonic systems in regions below 20°N latitude in the Bay of Bengal starting from 1950s is associated with declining trend of available moisture in the middle atmosphere, 600–300 hPa mainly over the Indian latitudes (Prajeesh et al. 2013). Pollution is also claimed as inhibitor of deep convective clouds and interaction among clouds (Krishnamurti et al. 2013). Western Ghats experience 60% of extreme rain events synoptic disturbances (Francis and Gadgil 2006). Sometimes meso-scale convective systems getting moisture from local water bodies and thermodynamic support from heating may lead to local extreme rainfall. The increasing temperature in over Indian subcontinent enhance evaporation leading to more moist airmasses in the atmosphere which is a positive forcing for strong convection triggered extreme precipitation events (Kothawale et al. 2010).

The landslide increases in Nepal, India, Bangladesh, Bhutan and north Pakistan during the monsoon season. India and Nepal have high rainfall triggered landslide events which is about 21% of global rainfall triggered landslides mainly during monsoons (Froude and Petley 2018). There exists inter-annual variability in landslide incidences occurring in globe. The years with more landslide incidences found associated with regional well distributed rainfall patterns like positive rainfall anomaly but there is no simple relationship with ocean–atmosphere coupling like ENSO. The improved seasonal rainfall forecast which can capture temporal and spatial variation in active and break spells may be helpful for probable landslide zone identification and impact reduction particularly for major affected areas such as India, China and Nepal. Climate change is casually linked with landslides (Gariano and Guzzetti 2016).

4.6 Regional Trends in Monsoon

Walker (1910, 1914) found no trend in monsoon rainfall during 1841–1908 periods over Indian region. Kumar et al. (1992) have done a study on spatial and intraseasonal nature of climatic trends of rainfall. West coast, North Andhra Pradesh and North West India are the areas where monsoon season rainfall trends were increasing, whereas in East MP and adjoining areas, North East India and some parts of Gujrat, the trends were decreasing. August rainfall contribution is more prominent to monsoon seasonal rainfall mainly over coastal areas of West and central parts of India. Parthasarathy and Dhar (1976) observed increasing trend for annual rainfall over East MP and West MP for 1901–1960 periods. Naidu et al. (1999) studied annual rainfall trends for 1871–1994 period; the negative trends are recognized in geographic region of west central India, middle parts of north India and north-eastern region of India. The enhancing trend observed over north-west India spanning states like Haryana, Punjab, Rajasthan and West MP, an isolated area in the east and the peninsular region.

Guhathakurta and Rajeevan (2008) observed no significant trend for monsoon and monsoon months for the country as a whole with large variations in different regions. The July rainfall is decreasing for most parts of the central and peninsular India but increasing significantly in the north-eastern parts of the country. August months' monthly rainfall has increased significantly (at 95% significance level) for the subdivisions Konkan and Goa, Marathwada, Madhya Maharashtra subdivision. Kerala and Tamil Nadu, dry days is on increase resulting in reducing trends of mean yearly rainfall. Rajeevan et al. (2008) examined variations in long period climatic trends of extreme precipitation events over the middle India using 104 years (1901–2004) high resolution daily gridded rainfall data and found that SST fluctuations over Tropical Indian Ocean are linked with year-to-year and decade-to-decade variations of rainfall extremes. The strong connection between the SST over equatorial Indian Ocean and very heavy rainfall (VHR) events over the central meteorological subdivisions of Indian region will lead to more and more VHR events and further supported by the atmospheric global warming condition the floods occurrence will increase over central India.

Annual normal rainy days are nearly 10 over extreme west Rajasthan to 130 days over north eastern states of the country. The north eastern areas of the country, sub-Himalayan West Bengal and extreme western coast region receive approximately 100 rainy days in a year. The frequency of rainy days and heavy rainfall days are decreasing significantly over central, north and some areas of eastern parts of India. Wet days frequency is increasing over peninsular India, mainly Karnataka, Andhra Pradesh and some parts of eastern India. Positive trends in the frequency of heavy rainfall days are observed in parts of Konkan and Goa and adjoining coast and some areas of eastern India. Single-day extreme rain events are on rising over costal districts of Andhra Pradesh Orissa, West Bengal, some northeast regions and on west coast of India parts of Saurashtra and Kutch and east Rajasthan. The extreme induced flood situation and associated risk has increased manifold during past decades mainly over coastal states (Guhathakurta et al. 2011). Extreme rainfall frequency is on decreasing line over some areas of states like Chattisgarh, Jharkhand and some areas of north India.

Goswami et al. (2006) using daily realized rainfall data set found that amount and occurrence of extreme precipitation events are significantly rising and moderate amount events and their frequency are decreasing significantly over central India in monsoon season based on data from 1951 to 2000. Kumar et al. (2010) observed no significant trend to address the variations for yearly and monthly rainfall for India as a whole.

Singh and Mal (2014) studied rainfall trends and variability over western Himalaya and found declining trend in annual and monsoon rainfall over high altitudes and increasing over low altitude. Agarwal (1952) investigated the rainfall variations over middle geographic land areas of India and found a steady change which was not significant during 1908–1940. Temperature and precipitation data of Ganga Basin analysed by Kothyari et al. (1997) shows that rainy days are decreasing, resulting in decrease of total monsoonal rain, and the annual record of daily maximum temperature is showing rise. These variations became noticeable after the year 1965, highlighting climate change signatures on regional scale.

Mullicka et al. (2019) analysed the trend of mean annual rainfall and reported increasing trend of 5.675 mm/y for Bangladesh during 1966–2015 period. The 1 day and consecutive 3-day maximum rainfall trends are increasing in few places and decreasing at other places with no significant change.

4.7 ENSO, IOD and MJO Links with Monsoon

Rainfall during monsoon season and associated planetary and synoptic scale circulation are mainly controlled by global parameters like ENSO and IOD, which are indicative of quantification of ocean–atmosphere coupling in which sea surface temperature also plays influential role. Mooley and Parthasarathy (1983) investigated the relationships of indices of dryness and wetness over India with SOI and SST anomalies are expected to be useful in understanding implications of large-scale anomalies in performance of Indian summer monsoon. Rasmusson and Carpenter (1983) and Shukla (1987) studied the link between the inter-annual variability (IAV) in the Indian summer monsoon rainfall (ISMR) and the El Nino-Southern Oscillation (ENSO) phenomenon. Yadav (2009) used surface temperature, pressure mean sea level (MSLP), geopotential height in the troposphere and global flow patterns of wind to study rainfall variations occurring over years for 1949–2005 period and found the El Nino-Southern Oscillation (ENSO) linkage with strength of monsoon has been deteriorated whereas it has become strong with SST over northwest (NW) of North Atlantic. Yadav (2008) established link between 2mST over tropical southwest Pacific and intensification of subtropical westerly jet over Indian Ocean and enhancement of monsoon circulation during negative phase of ENSO. While during non-ENSO year positive relationship of ISMR with 2mST anomaly over northwest of North Atlantic Ocean. Srivastava et al. (2020) observed ENSO impact on July and August rainfall and found significant changes at multi-decadal time scale. The influence of ENSO was significantly strong in August and significantly week in July during 1948–1980 and post 1980s, ENSO monsoon relationship less strong in August than in July. During 2017 monsoon three regions Central India, West Central India and North East states experienced extreme events in active phase and northeast region of Himalayan range experienced during break phase. Most of the extreme events happened during July with significantly high seasonal frequency favoured by weak La Niña and positive Indian Ocean dipole (Suthinkumar et al. 2019). ENSO (El-Niño Southern Oscillation) term is used for ocean–atmosphere coupling. It is a combination of southern oscillation in pressure field and temperature oscillations Pacific Ocean. Warm Phase of ENSO means El Niño; above average SSTs over eastern Pacific and cool phase of ENSO means La Niña, SSTs in the eastern Pacific below average. ENSO have opposite phase relationship or the inverse relationship with Indian monsoon, i.e. warmer ENSO event weaker is the monsoon. Indian monsoon rainfall has strong correlation with anomalies of SST over Nino 3.4 region mainly. The negative SST anomalies over crossing threshold (−0.5 °C) lead to La Niña event and above-normal or excess rainfall over the country. The La Niña events have positive influence on monsoon and its seasonal variation. The positive SST anomalies corresponding to El Niño over Nino regions [Niño1 + 2 (0°–10°S, 90°W–80°W), Niño 3 (5°N–5°S, 150°W–90°W), Niño-3.4 (5°N–5°S, 170°W120°W), Niño-4 (150° W–160° E and 5° N–5° S)] lead to deficient or below-normal rainfall and weak monsoon over the country. This SST–Monsoon correlation is also changing with decadal–epochal oscillations. The seasonal rainfall time-series have epochs of more than and less than the mean rainfall. El Niño with below-normal rainfall Epochs will be more severe creating rainfall deficiency and similarly La Niña with above-normal rainfall Epochs will give surplus excess rains. The major rain related extremes events (massive flooding/ acute droughts) are because of the reason that external forcing, i.e. El Niño and La Niña, variability and epochal variability are in same (Krishna et al. 1999).

The ENSO-monsoon relationship seems weakening (Kumar et al. 2010) in recent decades due to shifting of walker circulation anomalies south-eastward causing reduction in sinking motion over Indian region and favouring the monsoon. The persistent higher surface temperatures in winter and spring over Eurasia, the mid latitude warming enhancing land ocean temperature contrast required for monsoon.

The effect of ENSO on monsoon rainfall and its intra-seasonal variations are also influenced by Indian Ocean Dipole (IOD). The oscillations in SSTs over the eastern and western sides of Indian Ocean form the dipole. The dipole moment index (DMI) is used to quantify the Indian Ocean warming influence on monsoon rainfall. Positive IOD is favourable for monsoon rainfall and negative IOD is unfavourable for the monsoon. During the period 1958–1997 the El Niño/Southern Oscillation (ENSO) and IOD behaved in complementary manner with each other and overall balancing of monsoon rainfall during the last four decades claimed by research studies (Ashok et al. 2001). The temperature dipole in Indian Ocean (IOD) is acting as a modulator of rainfall over the Indian subcontinent and redefining the correlation between monsoon rainfall and ENSO.

Another important factor causing intra-seasonal variations in monsoon rainfall is Madden Julian Oscillation (MJO). Pai et al. (2009) analysed the linkage of various phases of MJO on day-to-day variation of monsoon rainfall. As MJO moves eastwards, northward shift of rainfall belt from peninsular India takes place. The above-normal rainfall band is observed along monsoon trough region in 5 and 6 phases of MJO. When MJO moves in 7, 8 phases, there is decrease in rainfall over various parts of country. MJO phase 1 and 2 are unfavourable for monsoon rainfall activity. MJO plays crucial role for onset of active rainfall spells and break spells and their duration. The amplitude of MJO is significant in this connection but phase of MJO is more important as related to a region.

4.8 Climate Change and Global Warming Impacts

Warming temperature trends, high magnitude extremes, are prominent over the interior land masses of various parts of Asia. From 1900 to 2005, precipitation declined in parts of southern Asia (IPCC 2007). The global warming will be enhancing and climate models are forecasting increase in annual and monsoon rainfall over Indian region. There is high probability of precipitation extremes to increase during monsoon season over various parts of southeast sector of Asian continent. All available climate-related models with the maximum possible emission regimes all are projecting rise of mean and extreme precipitation in Southern Asia (SAS). The different phases of Coupled Model Inter-comparison Project, mainly phase 3 (CMIP3) and Phase 5 (CMIP5), are forecasting weakening of large-scale monsoon circulation in future (Kripalani et al. 2007; Sooraj et al. 2015; Krishnan et al. 2012). The changes in location, intensity of large-scale systems like monsoon trough over Indian region, the Mascarene High, the western North Pacific (NP) subtropical high, and the upper tropospheric South Asian high are projected (Preethi et al. 2017).There is no clear consensus in models about genesis and track modification in future warming scenarios but more extreme rainfall events are projected over the coastal areas where cyclone landfall is expected to occur. The recent Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulations with Representative Concentration Pathway (RCP) framework are forecasting positive dilation of mean temperature greater than 2 degrees change in mean annual temperature above the reference temperature of late twentieth century over the most of the countries across the globe in the middle of twenty-first century according to RCP8.5 and are above 3 °C for countries situated in Southeast sector of Asia having high population density and big coastal boundary and of the order of 6 °C or even more over higher latitudes in the second half of twenty-first century. Model projections have uncertainties posing challenging situation for policy makers. Looking for more reliable forecast for South Asian monsoon (SAM) the uncertainty/over projection should be identified scientifically. The internal variability is mixed with forced rainfall trends, leading to over-projection, and inter-decadal Pacific Oscillation (IPO) is identified as cause of more uncertainties (Huang et al. 2020).The improved IPO predictions can considerably remove near-term over-projections of SAM.

Worldwide mean temperatures will be on rising trend during span of twenty-first century if greenhouse gas (GHG) emission remains on similar pattern of increase. The global temperatures averaged over the period 2081–2100 are projected to likely exceed 1.5 °C above 1850–1900 average temperature threshold. Heavy rainfall frequency will increase over many parts of South Asia. Increased count of warm days and less count of cold days are likely to remain on same track as the warming is likely to enhance in future century also. The problem of water scarcity will be amplified by increasing population and high sub-regional variability of precipitation. The well-known most fertile plains of Ganga may have 50% decrease of crop yield wheat due to expected double CO_2 emissions. Rise in sea level will inundate lower areas and Mangroves, salt marshes, and sea grass beds and rice growing regions may decline. Over Indian region localized heavy to very heavy rainfall events reported an increase during past 50 years. Land use pattern and urbanization and geographic location are the factors enforcing localized events. The year-to-year variations of monsoon will be more pronounced during twenty-first century. Heavy rainfall events and localized intense rainfall events will be enhancing flood risk as per Ministry of Earth Science (MoES) report 2020. The westerly wind over north Arabian sea brings strong moisture carrying spells and gives rise to exceptionally heavy rainfall events over districts of Gujarat and landlocked areas of Central Indian region. The main reason behind it is warming of north Arabian sea due to carbon emission making winds more variable. In ongoing climate change and warming scenario, pole ward shift of low-level jet is projected leading to more dry days and variation in precipitation over west coast adversely affecting biodiversity of Western Ghats (Sandeep and Ajayamohan 2015).

Floods are the result of monsoon extremes causing loss of human and animal life and property. Major flood events with largest loss of human lives and property occurred over the central India in 1989 and 2000, Mumbai in 2005, Uttarakhand floods 2013, Kerala floods 2018, etc., which resulted from 3 to 4 days continuous raining supported by westerly flow from the Arabian Sea. In 2016, due to heavy rainfall, widespread flooding damaged life and properties over west coast, Mumbai. The Kaziranga National Park in Assam submerged due to extreme rain. Drought is another climate extreme that arises due to rainfall deficiency. Although monsoon total rain remains normal, certain districts remain deficient in rainfall and suffer from drought. Drought is not instant but cumulative deficiency of rainfall for months and years. Drought declaration and management is state subject in India. Almost every year each state has some districts under drought conditions in spite of normal rainfall because of high spatial variability in rainfall. In 2016, 46 districts were drought affected in M.P. and in 2019 again 36 suffered acute drought conditions. In 2018, 18 districts of Jharkhand, in 2019, due to weak northeast monsoon, 23 districts of Karnataka suffered drought. Similarly, other parts of the country are also facing drought conditions mainly before and after the onset of monsoon and sometimes even in monsoon months. Delay of monsoon rain intensifies use of ground water resources, high heat leading to fast evaporation of water from surface water bodies and drying them fast and creating water scarcity in drought-affected area. Drought becomes more severe if it occurs during consecutive years at the same place. IMD can declare drought when rainfall is deficient or less by 10% and spatially 20–40% geographic area of the entire India is encountering dry weather situation or no rain type of situation. Rainfall-related drought is termed as meteorological drought but agricultural drought is different from it and several other crop-related parameters are taken into account for agricultural drought. Mainly lack of rainfall or uneven rainfall can lead to agricultural drought-like situation. In Rajasthan in 2002, due to almost 50% less rainfall as compared to July month normal rainfall, farmers could not sow kharif crop and drought was declared. The concept and definition of drought is subjective in nature. The methodologies for assessment and parameters under consideration are changing from state to state. In order to address various issues associated drought declaration and bring some uniformity in the process government of India brought the new guidelines for drought declaration in 2016. The monitoring of drought is done by Crop Weather Watch Group (CWWG) central and state level having responsibility of regular interactions, analysis of data coming from various institutes and government bodies and assessing its impacts on crop. The new guidelines brought by Indian government drought declaration given first priority to Meteorological information (a) the rainfall measured by the percentage deviation in rainfall from average or the Standardized Precipitation Index (SPI) along with the information of dry spell. Looking for future changes in critical meteorological parameter, standardized precipitation index (SPI) new research study (Guhathakurta et al. 2017) projected that out of 32 meteorological subdivisions seven are serious track of spatial increase of drought hit districts mainly covering states like Uttar Pradesh Uttarakhand, Jharkhand, Chhattisgarh, Kerala and seven sister states of India. Although many areas of India located on eastern side and northeast region have increasing percentage of areas hit by water shortage condition and drought, but still the SPI-based trends are not significant (SPI values with moderate dry, severely

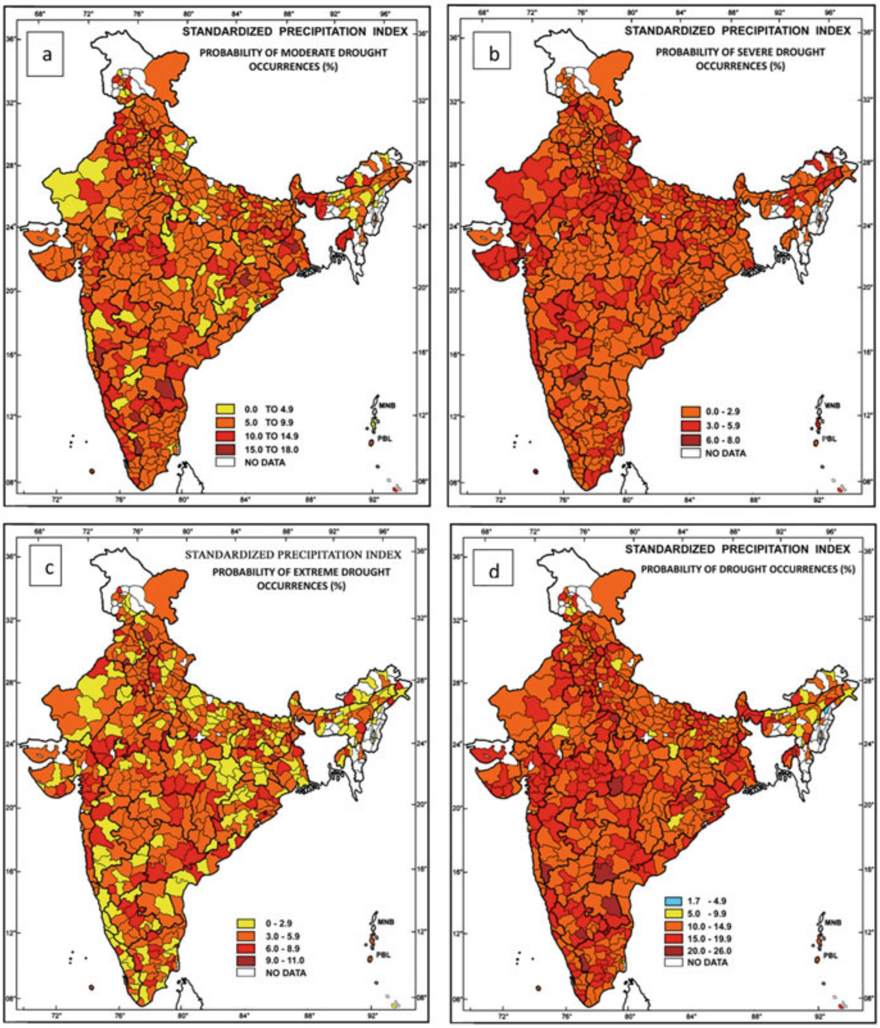

Fig. 4.4 Probability of occurrences of (**a**) moderate drought, (**b**) severe drought, (**c**) extreme drought, (**d**) combination of all drought types: Reproduced from Guhathakurta, P., Menon, P., Inkane, P., Krishnan, U. and Sable, S., 2017. Trends and variability of meteorological drought over the districts of India using standardized precipitation index. Journal of Earth System Science, 126(8)

dry or extremely severe dry conditions). Significantly decreasing trends are no where observed in Indian region. The probability stating that drought will occur in every district under three main categories of drought, i.e. moderate, severe or extremely severe and sum of all, over India using 1901–2015 data are shown in Fig. 4.4. Almost all states have some districts vulnerable to extreme drought conditions.

The evidence of observed climate change data during twentieth century highlighted the food grain availability issue and region-specific climate modifications have shown their signatures to noticeable extent to the scientific community. Nowadays, various models duplicating the various crop processes known as simulation models are being used to understand the influence of climate change on production and management practices of crops. The output generated by simulation models with some value addition can be shared with farmers, which can guide them to opt better management skill and technology and suggest them appropriate alternatives for their farming, thus making agriculture economically stable. In India, substantial research and analysis work has been done focusing on building an understanding of nature and amount of change in yield of various crops under the conditions of forecasted climate change (Aggarwal 2003; Uprety and Saxena 2021). The repeated droughts and massive floods seriously imperiled the working and earning conditions of billions of people depending on land and other natural resources for most of their needs (Hamdani Rizwana and Pathan 2016). The failure of monsoon increases pressure on available forest resources like trees, grasslands and water ponds and over-exploitation accelerates drought during dry years, hitting hard to soil moisture content and increasing dryness in soil making it loose and vulnerable for erosion.

The agricultural response to climate change will be the major deciding factor about the future food security in South Asia. Agricultural sector is very much sensitive for climate variations but it is one of the critical drivers for climate change. The modification of agricultural management practices according to weather changes and yield optimization are challenges for agricultural sector. The regional variation of weather parameters like temperature, rainfall, evapotranspiration, sun shine hours, crops and cropping patterns brings uncertainty in agricultural response to climate change. The crop damage/losses may be increasing if the forecasted climate change crosses the climate variability limit.

Scientific analysis and research done by Indian Agricultural Research Institute (IARI) and various other institutions estimated more loss/damage for Rabi season crops. Corresponding to each 1 °C increase in temperature, wheat production gets reduced about 4–5 million tonnes. Even small variations in temperature and precipitation have considerable impact on the quality and quality of various fruits, green vegetables, tea, coffee, aromatic plants and medicinal plants and basmati rice. The population of pathogens and insects have direct link with temperature and humidity of air. The alterations in weather condition play a dominant role in regulation of insects and pathogen population. The other diverse impacts of climate change on allied agricultural sectors include low productivity from dairy cattle and slow rate of fish breeding, migration of agri-employed population and poor harvests. Agricultural efficiency/output is reactive to two main types of broad climate-associated effects: primary effects by variation of temperature, rainfall and carbon dioxide concentrations and secondary effects from soil moisture and diverse spread and occurrence of pest attack and linked diseases. The productivity of main food crops rise and wheat estimated to decrease by considerable quantity with forecasted climate changes (IPCC 2007).

The climate change affects physiological response of the plant enhancing vulnerability of agricultural production system. The estimated net revenue loss at the farm level is around 9% to 25% for 2–3.5 °C increase in temperature. Scientific community also calculated that a 2 °C increase in average temperature and a 7% enhancement in average rain would decrease total revenues by 12.3% for entire India. Agricultural activities and production in coastal land areas of Gujarat, Maharashtra, and Karnataka states are bearing most adverse impacts of climate change. Agricultural losses of various extent come to notice form the major food-grain producing parts of states like Punjab, Haryana, and western Uttar Pradesh. On another front, states like West Bengal, Orissa, and Andhra Pradesh are forecasted to gain advantage to little extent due to warming (Aggarwal et al. 2004).

The period of unusual dryness is a normal feature of the climate and weather system in semi-arid and arid regions of the tropics, which covers more than one third of the land surface and is vulnerable to drought and desertification (Nagarajan 2003). Drought is seen as an outcome of monsoon failure causing to be occurring due to monsoon failure causing crop under stress, demand for supportive management practices. Intense drought leads to complete crop damage, fast drying of natural ecosystems and lack of drinking water leading to undue hard work for the rural and urban communities (NDMD Moha. GOI 2000).

Maharashtra state has some drought-affected districts almost every year but some districts received even less than half of normal rain during two consecutive years, almost 15,000 villages and 15 districts declared drought affected. So continuous poor monsoon for 2 years caused the question of livelihood for the rural and semi-urban papulation. Monsoon failure generates need of immediate help for villagers for their survival (Hamdani Rizwana and Pathan 2016; Warde 2016).

4.8.1 Remedial Measures

1. Effective monitoring and regulation of available sources of water in areas encountering problem of drinking water.
2. Arrangement of green fodder for cattle and other animals in drought-affected villages and districts.
3. Provide alternative means for livelihood and assured supply of eatable items and food grains to people through effective management of public distribution system (PDS).
4. Farmer awareness for adoption of drought-resistant varieties of crops and weather-linked new cropping practices and technologies.

4.8.2 Impact of South Asia Monsoon on Society

The high variability of South Asian monsoon and climate change are hitting hard densely populated South Asian region. The impacts of climate extremes are closely tied to population distribution, regional geography and development activities.

Monsoon in Indian subcontinent demonstrate large-scale atmospheric processes and important component of global climate system. Flood, drought, landslide and thunderstorms are the associated extremes affecting the population. Floods are natural disaster that account for 50% of the mortalities occurring because of extreme weather events (EWEs; Ray et al. 2021). Flood-associated mortalities reduced about 3–5% per decade since 1980 to 2009 and 20% reduction is seen in the recent decade, even with rise in flood frequency in India. The average frequency of cyclones per year has increased a little (2.0) in comparison to years of previous decades (1.7). The associated mortality rates have declined by 94% during last two decades (Ray et al. 2021) mainly due to improved model forecast, accurate track prediction and good management by Government of India (GoI). Loss of human life, livestock, crops and property, damage to kuttchha houses, roads, and railway tracks, breaking of bridges and dams, inundation of low lying areas, disruption of electric lines and local connecting routes, overflow of rivers and deterioration of water quality due to mixing of water coming from various sources are the immediate impacts of flood event. Rural employment, food security, migration of population for livelihood and health issues like waterborne diseases and with time lag vector-borne diseases spread or outbreak in affected population. Some well-known waterborne diseases are typhoid fever, cholera, leptospirosis and hepatitis A and vector-borne diseases are malaria, dengue and dengue haemorrhagic fever, yellow fever, West Nile Fever, etc. These are commonly observed during and after flood situation. Flood are known for associated diarrhoeal diseases causing significant morbidity and mortality in flood prone areas of the world. According to World Health Organization (WHO), flood of 1988 in Bangladesh, diarrhoeal disease accounted for 35% of all types of illnesses associated to floods and 27% of 154 deaths associated to flood out of total 45,000 patients in rural areas of Bangladesh. Large number of cholera cases were reported during 1998 floods in West Bengal. The coastal populations in South Asia are becoming more vulnerable for cholera outbreaks with increased SST and algal blooms (Huq and Reid 2007). Thunderstorms and lightening events are common in monsoon season and severe thunderstorm/lightening associated strong wind damage crops, trees and structures and even claim life of people. Lightning events and associated mortality rates are showing significantly increasing trend over the past four decades (Ray et al. 2021). The farmer community mostly hit hard by flood and excess rain. Excess rain damages the crop and reduces productivity. The problem of soil erosion is quite common. Specially in coastal areas where cyclone brings salty water to land during flood situation creates problem of soil fertility. The cities have grown with fast pace during past decades and generated problem of urban floods. The urban floods are more impactful as the urban areas are the main controller of economy. Most of the urban floods are not due to weather but due to human unplanned development, rapid urbanization and lack of proper drainage system and also effective application of technological tools during disaster management process.

Drought is climatic extreme which is subjective in nature and shows its signature almost every year in various regions of Indian subcontinent. Drought causes crop failure, depletion of surface water resources, more exploitation of ground water and creates food scarcity for the population leading to migration of population from one place to another in search of livelihood. Climatic extremes like flood and drought threat food security, food items become inaccessible for some fraction of population and social fragmentation becomes more evident in population. Looking at the past eighteenth century which was famous for long droughts witnessed great political of turmoil across Southeast Asia, during extended periods of drought of the past centuries. Coming to recent decades, water availability and crop-linked four kinds of droughts, i.e. meteorological, hydrological, soil moisture also known as soil water and greenery or vegetation drought, have high seasonal and spatial variation. The hydrological and greenery/vegetation droughts cause more impact on growth, quality and quantity of crop than meteorological and soil moisture droughts (Xiang et al. 2017).

Extreme climatic events as visually generate many adversities in social life and act as natural cleaning agents of natural and social atmosphere. During extremes various faults in management and technological practices and social gaps become more evident and thus opens the path for the science and society to identify the need and accordingly guiding the scientific community too.

4.9 Summary

The chapter deals with various kinds of monsoonal extremes such as floods and droughts resulting from accumulative variation in monsoon season and landslides and flash floods like weather extremes caused by lows and depressions and climate change aspects over South Asia. Along with extremes large-scale circulation features of monsoon, i.e. semi-permanent synoptic systems and probable implication of climate change, have been discussed.

The ocean–atmosphere coupling indicator like ENSO and El Nino, La Niña conditions have been linked with floods and droughts in Indian subcontinent but all the droughts are not due to El Nino and all the flood extremes are due to La Niña. The connection of ENSO with inter-annual variability (IAV) of the Indian monsoon rainfall has weakened while relationship with the northwest (NW) of North Atlantic sea surface temperature (SST) has become strong during recent decades. The ENSO monsoon relationship is changing due to shifting of walker circulation anomalies south-eastward and mid latitude warming. Also the IOD behaved complementary to ENSO during past few decades. The seasonal rainfall time series epochs of below-normal/above-normal rainfall coincide El Niño/La Niña resulted in major climatic extremes like flood and drought. Overall seasonal extremes are governed by external factors like ENSO, IOD, NIO, etc. and through natural dynamics. Monsoon intra-seasonal oscillations (MISO) are observed through low-pressure systems (LPSs) forming in Indian Ocean region and moving North, North Northwest, North West Wards give extreme rainfall over large geographic area covering many cities. More LPSs form in Bay of Bengal (BOB) than Arabian Sea. Recent years depressions are less as compared to lows. Why lows are not intensifying to depression or less depressions in monsoon season is still not clear. Reduction of relative humidity between 600 hPa and 300 hPa levels of atmosphere over the Indian latitudes and pollution claimed for less depressions during monsoon.

The precipitation extremes linked with monsoon are very likely to increase over East, South, and Southeast Asia. All climate models project are projecting an increase in both the mean and extreme precipitation in Southern Asia (SAS) during late twenty-second century.

The frequency and probability of extreme rainfall events increased over South Asian regions and likely to be on same track under climate change impacts but contrasting trends also observed in various regions on India, Bangladesh and Pakistan.

The significant increasing trend of frequency of rainfall extremes (rain above 124.4 mm during 24 h) mainly at districts of west coast and some land areas of central and northeast region of India. The increased number of rainfall extremes is compensated by a considerable decrease in number of moderate and heavy precipitation events ($\leq$64 mm in a day) and balancing overall monsoon robustness. There is no statistically significant trends for annual, seasonal, and monthly rainfall over Indian region whereas mean annual rainfall increasing trend of 5.675 mm/y. for Bangladesh during (1966–2015). The frequency of rainy days is decreasing significantly over central, north and some areas of eastern parts of India and wet days frequency is increasing over peninsular India. Single-day extreme rain events has increased over coastal states and parts of northeast India and some parts of Bangladesh. The core monsoon region, i.e. central India, extreme associated to heavy rain events are influenced by variations of SST over Indian Ocean and number of extreme rainfall events estimated to rise in coming future under warming and associated floods will also increase. Floods are frequent in South Asia. Nepal, Bangladesh and Indian states encounter flood during monsoon. The flood water carries silt load and deposits in plains; the course of river also changes sometimes, like river Kosi in Bihar. Floods submerge hectares of farmland and destroy crops, loss of life, livestock and property and cause landslides in hilly regions. India and Nepal have 21% of global rainfall triggered landslides mainly during monsoons. The problem of safe shelter to the people and water quality arises concerns mainly during floods. Bangladesh is one of the world's most densely populated countries and prone to cyclones and flooding due to its low-lying position, so it is more climate-sensitive economy. Major floods are quite often in phase with active spell and drought is accumulative picture of dry days. The drought is subjective in nature and methodologies for assessment and parameters under consideration vary from region to region. The number of dry days, dry spell information, Standardized Precipitation Index (SPI) values along with rainfall departure from normal have been included in the list of important parameters for drought declaration in India. Area under drought-affected districts is showing significant increasing trends or no trend in India. Drought situations occur every year in many states of India and some coastal states like Tamil Nadu, Kerala and Karnataka. Flood and drought both lead to question of food security and health issues due to diseases outbreak linked with post flood weather conditions.

Coming to climate change and warming aspects, South Asian regions observed decline in precipitation from 1900 to 2005. The monsoon extremes very likely to increase over East, South, and Southeast Asia. The recent Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations with Representative Concentration Pathway (RCP) scenarios are projecting greater than 2 degree rise in average mean yearly temperature with respect to reference level temperature of period 1970–1999 twentieth century estimated by ensemble of climate over huge and extensive land mass of the world during middle of twenty-first century under RCP8.5, and above 3 °C over continental land areas of Southeast sector of Asia in the late twenty-first century. Increased frequency of heavy rainfall with non-uniform spatial and temporal distribution, more number of warm days, and less cold days will be increasing and create acute water scarcity problem amplified by rising population and its demands, huge pressure on natural resources and ecosystems, extinction of more species, and loss of biodiversity.

The large-scale circulations associated with SAM will be modulating under the warming atmosphere. Weakening of circulations projected by models but extremes will increase. The future modulation of six semi-permanent synoptic circulation will lead to more extreme events. The future poleward shift of LLJ. The position of Tibetan anticyclone and associated wind strength determining reversal of temperature gradient in troposphere will be playing crucial role for monsoon advancement in South Asia. Large-scale circulations inducing/favouring regional circulation modifying regional weather and governing internal variability of monsoon will be more pronounced under changing climate. The projections of climate models with probable emission ranges have deviations and uncertainties. The reduction in range of uncertainty is required for planning technology driven solutions and sustainable practices for better adaptability of changing climate.

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Contribution of Fog in Changing Air Quality: Extremities and Risks to Environment and Society

5

Saraswati

Abstract

This chapter presents a brief review on the contribution of fog in changing air quality, its extremities and risks to environment and society. Fog is one of the extreme environmental phenomena which cause significant societal and economic problems specially as a great devastation to road and air traffic. As the hazardous effect of fog events is very high, their formation, spatial extent and evolution are needed to be investigated in detail. The detailed characterization of the formation and evolutionary mechanisms of fog pollution is necessary. The purpose of this chapter is to provide a brief outline on fog formation, development, distribution, characterization as well as its extremities and impacts on environment and society. In this chapter, we have started our study with the description of fog, its types and distribution worldwide, specifically in northern India. The microphysical structure, chemical composition and interactions which determine the behaviour of fog is also explained. The physicochemical characterization is described in detail which is necessary to understand the fog formation and its impact on environment and society. The chapter also describes the different factors responsible for fog formation. The different meteorological conditions and role of aerosol were explained which were amenable for fog formation. In the last section, the fog as an extreme event is described. The causes and their extremities on different aspects of environment and society are also provided in detail.

Keywords

Fog · Microphysical · Meteorological · Formation · Evolution

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5.1 Introduction

Fog is one of the important climatic phenomena which set up crucial societal and economic problems specifically as a notable disruption to air and road traffic. The many regions of the world are affected by fog (Gautam and Singh 2018; Saxena and Kulshrestha 2015) as it results in low visibility, has effects on air quality, disrupts transportation, increases economic losses and intensifies health risks. The different parts of the world including Po valley in Europe, the central valley of California, Indo-Gangetic Plains (IGP) and North China Plains (NCP) in south Asia are distressed with dense fog cover (Baldocchi and Waller 2014; Gautam et al. 2007; Ghude et al. 2017; Giulianelli et al. 2014; Hameed et al. 2000; Herckes et al. 2015; Quan et al. 2011). The fog is mostly observed in plain areas adjacent to continuous mountain ranges and extensively spread over hundreds of kilometres during the winter season. The steady boundary layer structure, calm winds, high relative humidity (RH), lower temperature and local radiative cooling are some of the characteristics of these regions (Duynkerke 1991). These prevalent factors result in the cooling of air near the earth's surface, provide moisture and are responsible for the formation of widespread fog in these regions. The build-up of fog is further intensified due to the availability of high aerosol concentrations and their accumulation in lower planetary boundary layer (PBL) in these polluted regions (Duynkerke 1991; Quan et al. 2011; Wang et al. 2016; Saxena et al. 2020). Hence, the height of the PBL plays a crucial role in restraining severe air pollution episodes and weather phenomena. The dispersion of particles is also affected by PBL in the concerned regions (Petäjä et al. 2016). The insight of characterization of hygroscopic particles present in the boundary layer and their effect is necessary, as visibility is reduced by these particles. The life cycle of fog is modified by atmospheric aerosol as they can act as cloud condensation nuclei (CCN) and impact the development of fog (Safai et al. 2019).

There is a tremendous challenge in relation to air quality, as frequency and severity of haze and extremities of fog event around the world have enhanced in recent years as a result of rapid urbanization and industrialization, which has caused great concerns worldwide (Chan and Yao 2008). The fog and haze events were observed and segregated into different phases like haze, wet haze, mist and fog in relation to relative humidity and visibility by Yang et al. (2010) in the winter of Nanjing (Yang et al. 2010). The haze, mist and fog extremities are more prevalent in the winter season and result in visibility reduction often even up to zero. In the winter season, the northern Indian cities are more affected by the visibility reduction as increasing pollution results in radical deterioration of air quality in these regions which further reduced the atmospheric visibility adequately (Goyal et al. 2014). The fog and haze particles present in the stable boundary layer attenuated the visible light (Pinnick et al. 1978) and result in lower visibility which greatly impact aviation. The travellers are badly distressed due to delays, diversions and cancellations of flights as a result of the existence of dense fog extremities. The airlines also suffered huge economic losses due to disruption in flight operations at airports (Kulkarni et al. 2019). The effect of fog and poor visibility on land, marine and air transportation results in huge financial and human losses which can be compared with other weather events like hurricanes, winter storms and tornadoes (Gultepe et al. 2007).

The extreme fog event becomes a topic of research for public, government and atmospheric scientists in the world to understand the mechanism behind its formation, as it greatly affects the human being. The multiple car accidents each year are the result of unsafe road conditions caused by fog. Most people have heard of the horrific chain reaction accidents which occur in fog. It is hardly surprising, given the effects of fog on perception. Fog obviously produces accidents because a driver cannot see as far ahead. The droplets in a fog vary in concentration, which can cause partial to zero visibility. Other methods of transport such as ships and planes are also badly affected by the poor visibility associated with fog (Saxena and Kulshrestha 2016). The aviation industry is particularly prone to the effects of fog, as limited visibility can make flying unsafe, especially during take-off and landing. The human health is also affected by fog episode in addition to reduction in visibility which severely affected transportation. Renhe et al. (2014) observed increase in cases of respiratory and cardiovascular diseases during these extreme fog events (Renhe et al. 2014). The discerning of physical and chemical characteristics of fog, meteorological factors responsible for its genesis, sustenance and intensity is necessary for the detailed characterization of the fog pollution and its extremities over various space and time scales (Gultepe et al. 2007). The initiation, persistence and enhancement of this severe and extreme fog event are contributed by large-scale circulation patterns, atmospheric circulations and boundary layer processes at all scales. This extreme fog event has a tremendous effect on air quality, visibility, human health and transportation.

Thus, the insight of complicated chemistry of different atmospheric activity accountable for the fog formation is necessary and the chemical makeup of aerosols is also required to estimate the influence of aerosols in the atmosphere which result in evaluation and improvement of existing fog forecasting systems. The comprehensive understanding of the mechanisms controlling fog formation and evolution is needed to provide much-needed knowledge benefiting public health, efficiency of transport as well as areas of environmental research and development. The persistence and enhancement mechanism of extreme fog event was described in detail in this chapter. This chapter reviews the fog types and distribution, physicochemical characterization, factors for its formation and evolution and extremities of this fog pollution phenomenon on environment and society.

5.2 Fog

Meteorological fog can be defined as thin cloud consisting of microscopically small water droplets which are kept in suspension in the air near the ground surface and reduce horizontal visibility (Canada and Toth 2010). The fog is a natural, climatic condition in the form of clouds coming close to ground surface, formed by warm air currents touching cold surfaces or when cold air currents blow on warm surfaces. Fog is formed when the moist air (with relative humidity above 97%) becomes saturated, reaches its dew point and further cools so that water vapour is condensed

Table 5.1 Visibility through the various types of fog denoting with international number (0–9) (Source: Al-Mutairi 2017)

International number	Fog	Maximum distance to see clearly
0	Opaque fog	50
1	Heavy fog	200
2	Show?? is very poor	500
3	Show is poor	1
4	Rusk??	2
5	Show weak	4
6	Show moderate	10
7	Opaque fog	20
8	Heavy fog	50
9	Show is very poor	More than 50

around dust particles, smokes etc. to form tiny water droplets which being very light are suspended in the air. It is a form of condensation, containing minute water drops with the diameter of each is no more than 100 μm (Al-Mutairi 2017). The horizontal visibility is used as a criterion to define fog and haze by World Meteorological Organization (WMO). WMO reported that the fog can be defined with the visibility below 1 km and light fog or haze with the visibility in the range of 1 km and 5 km. The fog and haze cannot be identified separately when they are coexisted under the condition of pollution. The fog and haze can also be pinpointed on the basis of relative humidity (RH) as according to UK Met Office (UKMO). It represents fog when RH is 100%, mist, when RH is in the range of 95–100% and it represents haze when RH is less than 95% (Guo et al. 2015). The increasing haze aerosol could intensify the formation of fog and its build up as reported in some studies (Jia and Guo 2012).

Fog dissipates at sunrise when air temperature begins to increase. It is thicker in cities than in rural areas due to dust and grime pollution where dust and grime cling to the water drops. As a rule, upon formation of fog, visibility becomes low which leads to accidents, particularly in the event of thick fogs. Owing to the risks involved in fogs, scientists have developed an international fog measure (from 0 to 9) relying on the naked eye for observation (Table 5.1) (Al-Mutairi 2017).

5.3 Types of Fog

Fog is physically no different than a cloud. However, what differentiates one from the other is the location and mechanism of formation (Lutgens and Tarbuck 2004). Both fog and clouds form when air becomes saturated and the water vapour condenses. Fog may also form from cloud base lowering to the surface in relation to temperature inversions (Lewis 2004). Peter Nolan (2010) classifies fog according to the manner it is formed: it can occur as a result of the air being saturated with water vapour or through cooling the air until it has reached saturation point. So, the agents that caused air saturation with vapour, the speed of evaporation and the factors affecting the cool air that is close to ground surface are the determinants for classifying fog types.

The approach of recognition and categorization of fog events into a particular category which emulate the primary mechanism accountable for their formation is deemed more insightful as it stipulates particular information about the disposition of formation mechanisms of fog (Croft and Burton 2006). The fog formation is the result of boundary layer structure, different meteorological conditions, synoptic causes and geographical conditions (Li et al. 2011b). Irrespective of the mechanism, fog has generally been observed to be associated with a stable atmosphere and calm wind conditions (Holton et al. 2003). For fog, there are two main mechanisms that can take place, namely: the addition of water vapour close to the surface and cooling. Both are further explained below.

5.3.1 Fog Formed Through the Addition of Water Vapour

Steam fog and frontal fog are examples of fog formed by this mechanism.

5.3.1.1 Steam Fog

Steam fog is a fog resulting from intense evaporation from water to relatively cool air, so the state turns from saturation to condensation to fog. Steam fog is formed when cold air travels over relatively warm water (Gultepe et al. 2007). The evaporation of surface warm water supplies the cold air above with water vapour. The colder temperature causes the water vapour to cool and condense, causing steam fog at the air-water interface (Gultepe et al. 2007). Steam fogs are produced with the moving of cold air from land to oceanic surface and there is evaporation of large quantity of moisture from water surface to saturate the overlying cold air. It is fascinating to notice that in such situation overlying cold air is warmed from below and thus water vapour due to evaporation of warm water surface rises upward and condenses after meeting cold air above to form fog. The vapour particles above the water surface look as if steam is coming up from the water. This is why such fogs are called steam fogs. They are also called evaporation fogs (Okland and Gotaas 1995). Evaporation fog can be noticed over water bodies and in tropical areas. Sometimes it occurs in warm areas or wet lands, or immediately after rains as is the case in Northern Borders.

5.3.1.2 Frontal Fog

Frontal fog forms with the lifting of a warm air mass over a colder air mass and supplies it with moisture or is cooled to dew point (Gultepe et al. 2007). If the cold air is near dew point, a slight addition of moisture can lead to frontal fog. As the name suggests, this is formed along the edges of two masses or fronts of air: warm rain evaporates, falling from a higher layer, through a drier air mass, in a lower layer, thus bringing about a state of water-vapour-saturated air, followed by a state of condensation of colder layers thus forming frontal fogs (Stewart et al. 1995). Fronts are formed when two contrasting air masses (warm and cold air masses) converge along a line. Warm air is pushed upward by cold air and hence overlying warm air is cooled from below due to underlying cold air and fogs originate after condensation (Guo et al. 2015). Such fogs are formed in temperate regions. In fact, the saturation and condensation of overlying warm and moist air causes rainfall which saturates the underlying cold surface air and thus fog is produced.

5.3.2 Fog Formed by Cooling

This mechanism involves the earth or ice surface to cool the overlying air. When air with a high relative humidity is cooled to below its dew point, condensation takes place and fog forms. The warm and moist air when blows over cold surface (either land surface or sea surface) is cooled from below so that dew point is reached and condensation of water vapour occurs around hygroscopic nuclei and thus microscopic water droplets are formed to create fogs. There are four main types of fog that are formed through this mechanism, namely radiation fog, advection fog, upslope fog and mixing fog.

5.3.2.1 Radiation Fog

Radiation fog is formed after nightfall when the ground has released its heat through emission of longwave radiation, and the ground is cooler than the overlying air (Gultepe et al. 2007). Due to this situation overlying warm and moist air cools and thus dew point is reached, with the result condensation of water vapour around hygroscopic nuclei (dust particles and smokes) forms numerous tiny water droplets and thus fog is originated. It is particularly formed when the wet air touching ground is fully quiet. As a result of cooling, saturation occurs, followed by condensation and then fog is formed. This takes place as a result of radiation at night time, when air is fully quiet, dew or frost is formed. At the slightest air motion, fog becomes deeper. If air motion further increases, fog disperses and clears up. As a rule, radiation fog occurs on flat ground (Bergot and Guedalia 1994). Under this scenario, fog formation has been shown to be sensitive to the coupled dynamical and thermodynamical structure of the evolving boundary layer over land (Duynkerke 1999; Roach 1995). The occurrence of radiation fog requires certain conditions, e.g., long and cool winter nights, cloudless sky, sufficient amount of moisture in the air, very weak air motion (light wind having speed of 3–5 km per hour) and ground inversion of temperature. Fog is formed at the ground surface during nights and thickness upward. It disappears in the morning with the sunrise because the water droplets are evaporated due to the rise in air temperature.

Advection-Radiation Fog

The radiative cooling of moist air in the coastal area results in advection-radiation fog. The advection of moist air takes place over land which is coming from the ocean or from any large water body during the previous daylight hours. The moisture availability and radiative cooling potential result in inland radiation fog in the fall season. The occurrence of radiation fog in the coastal plains in the spring season is due to the influence of advection inland of moist marine air during the previous afternoon (Ryznar 1977). The fog formed as a result of mixing of warm moist air and cold air due to the arrival of moist and warm air over the cold ground surface is called advection-radiation fog. There are certain required conditions for the origin of advection radiation fog, e.g. (1) horizontal movement of air, (2) greater contrast between air temperature and the temperature of the ground surface, (3) moist air or say high relative humidity in the air, and (4) stable stratification in the atmosphere, etc.

High Inversion Fog

The strong inversion over a deep moist layer in valleys results in the formation of high inversion fog (Holets and Swanson 1981). The prolonged subsidence and radiative cooling in association with a persistent anticyclone results in the inversion. The Central Valley of California is afflicted with inversion fog commonly during the winter season (Underwood et al. 2004). Radiation fog is more common over large cities and surrounding areas because of the abundance of hygroscopic nuclei. When fog is combined with sulphur dioxide it becomes poisonous and causes human deaths. Such fog is called urban smog. Sometimes, such fogs also occur at higher elevation due to upper air inversion of temperature.

5.3.2.2 Advection Fog

The formation of advection fog occurred when warm humid air travels over a cold surface such as sea ice. The cold surface cools the overlying warm moist air to dew point, condensation takes place, and advection fog is formed. It is formed when wet air passes over a cold surface, thus effecting saturation and dew drops formed on the ground. Further cooling of the air layer touching the ground results in high saturation rates. With the light air movement, air mixes up, leading to condensation on higher layers above ground level and so fog covers the whole area. Advection fogs are generally originated during winters on land surfaces and during summers on sea surfaces because lands are relatively colder than seas and oceans during winters (Gultepe et al. 2007).

Advection fog shows up mostly in places where warm, tropical air meets cooler ocean water. The Pacific coast of the United States, from Washington to California, is often covered in advection fog. The cold California Current, which runs along the western coast of North America, is much cooler than the warm air along the coast. Dense advection fogs are also formed where cold and warm ocean currents coverage (Guo et al. 2015). For example, dense fogs are formed near Newfound land due to the convergence of cool Labrador and warm Gulf Stream ocean currents. Similarly, dense fogs are formed near the Japanese coast due to the convergence of cool Kurile and warm Kuroshio currents (Duanyang et al. 2010; Pu et al. 2008). The different types of advection fog are explained below:

Sea fog is formed over the ocean with advection of relatively warm marine air over the cold sea ice in the summer during sea ice break-up (Lewis et al. 2003). The fogs occurring over sea surfaces are called sea fogs which are generally formed near the coastal areas frequented by cold ocean currents. For example, cool California current (along the Californian coast), cool Peru current (along the Peruvian coast), cool Benguela current (along the western coast of South Africa) and cool Western Australian current cause sea fogs (Lewis 2004).

Land and sea breeze fogs are formed with the transportation of warm moist air from land to cool coastal ocean. The sea-breeze circulation results in the moving of this fog over the land during the following afternoon hours. The formation of land and sea breeze fogs is particularly a coastal occurrence.

Tropical air fog is also a kind of advection fog. The air mass is gradually cooled due to ocean temperature gradient and long-range transport of tropical air towards the pole (Friedlein 2004) during this phenomenon.

5.3.2.3 Upslope Fog

Upslope fog, on the other hand, is formed when relatively humid air is cooled by moving up a sloping terrain. Upslope or hill fogs originate when continental warm and moist air rises upslope along the hillslopes because the rising air is saturated due to cooling and condensation of moisture around hygroscopic nuclei and forms fogs which cover the lower segments of hillslopes (Gultepe et al. 2007; Lutgens and Tarbuck 2004). It may be mentioned that such fogs are formed due to adiabatic expansion and cooling of moist air. Such fogs are very common on the hillslopes in temperate regions. They may occur in any season (Nolan 2010).

5.3.2.4 Mixing Fog

The formation of mixing fog occurs when a wet, warm air mass meets a wet, cold one. This mixture results in a temperature drop enough to effect saturation and condensation, yielding mixed fog. An example of mixing fog is when a person exhales in very cold days in a mist that he can see before his eyes. The fog lowers visibility on highways and open spaces, endangering lives. The reason for these in most of the cases is the drop in the temperature of the air that is close to ground so much so that it gets to zero or below, accompanied with a considerable increase in the rates of relative humidity during night time, especially in winter following rains. The Northern Borders witness annually a number of fog formation cases which has negative impacts on people's health and life since it limits visibility on roads leading to accidents (Nolan 2010).

5.4 World Distribution of Fog

If the world distribution of fogs is considered it becomes apparent that they are more widespread over oceans. The oceanic fogs are generally advectional in origin because relatively warm air coming from over the land surfaces produces fog over relatively colder oceanic surfaces. Fog areas are positively related to cool ocean currents. The eastern portions of the oceans and western continental margins are characterized by most fogs because these areas are frequented by cool ocean currents (e.g. California current, Peru current, Benguela current, Canary current, Western

Australia current, etc.). Frontal fogs are produced in the high latitudes due to convergence of cold polar air mass and warm westerlies mainly in the eastern North Atlantic Ocean and western coasts of north-west Europe and in the eastern North Pacific Ocean near Aleutian Islands and Alaska coast (Guo et al. 2015). Radiation fogs are produced in low latitudes on continental areas during the winter season. Dense fogs are formed at the places where cold and warm Ocean currents converge, e.g., near Newfoundland and Grand Banks (due to convergence of cold Labrador current and warm Gulf Stream) and near Japanese coasts (due to convergence of cold Kurile current and warm Kuroshio Current). Important foggy areas of the USA are California coast, New England outer coast, Northern Pacific coastline, Appalachian valleys, Pacific coast valleys, Middle Atlantic coast, Great Lakes, Southern Atlantic and Gulf coastal waters, Ohio, Missouri, Great Plains and upper Mississippi valley.

5.4.1 Northern India Fog

The pervasive layer of fog can usually be observed with the satellite during the winter season in the northern India, which is the remarkably fog prone areas in the world (Gautam et al. 2007). The stable atmospheric conditions, vigorous temperature inversions, probable amount of moisture as a result of western disturbance (WD) (Dimri et al. 2015) and prevalent terrain characteristics of Indo-Gangetic plains of Northern India lead to fog formation and its subsistence during the winter season in this region which result in lower visibility. Compared to other areas of the world, fog events observed over the northern region of India form rapidly, with largest coverage area and longest duration. The current research on fog in India during the past 10–15 years have raised significant concerns as a result of enhancement in frequency, persistence and severity of fog occurrence over the northern India (Jenamani 2007; Syed et al. 2012). The fog days were gradually increasing for the last three decades, starting from the 1980s. The days having visibility <200 m are represented as dense fog days which enhanced from 10 days in 1980s to 20 days in recent years over Delhi as recorded by some studies (Jenamani and Kalsi 2012: Ghude et al. 2017). The 60% days having fog events and 16% days with dense fog events are indicated by the research on instances of fog in Delhi (Jaswal et al. 2013; Safai et al. 2019). Maximum fog and dense fog events are mostly seen in December and January. A similar trend is also seen in eastern–central China and linked to increased urban aerosol loading (Niu et al. 2010). The results can be interpreted as an indication of the role of increasing air pollution and humidity (Jenamani 2007; Syed et al. 2012) to increase fog events over this region. The atmospheric aerosol nuclei emitted from various human activities along with favourable meteorological condition result in the formation of haze and fog in the winter season in Indo-Gangetic plain (IGP) region of India (Badarinath et al. 2007). The interaction amid particulate matter (PM) gaseous pollutants and atmospheric water vapour affect the chemical composition of fog and also reduce visibility on the basis of concentrations, size and chemical characteristics of the particles. The condensation nuclei are particularly formed due to small particles such as accumulation mode particles which are also very effective in lowering visibility (Goyal et al. 2014). The annual morning poor visibility days (PVDs $<$ 4 km) in India have enhanced from 6.7% days in 1961 to 27.3% days in 2008 (Jaswal et al. 2013).

The rapid urbanization and industrialization result in lower visibility during prolonged fog phenomena in India which caused disruption in trains and flight operations and large vehicular accidents. These severe fog events even affect human health, disrupt daily life and sometimes fully shut down airports services for hours as a result of zero visibility induced by dense fog extremities in the winter season (Badarinath et al. 2009; Chandra et al. 2018). There is serious compulsion from air, road and rail transport authorities to know whether a fog will occur during the next 24 h, and if so, what could be its intensity, onset time and dissipation rate. The understanding of fog physical characteristics, factors responsible for fog genesis, intensity and expeditious thickening of the fog layer over IGP is necessary.

5.5 Characterization of Fog

The understanding of microphysical structure, chemical composition and interactions is required for determining the behaviour of fog. The in-depth exploration of microphysical and chemical properties of fog is needed for understanding its formation and development and also for discerning its aftermath on transportation and flight operation. Thus, physicochemical characterization is necessary to discern the generation of fog and its impact on environment and society.

5.5.1 Microphysical Structure of Fog

Once fog is formed, it is largely the atmospheric stability but also the fog's microphysical structure that determines its occurrence, intensity, duration, horizontal and vertical extent. The microphysical structure is determined by the type of condensation nuclei, local nuclei populations, drop size distribution and atmospheric chemistry. An essential process in fog formation is nucleation. Condensation nuclei are agents that facilitate droplet formation due to their properties such as surface curvature, electric charge, ionic charge and hygroscopy (water seeking), that make them effective sites for condensation (Gueye 2014; Willett 1928). The surface with fog formation plays a crucial role in determining the type of microphysical structure.

The accumulation of aerosol, transition process of mixing of aerosol and fog and dissipation are the three main stages of the process of fog formation. The increasing Aitkin and accumulation mode nuclei number concentration of aerosol is the characterization of aerosol accumulation stage. In the mixing stage of haze and fog, the enhancement in the activation process of CCN and increase in the growth of small size aerosol to larger ones is the result of Brownian coagulation process, which is aggravated by higher aerosol number concentration and latent heat production from condensation process of fog droplet. This stage results in hysterical development of the fog. The increased heating due to solar radiation or passing cold frontal system results in the decrease and dissipation of the fog (Guo et al. 2015).

5.5.2 Haze to Fog Transition

The transformation of haze aerosols into fog droplets takes place in the presence of some particular condition. The size of haze aerosol plays a crucial role in the transition of these particular aerosols to fog droplets. The formation of fog droplets takes place due to the activation of haze aerosol having size larger than 1 μm. The haze particle having size between 0.3 and 1.0 μm does not change and remains almost consistent during the entire life cycle of fog. Eldridge (1969) reported the transformation of haze into fog with the presence of visibility in the range of 500–1000 m (Eldridge 1969). The sporadic and unusual transformation occurs in the relationship of aerosol number concentration and visibility was observed by Meyer et al. (1980) during the transition process of haze to fog, as visibility reduced from 2.1 to 1.4 km (Meyer et al. 1980). Generally, the clear, haze and fog days were categorized on the basis of relative humidity (RH) and visibility as done in some studies (Ramachandran et al. 2006). The days were represented as clear days with visibility of 10 km, haze days with visibility between 1 and 2 km and fog days with visibility of 0.2–0.5 km (Ramachandran et al. 2006). In concern with relative humidity, when RH was less than 70%, the days are represented as clear days. In comparison, when the RH was in the range of 80–100% represents hazy and foggy days. The classification of weather into fog, haze and clear days was also done by Elias et al. (2009) during the investigation of haze and fog events in Paris. The researcher done this classification on the basis of attenuation contributions of fog, haze and clear days and observed the transformation of haze into fog with the visibility reduction from 0.88 to 0.4 km (Elias et al. 2009).

5.5.3 Chemical Composition of Fog

The conversion capacity of hygroscopic aerosols into fog droplets with the increase in moisture can be discovered by analysing the chemical composition of the fog (Fahey et al. 2005). Data from the aerosol and fog water chemistry so far indicate a highly polluted environment in which the fog developed. The concentrations of NH_4^+, SO_4^{2-}, Cl^-, Ca^{2+} and NO_3^- were found to be very high, indicating that fog water is highly polluted. The ionic composition was found in the order of $NH_4^+ > SO_4^{2-} > Cl^- > Ca^{2+} > NO_3^- > Na^+ > Mg^{2+} > K^+ > F^- > HCO^{3-}$. Among the anions, the concentration of SO_4^{2-} (3763 μeq/L) was maximum, whereas NH_4^+ (4162 μeq/L) showed maximum concentration among the cations (Ghude et al. 2017). The sulphate (SO_4^{2-}), ammonium (NH_4^+), nitrate (NO_3^-) and chloride (Cl^-) were the major constituents of fog droplets as also implied by chemical analysis of fog droplets in some studies (Li et al. 2011a). The highest values of chemical species were observed during stable conditions especially during night hours on foggy days (~11% higher). Secondary inorganic aerosols (sulphate and nitrate) were the dominant ions (38%) in the chemical constituents of the fine particle and were higher during the fog events. The chemical partitioning of fog water samples suggests that NH_4^+ (28%) and SO_4^{2-} (26%) dominate the chemical composition (Ghude et al. 2017). Ammonium and sulphate are in the form of ammonium sulphate ($(NH_4)_2SO_4$). Even though the acidic ions SO_4^{2-} and NO_3^- are very high, fog water is not acidic because of the very high concentration of neutralizing ions $NH_4^+$and Ca^{2+} in the samples. The major neutralization was due to NH_4^+ followed by Ca^{2+}. The alkaline nature of fog water was also reported by Lakhani et al. (2007) during chemical probe of fog water at Agra (Lakhani et al. 2007). The ammonium (NH_4^+) was showing higher concentration followed by SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ in this study. The SO_4^{2-} was present in higher amount than NO_3^- in fog water as indicated by SO_4^{2-}/NO_3^- equivalent ratio of 1.4 in fog water (Singh and Gupta 2014). The acidic effects of SO_4^{2-} and NO_3^- could also be neutralized by Ca^{2+} as there is presence of higher concentration of soil-oriented aerosols (Ca^{2+}, Mg^{2+}, K^+ and Na^+) with dominance of Ca^{2+}in Delhi as reported by Kapoor et al. (1993) in this particular region which also justified the alkaline nature of the fog (Kapoor et al. 1993).

5.6 Factor for Fog Formation

Fog formation is mainly reliant on complicated interactions amid microphysics, radiation, turbulence, availability of moisture and surface processes (Gultepe et al. 2007). The fog formation was triggered by the physical mechanisms representing different meteorological conditions in a particular area (Chaouch et al. 2017). The pollution in a particular area greatly influenced fog formation and the heterogeneous nucleation of pollution particle led to fog particle formations (Gultepe et al. 2001). The increasing concentration of atmospheric aerosol (condensation nuclei) and enhanced condensation of water vapour on higher available condensation nuclei result in the formation of long-lasting and denser fog (Ram et al. 2012).

5.6.1 Meteorological Condition

Fog occurrence is correlated with the relative humidity, temperature, wind velocity, cloud cover and weather thermal stability. The dew point occurs when air temperature is saturated with water vapour. This takes place when air or the water drops clinging thereto takes in more humidity (Nolan 2010). When air temperature nears the dew point, a little humidity condenses on the particles suspended in the air, such as dust and snow, and turns into liquid state matter that results in the fog. Therefore, air saturation with vapour and the condensation of minute water particles are two major conditions for fog formation (Nolan 2010). The scenarios that most commonly come to mind when considering fog are associated with calm clear nights over land or fog observed at sea over cold waters. But the fact is that fog presents itself under various scenarios, including some associated with large-scale mid-latitude cyclonic disturbances. The various scenarios are often described through a classification according to fog types. Due to the numerous factors involved, it is not surprising that fog forms under a wide range of scenarios. The fog formation and subsequent evolution is driven by a plethora of mechanisms and interactions that span several time and space scales.

5.6.2 Role of Aerosol

Mensbrugghe (1892) acknowledged the role of aerosols in the formation of fog and declared that the solid particles present in the air result in aqueous vapour condensation (Mensbrugghe 1892). The turbulent mixing, growth of droplet due to radiative cooling, differential gravitational settling of different size drops and activation growth of droplets are some of the crucial exercises that shape the microstructure of fog. There is the presence of sophisticated relationship amid characteristics of fog and aerosols, as the aerosol drives the activation growth of droplets. The area with higher aerosol concentration results in larger fog as compared to other (Knott 1923). The dependence of microstructure of fog on condensation nuclei was entrenched by many researchers in the past by studying the relationship between aerosol characteristics and droplet nucleation under different meteorological conditions (Eldridge 1971; Neiburger and Wurtele 1949).

The formation of fog droplet is the result of water vapour condensation on the accumulation mode particles which are acting as cloud condensation nuclei (CCN) during the foggy conditions (Seinfeld and Pandis 1998). The mass of accumulation mode particles increased due to aqueous reactions in the fog droplet (Kaul et al. 2011). The presence of meteorological conditions like lower temperature and higher relative humidity and along with higher concentration of aerosol which particularly acts as CCN in a particular area results in the appearance of fog. The saturation of water vapour during the generation and fog evolution mainly occurs in the presence of higher relative humidity (RH), sometimes at 100%. When the condensation of water vapour takes place on the available surface area of aerosol, dew point reached and growing of droplet results in perpetual fog (Singh et al. 2011). The formation of secondary organic aerosol (SOA) and other inorganic species also increased in presence of fog which further provide more surface for condensation (Kaul et al. 2011; Singh et al. 2011). Some researchers in India over the IGP investigated the role of local meteorological conditions and primary and secondary aerosol in the modulation of fog and haze formation in the wintertime. Where, low ambient temperatures, weak winds, and stable boundary layer height result in pollutant accumulation (Nair et al. 2007; Ram et al. 2010). The researcher worldwide has also observed the fog formation as a result of higher aerosol concentration emitted from human activities along with secondary aerosols formations via gas-to-particle conversion under favourable meteorological conditions (Fang et al. 2011; Husain et al. 2004; Reilly et al. 2001; Sun et al. 2006; Zhang et al. 2010; Sonwani and Saxena 2021).

5.7 Fog as an Extreme Event: Causes and Impacts

5.7.1 Fog as an Extreme Event

Today, there are many tools for identifying and predicting severe and high-impact meteorological events. However, short-lived weather phenomena like fog does not lend themselves as easily to identification and prediction. Fog creates low visibility conditions, which increased a greater crash risk. According to the Federal Highway Administration (FHWA), every year, over 38,700 vehicle crashes occur in fog, killing more than 600 people and injuring more than 16,300 people annually. And vehicles are not the only mode of transportation affected by fog; there can be significant impact to aviation and marine operations as well. On all, fog is an extreme event which causes more deaths (from traffic accidents) than heat, tornadoes, floods and lightning.

5.7.2 Causes

The changes in meteorological conditions and concentration of aerosol are correlated with the formation and intensification of the fog. The advection and radiation effects in combination effects the strength and intensity of extreme fog event. The maintenance and fog deterioration are mainly the result of alternative temperature advection. The strengthening and weakening of the extreme fog event were also affected by boundary layer height. The dynamic factors like weak vertical wind shear persistence in middle-lower layer and weak vertical motion were favourable for the formation of extreme fog event. The multiple factors like atmospheric stratification, the atmospheric circulation background, vertical wind shear structure, temperature advection, aerosol pollution characteristics and the meteorological conditions play a crucial role in the conversion and enhancement of fog events. The crucial condition for the formation of fog is the inversion stratification. The advection and radiation cooling were liable for the strengthening and intensification of dense fog event in the area of wetter and thicker ground layer where the middle high layer with colder and drier characteristics results in more formation and strengthening of fog. The worst air quality in urban area further increase the occurrence of fog weather and impacts human being in many ways.

5.7.3 Impacts

The high occurrence of fog has numerous and diverse impacts on human activities, ecosystems and regional climate which caused deep concern in the scientific community recently. The fog event has wider impact on environment, as it plays an important role in the degradation of air quality by increasing pollutant concentration which further reduced the visibility. The people's daily life is badly affected due to prolonged fog episodes and the reduced visibility further affected the road, marine and air transportation. The number of roads, rails and air accidents also increased due to poor visibility in the presence of fog events (Gultepe et al. 2007). The low visibility results in delay, diversion and cancellation of flight which lead to huge economic losses. Studies also provide evidence that the occurrence of fog in polluted environments leads to adverse health effects in the human population (Villeneuve et al. 2005). Among these, low visibility and degradation of air quality is of main concern (Zhang et al. 2010) as they are causes of all the fatalities occurring related to fog.

5.7.4 Effect on Air Quality

The occurrence of fog events in a particular region has great effect on the air quality of that region. The increasing concentration of fine particulates ($PM_{2.5}$) during the events of fog results in many environmental problems by reducing visibility, affecting human health and climate (Bi et al. 2014; Zhang et al. 2015). The concentration of secondary aerosol increased due to increase in aqueous phase oxidation reaction in presence of fog, which also has substantial impact on visibility, atmospheric chemistry and air quality in these fog events. The fog episode in a region represents the reduction of visibility below 2 km, lowering of PBL below 1 km, reduction in wind speeds below 1 m/s and increase in concentration of different pollutants in that region (Guo et al. 2015).

5.7.4.1 Effect on Pollutant Concentration

The increase in mass concentration of particulates matter (PM) has been reported by Tiwari et al. (2011) due to the event of fog (Tiwari et al. 2011). The increase in total suspended particulates concentration during the foggy period was also reported at Hisar because of higher relative humidity (RH) in the combination of fog. The increase in particulate mass loading and reduction in visibility was observed by Shen et al. (2015) in Yangtze River Delta, China during the fog event of January 2013 (Shen et al. 2015). The foggy days in Kanpur also observed increase in mass loading of PM_1 as reported by Gupta and Mandariya (2013) (Gupta and Mandariya 2013). The increase of hygroscopic growth of increased aerosol particles in the presence of higher relative humidity results in enhancement in the light scattering efficiency during the foggy periods as observed by Malm and Day (2001) (Malm and Day 2001). The study in Kanpur, India (Kaul et al. 2011) and in London (Dall'Osto et al. 2009), both recorded increase in production of secondary organic aerosol during fog events. The fog processing results in increase in ratio of organic carbon to elemental carbon (OC/EC) and water-soluble organic carbon to organic carbon (WSOC/OC) as observed by Rajput et al. (2018) during the winter season and also observed increase in organic matter (OM) from non-foggy to foggy periods (Rajput et al. 2018).

During the severe foggy days, all the chemical components of particulates matter specifically SO_4^{2-}, NH_4^+, BC and NO_3^- represent increase in their concentration. The mass concentration of all ions was observed higher at day and night-time both during the time of fog. Ghude et al. (2017) reported aqueous-gas phase partitioning of ammonia due to increased ammonium ions concentration in fog water which is recorded as 4162 μM in the fog water. The gas to particle conversion increased due to the presence of aqueous phase, i.e. clouds or fogs in the atmosphere which acts as a physicochemical processor for gases and particles which result in higher concentration of ammonium, sulphate and nitrate during fog events (Kaul et al. 2011; Gupta and Mandariya 2013). Several chemical reactions take place at the medium provided by the aqueous phase during the fog processing.

5.7.4.2 Visibility

The level of atmospheric quality can be indicated by visibility, as it is an eminent index for assessing the air quality of urban environment. The increasing air pollution leads to increase in optical extinction coefficient of gas and particulates which result in poor visibility (Chang et al. 2009; Deng et al. 2011). The studies on air pollution and climatology included visibility for representing the air quality (Chen and Wang 2015; Shi et al. 2014). The atmospheric aerosol results in low visibility with the process of light extinction, as the increased concentration of particulates in atmosphere degrades visibility through scattering light (Deng et al. 2011). The reduction in visibility was mainly occurred due to the presence of fine particulates ($PM_{2.5}$) in the atmosphere as reported by several studies (Yang et al. 2012; Zhang et al. 2015). The smaller size (0.1–1.0 μm) particulate matter (PM) has higher extinction efficiency as compared to larger ones as observed by Shi et al. (2014).

5.7.5 Effect on Transport System

The lower visibility as a result of extreme fog event exemplifies an imperilment to road, marine and air transportation. Fogs effectively hinder sea navigation, land and air transport systems. Dense fogs cause severe accidents on high-speed highways involving collision of trucks, buses, cars, etc. Dense fogs are navigational hazards in the seas as ships and huge super tankers carrying oil sometimes collide resulting in spilling of huge quantity of oil causing enormous oil slicks on seawater which cause ecological disaster. Vehicular traffic comes to grinding halt in the event of dense fogs. Landing and take-off of aircrafts are delayed by dense fogs causing economic loss to airlines and inconvenience to stranded passengers (Kulkarni et al. 2019).

5.7.5.1 Traffic Accidents

Fog is formed when water vapour is condensed on the surface of the atmosphere in the form of small drops; the diameter of each is no more than 100 microns. Because of the smallness of these drops, they remain suspended in the air, the thing that limits visibility hence causing traffic accidents. In fog days, there are more incidents of traffic accidents which aggravate the economic situation since they necessitate exceptional measures and continuous lighting of streets, to say nothing of the cost of repairs due to damages incurred. Visibility, on fog formation, is correlated with the rate of water vapour in the air, the higher the relative humidity, the less the visibility. The major meteorological criteria directly affecting the users of roads and their safety are: snow, rains, ice, winds and fog. As compared with other phenomena, fog is relatively rare. Fog occurrence is not easy to predict since fog varies in density and occurrence location. It moves horizontally and vertically from a place to another, covering small and large spaces, and it can clear up quickly. Fog accidents have recently become a topic of interest in different parts of the world where this problem featured in the areas witnessing cases of dense fogs. The fog blocks visibility, which leads to numerous traffic accidents since the suspended water drops work to disperse the light, which sometimes causes visibility to be as low as a few metres, thus arresting traffic and causing accidents. Therefore, this fog phenomenon has become the concern of traffic and transport system planners in most of the world.

With the proliferation of motorized vehicles in the early part of the twentieth century, occurrences of fog began to be reported as a cause of road and air accidents (Case 1916; McAdie 1929). Ingenious minds have tried to minimize the risk of accidents by devising methods of detecting nearby objects in poor visibility (Bell 1885). In spite of these efforts, the most infamous maritime disaster occurred when the Titanic collided with an iceberg shrouded in fog. Nowadays, continued technological advances have reduced but not eliminated the risk of accidents in adverse weather conditions. Accidents in which the presence of fog played a role still occur. Technical problems, human error and poor visibility in fog contributed to the worst aviation accident in history in which two Boeing 747 s collided on the runway at the Los Rodeos Airport on the island of Tenerife, Canary Islands in March of 1977. More recent accidents have also occurred (Pike 1998), underlining the persisting danger linked with the presence of fog in spite of our technological advances. The presence of fog also creates more perilous driving circumstances on the roads by reducing the visibility of road signs (Munehiro et al. 2005) and reducing the ability of drivers to react in a timely manner to changing driving conditions as manifested with the large number of multi-vehicle accidents which occurred under lower visibility conditions (Whiffen et al. 2004). Fatalities are often an unfortunate outcome of accidents occurring under foggy conditions, as evidenced by 6000 fatalities reported over a 9-year period as a result of accidents on foggy highways in the United States (Shepard 1996).

5.7.6 Economic Impact

The occurrence of dense fog affected the flight operations by increasing delay, diversion and cancellation of flights (Fig. 5.1) which result in huge financial losses to the aviation industry. The take-off and landing of airlines are not allowed with visibility lower than 500 m under visual flight rules (VFR), as according to International Civil Aviation Organization (ICAO) guidelines. At the time of occurrence of extreme fog event, the slowing down of air traffic, increase in runway occupancy time (ROT) and increase in spacing amid landing and take-off of each aircraft result in the reduction of airport capacity. Due to safety concerns, fog occurrences continue to be associated with reduced airport capacity and as a consequence important

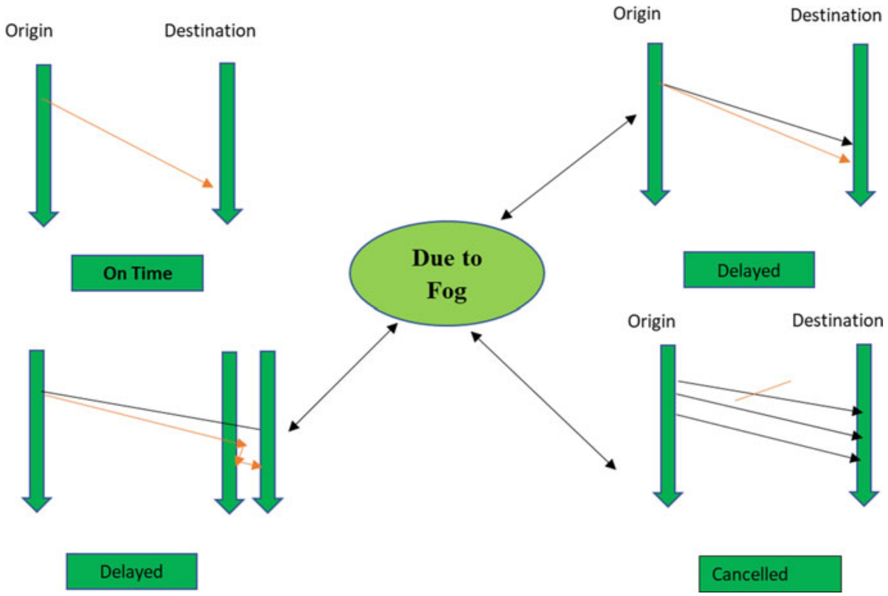

Fig. 5.1 Schematic showing the possible effects of fog on flight operations. (Source: Modified from Kulkarni et al. 2019)

disruption in air traffic and associated cost. The dense fog can cause a huge loss of approximately US$200,000 to an airline in a single day at a single airport as reported in one study (Robinson 1989). The extreme dense event also caused huge disruption to flight operation at UK airport in December 2007 as discussed in another study (Milmo 2007). Gadher and Baird (2006) reported the loss of £25 million to British Airways alone due to dense fog (Gadher and Baird 2006). The total estimated economic cost of 3.9 million USD as a result of the occurrence of extreme fog event at IGI Airport through 5 years period from 2011 to 2016 was also reported by Kulkarni et al. (2019).

5.7.7 Health Effect

The composition of fog particles is different in clean air condition as compared to polluted air conditions. It is purely made of water drops or ice crystals in clean air, while the coexistence of fog and haze particles in polluted environment can be considerably pernicious to health of human being and ecological environment besides transportation (Guo et al. 2015). When fogs are polluted through sulphur coming out of the chimneys of the mills, they become poisonous and health hazards. For example, killer poisonous smog was formed due to mixing of dense fog with smokes and sulphide fumes coming out from the chimneys in the Donora Valley of Pennsylvania (USA) on 26 October 1948. This toxic fog (smog) caused 20 human deaths and 43% inhabitants fell ill due to cough and respiratory problem. Similar poisonous fog was produced due to mixing of sulphur dioxide coming out of the factories of zinc smelters and sulphuric acid in the Meuse Valley of Belgium in the month of December 1930. This killer fog claimed 63 human lives due to obstruction in respiratory system. The poisonous fog of December 1952 claimed 4000 human lives in London which make this extreme fog event as of worldwide concern.

5.7.7.1 Fog and Chest Infection

Fogs pose a threat to people's health as a consequence of the diseases resultant from change of weather conditions, drop of temperatures, and fogs that carry viruses and bacteria. Due to high humidity, there are more and more cases of infections related to respiratory system as well as allergic complaints. This is but common in the light of weather changes particularly in winter where fog may lead to inflammation of the upper respiratory system resulting in breathing problems as well as causing of fatigue, laboured breathing and buzz in the ears. In the event of infection getting worse, things may go even further and develop into low blood pressure, imperfect sight and hearing, sense of congestion and irritation of mucus membranes, sore throat and inflammation of the trachea (Al-Mutairi 2017).

The researcher argues that the spread of fog phenomenon in Northern Borders area adversely affects human health, especially those suffering from asthma, because relative humidity in the air gets higher than 40%, this being accompanied by an acute drop in temperatures, which aggravates asthmatics health condition. It further leads to the formation of mould and rot inside houses, which worsens the health condition of asthmatics (Al-Mutairi 2017).

5.7.8 Wireless Communication

A more recent concern, albeit from a less hazardous perspective, has emerged and is related to the effect fog has on the reliability of wireless communications (Fischer et al. 2004). The presence of fog in itself and its microphysical characteristics affect the capacity, availability and reliability of free space optics and laser telecommunication systems (Harris et al. 2006; Kedar and Arnon 2003).

5.7.9 Impact on Vegetation

Another important consideration is the influx of pollutants to ecosystems by the deposition of fog water on surface elements. The deposition of fog water by gravitational settling of fog droplets or downward turbulent fluxes of fog water can contribute a significant amount of pollutants to vegetation (Lange et al. 2003), possibly leading to an adverse impact on its health (Jagels et al. 2002).

5.8 Conclusion

Data from the aerosol and fog water chemistry so far indicate a highly polluted environment in which the fog developed. Secondary inorganic aerosols (sulphate and nitrate) were the dominant ions (38%) in the chemical constituents of fine particles and were higher during the fog events. The role of aerosols as CCN and fog droplet formation needs to be understood for accurate representation of fog droplet activation and growth. The systematic studies with detailed observations for several fog episodes are necessary to make progress in forecasting these events, their duration and dissipation, etc. The fog formation act as an extreme event which results in delaying and cancelling of flights, also disrupts train schedules lead to huge economic loss and also effects human health in the northern part of India and other parts of the world. The different studies worldwide find that fog phenomenon extremities occasioned several traffic problems, owing to blocked visibility, such as car accidents and traffic jams. Aviation forecasters in northern India as well as worldwide require exact information about dense fog formation for the safe operation of flights. The increased forecasting ability of fog in the affected region is of central interest to the agencies responsible for public safety and the transportation industry as accurate and timely forecasts would provide a basis for increased safety, as well as leading to economic benefits through better management of disruptions in air and surface transportation activities.

The improved forecasting of fog can be obtained through an increased discerning of different physical mechanisms concerned with the formation and subsequent evolution of extreme fog event. The understanding of different parameters like kind of near-surface thermodynamical conditions which lead to the initiation of a fog event, the high aerosol number concentration which is prerequisite for fog formation, different physical processes which are responsible for extended-period fog extreme event, microphysical aspects which are decisive for the fog lifecycle and boundary layer dynamics which control fog microphysics is necessary. These key parameters are needed for physical parameterization of fog extreme event and to improve fog prediction.

Overall, the detailed observations undertaken will be used to better understand the fog and improve its prediction, by tuning the physical parameterizations and also possibly finding the chains of associations for fog droplet formation. The ultimate goal of this study is thus to identify and describe the physical processes and interactions that influence the occurrence of fog events in the different complex regions of the world.

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6

Nature of Sand and Dust Storm in South Asian Region: Extremities and Environmental Impacts

Sanjoy Maji and Saurabh Sonwani

Abstract

Sand and dust storms (SDS) are very important atmospheric extreme events that occurred under the influence of turbulent winds with dust particles in any arid region. These are the lower atmospheric meteorological events and their environmental implications are being recognized in recent years due to their growing significance with the climate, human health, and socio-economy. The SDS involves a reduction of visibility to less than 1000 m. The identification of SDS events and their frequency is important to assess their role as climatological and geomorphological agents. The SDS events pose a challenge to the goals of sustainable development. Generally, SDS is a common atmospheric phenomenon in arid, semi-arid, and dry sub-humid areas, though it can travel thousands of kilometers across the countries and oceans, and depends on the wind speed and particle size distribution. Sometimes, SDS accumulate other pollutants on their way and transport them from one place. On the routes of transportation SDS also affects the regional biogeochemical cycle. SDS have a several beneficial and adverse impact on the environment. The primary impacts of SDS events include atmospheric radiation balance, regional precipitation, and hurricane activity. The SDS events are also responsible for elevated levels of fine particulates in the atmosphere that are associated with premature mortality and cardiovascular problems, respiratory problems, lung carcinoma, and severe respiratory tract infections. Such inhaled fine particle is not only composed of fine mineral

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particles but also contains a hazardous mixture of chemicals, spores, microorganisms, fungi, and harmful allergens. Apart from their adverse effects on human health, they also pose several economic impacts such as disturbance of infrastructures, transportation, and supply chain set-ups. SDS events are also responsible for the elimination of the top fertile layer of the soil resulting in the decrease in the mineral content in the soil that ultimately affects the plant health and productivity of the landmass. The United Nations General Assembly (UNGA) adopted resolutions entitled "Combatting sand and dust storms" in 2015 and mentioned that SDS signify a major obstruction to the sustainable development that affect developing nations and their peoples. The objective of the current paper is to understand the nature and phenomena of SDS processes, current and past trends of SDS impacts, as well as to understand the impact of SDS hazards on environment and human health as well as extremities and their correlation with climate change.

Keywords

Sand and dust storm · Distribution · Transportation · Climate · Environment · Human health

6.1 Introduction

The dust storm events, though a common atmospheric phenomenon in arid and semi-arid areas during summer months, have gained great interest in recent times throughout the world due to the environmental implication and geomorphological importance of events of extreme nature. In the last few decades, there are almost a significant rise in the number of scientific contributions on understanding the nature, mechanism, extremities, and environmental impact of dust storm events (Ramanathan et al. 2001; Stout et al. 2009).

SDS event is a consequence of wind erosion releasing participles from the top soil profile. Sand storms happen very near to the ground, but fine particles may be raised up to several kilometers into the atmosphere, where high-speed winds convey them long distances. Bare grounds where vegetation cover is limited are most susceptible to sediment entrainment. Dust storms may travel up to thousands of kilometers from their source location and transport suspended materials over land and ocean, other available surfaces. It was also reported that the dust storm trajectories are part of natural ecological systems and the rate of aeolian deposition may be of same extent to rates of fluvial and aeolian erosion (Goudie and Middleton 2006; Muhs et al. 2014).

However, as of today, there is not a firm delimitation in the explanation of dust storms versus sandstorms. The World Meteorological Organization (WMO 1975) defines dust storms and sandstorms as "An ensemble of particles of dust and sand energetically lifted to great heights by a strong and turbulent wind". As a convention, winds raise a large quantity of dust into the atmosphere and reduce the visibility to less than 1000 m, considered as an SDS event (McTainsh and Pitblado 1987).

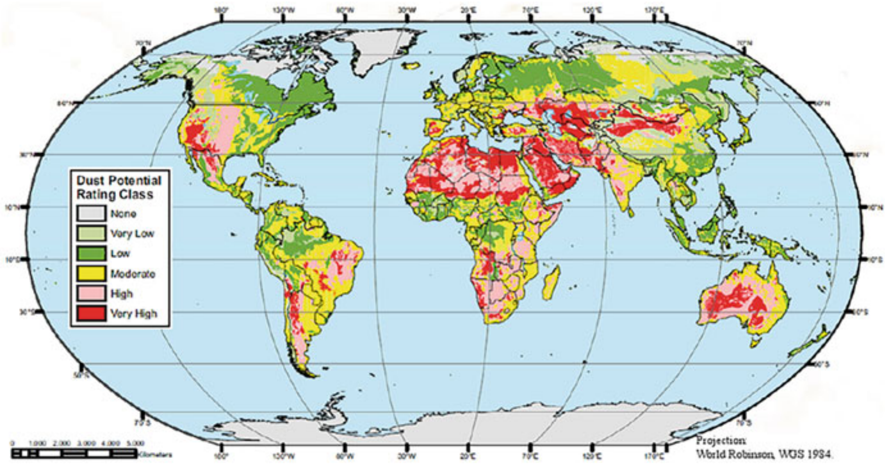

Fig. 6.1 Dust potential map of the World (Source: UNEP, WMO, UNCCD 2016)

Silica (SiO_2), iron, magnesium, calcium, aluminum, and sodium are some of the important components of the dust particles that make up SDS. Other chemical species commonly found include traces of arsenic, chromium, zinc, strontium, lead, nickel, cobalt, cadmium, manganese, vanadium, and copper. However, dust particles may also carry organic matter including pathogenic microorganisms like fungi, bacteria, and viruses. The relative composition of different components depends on the source regions as well as transport pathways (Sun et al. 2005).

Worldwide 45 countries are identified as SDS source-areas, whereas more than 151 countries are identified as direct suffering by SDS events (Middleton and Kang 2017). The major source-areas of SDS are in North Africa, the Middle East, and Central Asia (Herman et al. 1997). About 32 million km^2 of the global land area is susceptible to wind erosion. Stretch extending all the way from the tropical and subtropical deserts of the Sahara through the Middle East to the Great Indian Desert and the mid-latitude deserts of Central Asia, China, and Mongolia is considered as the high-risk belt of SDS. In the Northern Hemisphere, the area extended from the west coast of North Africa, over the Middle East, Central and South Asia, to China is referred to as “dust belt”. The Asia-Pacific region is considered as the second largest contributor of dust emissions, accountable for more than half a billion tone of dust to the atmosphere every year. Impacted areas include East, North-East, South, South-West and Central Asia and the Pacific (Fig. 6.1).

6.1.1 Dust Storms: a Global Phenomenon and a Transboundary Hazard

The sites of the main dust sources are: (1) North Africa (Tunisia and Northeast Algeria, Eastern Libyan Desert, Egypt, Sudan, Mauritania, and Western Sahara),

(2) Middle East Asia (Arabian Peninsula, Oman), (3) Central and South Asia (Afghanistan, Iran and Pakistan Basins, Indian subcontinent), (4) North East Asia (Mongolia, China), (5) North America (Mexico), (6) South America (Bolivia, Western Argentina), and (7) Australia (Lake Eyre and the Great Artesian Basin). Dust storm events are considered as a transboundary hazard and their dispersion across the continents depends on wind speed and particle size distribution. SDS can accumulate other pollutants on their way and is the cause of transport of pollutants from one place to another on the routes of transportation impacting the regional biogeochemical cycle. Estimates put figure of about 2 billion tons of dust are released into the air every year (Goudie and Middleton 2006). However, it is mentioned that a maximum (75%) of current emissions originate naturally, not anthropogenically.

Dust is usually created from a small terrestrial area and is spared to cover transboundary regions. The length of SDS can differ from a few hours to several days depending on atmospheric pressure gradients. When SDS originate, initially, they tend to drift near to the earth's surface. However, with the convective currents, fine particles are raised high into the atmosphere and travel thousands of kilometers. The transportation also depends on particles size and wind speed that pass beyond regional-political boundaries and even across continents. The average atmospheric lifetime of dust particles differs from a few hours for particles with changing aerodynamic diameter (particle $> 10\ \mu m$), to more than several days (for the ultrafine particles) and the relative polarity of the particle (Van Der Does et al. 2018). Coarser particulates are dumped within short distances from their origin and particles of size below 10 μm are transported to very distant locations. The Saharan dust which is considered as the largest single source of wind-blown sediments is capable of transportation from their sources to Amazonia, North America, Europe, and China. Dust from Central Asia and China reaches Korea, Japan, the Pacific Islands, and North America. Dust from China has been reported as reaching the European Alps, a distance of over 20,000 km (Grousset et al. 2003). It has been observed that Saharan dust reaches up to Amazon rainforest and carries micronutrients which is the source of natural fertilizer (phosphorus) inputs for the rainforest (Nogueira et al. 2021). Likewise, Hawaiian rain forests obtain nutrients from Central Asian dust. Simultaneously, dust from Africa and Asia is believed to damage Caribbean coral reefs (Garrison et al. 2003).

Many countries located outside to the drylands receive dust due to the long-range transport from different sources located inside the dryland, such as Japan receive dust deposits from Chinese and Mongolian deserts (Hong et al. 2010), and Panama which receives Saharan dust (Gross et al. 2016). Nevertheless, some nations experience desert dust while also undergoing wind erosion on their own lands. Northeast Asian deserts are other important sources of dust that frequently carried over the Korean Peninsula and Japan (Kashima et al. 2016), across the Pacific Ocean to the North American continent (McKendry et al. 2001), Europe (Grousset et al. 2003) and on occasion even further (Uno et al. 2009). Antarctica receives deposits of desert dust from Patagonia and Australia (Li et al. 2008) and material from farmland in Ukraine has been traced to Central Europe (Birmili et al. 2008).

SDS involve in various atmospheric processes and are responsible for several positive and negative impacts on the environment (Knippertz 2014). Dust not only affects the atmospheric process but also involves in changing marine, biotic and terrestrial processes (Nickovic et al. 2012). Thus, it disturbs the strengths of tropical storm and cyclone (Evan et al. 2006) and the earth's radiative balance, which can intensify the drought (Han et al. 2008; Highwood and Ryder 2014). It is also a well-known fact that the fine dust particles act as cloud condensation nuclei (CCN) and participate in precipitation (Nenes et al. 2014). Suspended dust particle causes human health issues (Sonwani and Kulshrestha 2016), like atmospheric fine particles are associated with cardio-pulmonary problems and severe respiratory infections that are responsible for premature death (Sonwani et al. 2021c). Inhaled fine dust particles have been reported with the harmful combination pollutants, spores, bacteria, fungi, and potential allergens with mineral dusts (Kellogg et al. 2004; Goudie (2014)). SDS also increase incidences of road accidents and aviation hazards due to the degradation of atmospheric visibility. Apart from the human health impacts, they also pose adverse impact on economy by disrupting communications, transportation, and supply chain set-ups (Goudie and Middleton 2006). SDS remove the top layer of soils and damage crops, kill livestock, thus increase the cost of food production and threaten sustainable food production (Middleton and Sternberg 2013).

However, SDS have some positive impacts also on the ecosystem. Air blown dust forms loess soils which are considered as one of the most fertile soils for agriculture. Mineral dust deposition provides micro-nutrients to terrestrial and marine ecosystems, boosting primary productivity. SDS also plays a significant role in changing biogeochemical cycles and sustaining both oceans and forests (Goudie 2009).

With the growing focus of bearing of dust storm events on the climate, human health, socio-economy, and the environment, dust storms pose a formidable challenge to the goal of sustainable development, particularly in arid and semi-arid regions. Thus, the impacts of SDS also play an important role in achieving sustainable development at the local, regional, and global levels. Over the past few decades, the social interest to enhance the understanding of the mechanism and nature of SDS processes, and to prevent their undesired impacts on the socio-economic sector is increasing rapidly. With the global collaboration, two resolutions have been approved by the United Nations Global Assembly (A/RES/71/219in 2015 and A/RES/70/195 in 2016) to promote a coordinated approach to combat SDS globally.

This article provides information about the dust cycle and discusses its interaction with weather, the climate system, and terrestrial and marine ecosystems. It also summarizes about the adverse impact of SDS on health and economic sectors. The article also makes an attempt to understand the nature and phenomena of SDS processes in relation to current and past trends of SDS event, as well as understanding the interaction of SDS events with the climate change.

6.1.2 How SDS Act as Extreme Event?

SDS events happen when turbulent winds combine with soil/sand particles in any arid area and transport them along with their movement. Mostly, SDS originated through natural causes that contribute around 75% of total current worldwide emission. Climatic factors affect the dust storm while anthropogenic factors can alter that climatic factors. Human-induced sources, like agricultural activities, deforestation, changes in land use, water diversion contribute rest of 25%. SDS happens as a result of a series of interconnected direct and indirect drivers acting at different levels. The duration of SDS events ranges from a few hours to many days. The intensity of SDS is usually revealed in terms of the particle's concentration and visibility reduction in atmosphere. The common and intense SDS are usually linked with particular synoptical meteorological conditions like: (1) steep atmospheric pressure gradients around subtropical anticyclones, (2) surface cyclones and their associated fronts, (3) monsoonal airflows, (4) local winds associated with strong gradients in relief, and (5) dust devils and convective plumes as a result of daytime turbulence in the planetary boundary layer. Sandstorms arise comparatively adjacent to the soil surface, but finer dust particles may be lifted kilometers high into the atmosphere and transported up to several kilometers through strong winds. Bare land is most susceptible to SDS events and usually happen in semi-arid and arid areas (the area with less or no vegetation cover). Their impacts, however, are frequently felt far beyond those dry lands due to the propensity of dust to be transported over long distances. Thus, due to high-speed violent winds along with sand and dust, SDS events cause significant negative impacts on society, economy, and environment at local, regional, and global scale.

6.2 Sand and Dust Storm Processes

In arid and semi-arid regions, high-speed winds carry huge quantities of dust with them resulting in visibility reduction to below 1000 m. The various sources of dust in the atmosphere may come from natural as well as anthropogenic sources. Natural sources of dust are due to entrainment and re-entrainment of loose dust particles from the ground surface to the atmosphere by the action of high wind speed. Entrainment of dust particles happens when the force exerted by the high wind speed on the dust particle overcomes the retention force. Secondary fine particulates like sulfate and nitrate particles are derived in the atmosphere by the photo-chemical conversion of primary sulfur and nitrogen oxide emissions. As per the WMO (Cuevas Agulló 2013), SDS events are classified on the basis of visibility and segregated into the category of:

1. Suspended dust: dust in suspension that is not elevated at or near the station at the time of observation; visibility is less than 10 km.
2. Blowing dust: such type of SDS particles that raised at the time of observation, visibility is between 1 and 10 km.

3. Dust storm: strong winds push up a huge quantity of dust particles in atmosphere, visibility ranges between 200 and 1000 m.
4. Severe SDS: very strong winds push up a huge quantity of SDS particles in atmosphere, visibility usually ranged below 200 m.

SDS event frequently happen under the influence of high-pressure gradient associated with cyclones that surges wind speed in atmosphere above the wide area. In this process, strong winds lift and transport a huge quantity of dust and sand from bare, dry area to hundreds to thousands of kilometers. Particles with huge size, density or with the presence of more water content deposit in the soil easily under the gravitational pull. Dust storm happens when the value of threshold loose particles increases that can be lifted up from ground due to rise in the wind's force. Floral community acts as a protective covering to the earth's surface from the wind erosion. In the absence of vegetation, drought also contributes to the appearance of dust storms due to poor farming/grazing practices/inadequate water management and by exposing dry and loos soil to wind. About 40% of atmospheric particles are dust particles as a result of wind erosion. After their release from soil surface, dust particles are elevated to higher in the troposphere through turbulent mixing and convective updrafts. The transportation of suspended dust depends on their size, wind speed, and meteorological conditions while gravitational force is also an important constrain that decides the deposition of dust particles back down to the ground (Saxena et al. 2021). Such dry deposition is a result of impaction and turbulent diffusion, where coarser particles are deposited more frequently than finer particles. Atmospheric dust load can also decrease through wet deposition through various precipitation phenomena like rain, fog, and hail (Sonwani and Kulshrestha 2019; Saxena et al. 2020; Sonwani and Saxena 2021).

There are three different physical processes which cause dust particles to be emitted into the atmosphere: (1) direct aerodynamic lifting, (2) ejection of dust aerosols from soil aggregates by impacting saltating particles, and (3) ejection of dust aerosols from soil aggregates that are participating in saltation. Aerodynamic lifting of dust particles to the atmosphere happens when the aerodynamic force exerted on the dust particle dislodge particles from the surface. The dust entrainment to the atmosphere from the ground is related with the saltation process. Saltation refers to a layer of soil moving with the wind just above the surface. The vertical mass flux carries lifted particles which undergo ballistic trajectories and can eject new particles into the stream.

Wind causes trigger the processes of creep, saltation, and suspension to transport the dust particles. Larger particles (>500 μm diameter) usually creep on the soil surface. In the process of saltation, wind transports particles of 60–500 μm diameter size at a height less than 1.5 m above ground level. Moreover, suspension refers to longer range transport of smaller particles (<60 μm diameter). The transport of soil particles by wind can thus be crudely separated into several physical regimes: long-term suspension (< ~20 μm diameter), short-term suspension (~20–60 μm), saltation (~60–500 μm), and creep (> ~500 μm).

Particles of size greater than 100 μm are generally called settleable particles and settle down under the influence of gravity. Particles of size below 100 μm are called suspended particles and can remain suspended in the air for several days. The aerodynamic behavior of dust is generally governed by shape, size, density, chemicals composition, and electromagnetic properties of the dust particles. Normally, coarser particles usually return to the ground soon after being entrained whereas smaller and lighter particles are carried to a long distance (Gillett and Morales 1979).

Long-term suspended dust can remain in the atmosphere up to several weeks and can thus be transported thousands of kilometers from source regions (Miller et al. 2006). However, particles with diameters <10 microns (PM10) and those with diameter <2.5 microns (PM2.5) are the focal area of research from the health impact point of view (Sonwani et al. 2016; Goel et al. 2021). Following the SDS event, atmospheric PM10 dust concentrations can reach up to 15,000 μg/m^3 whereas hourly PM2.5 concentration touches about 1000 μg/m^3 (Jugder et al. 2011).

The most important climatic factors which influence the frequency and severity of SDS events depends on (1) local winds, (2) atmospheric turbulence, (3) weather fronts, and (4) anticyclonic condition. Wind is the result of differential heating of earth's surface producing differential pressure and temperature which causes local wind. The profile of local wind varies widely from region to region based on topography and other meteorological factors. Depending on the velocity, local winds can cause severe SDS events. Atmospheric turbulence results in spatially dispersing the dust particles from the source-areas. Higher the turbulence, higher will be the spatial spread of the dust particles. Weather fronts play an important role for the regional SDS events. The weather fronts are created when two different air masses with different air temperature, humidity, density pressure, and direction come face to face. The consequent weather becomes active and aggressive. Anticyclonic weather condition is the main causal factor for dust emission and large-scale circulation of dust. An anticyclone is defined as a large-scale circulation of winds around a central region of high atmospheric pressure, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Anticyclonic condition often creates severe SDS events.

6.3 Drivers of Sand and Dust Storm

About 40% of particulate in the lower atmosphere is a result of dust particles released from wind erosion. The main regions for the origin of these mineral dusts are the arid regions of Northern Africa, the Arabian Peninsula, Central Asia, and China. Comparatively, Australia, America, and South Africa make minor contributions. Global estimates of dust emissions vary between one and three Gigatons per year. SDS happen as a consequence of a sequence of interwoven direct and indirect and independent causes. Land degradation, desertification, and changing climate are some of the major drivers of SDS that are aggravated by careless land use planning, strong winds, frequent and severe drought condition for longer period of time. There

Table 6.1 Factor affecting wind erosion

Factors	Soil/sediment	Vegetation	Landform
Wind speed (+)	Soil/sediment type	Type	Surface roughness (+/−)
Wind direction	Dust composition	Coverage (−)	Slop (−)
Turbulence (+)	Soil/sediment structure	Density	Ridge
Precipitation (−)	Organic matter (−)	Distribution (+/−)	
Evaporation (+)	Carbonate (−)		
Air temperature	Bulk density		
Air pressure (+)	Degree of aggregation (−)		

Note: (+) indicates that the factor promotes wind erosion; (−) indicates that the factor has a shielding effect, reducing wind erosion; (+/−) indicates the effect can be positive or negative

are few important factors that are identified for the SDS events in the South Asian region. The first is changing wind pattern and the second is expanding sand and dust source areas. The changing wind pattern can be classified into (1) surface winds exceeding the erosion threshold, (2) incidence of extreme weather events, and (3) variable wind direction. Moreover, the expansion of the dust storm and sand storm source area can be identified on the basis of (1) increasing frequency of drought and dry arid region; (2) sparse vegetation; (3) degradation of land use pattern; and (4) interference with defensive earth surface crusts. There is a necessity to identify drivers (natural and anthropogenic both) of SDS that contributes most of the global dust emissions. Wind erosion acts as a key driver of SDS emissions in every system. Basically, erodibility of surface material along with dryness is a natural governing factor of SDS events. Table 6.1 shows the factors affecting the wind erosion responsible for SDS.

6.3.1 Natural Drivers

Topographic depressions in the arid region contribute 75% of the current global dust emissions (ESCAP 2018; UNEP, WMO, UNCCD 2016). Identification of the natural drivers is one of the important tasks to recognize the global dust emission. Strong winds (frequently originated by thunderstorms) are main drivers of SDS event in every region of the world. In arid and semi-arid regions, strong winds pull dust from the ground up in the atmosphere and create sand and dust storm. When the wind force surpasses the threshold limit for the loose soil particles to be lifted off the ground, dust storm occurs. After released, dust particles are elevated to high in the troposphere by turbulent mixing and convective updrafts. Then these particles are transported by winds and their transportation depends on their size and meteorological variables such as air temperature, humidity, and height of the boundary layer (Knippertz 2014). Distribution of vegetation across the geographical area is also responsible for the occurrence of sand and dust storm in that area. The sand and dust storms are frequent in plain area with sparse vegetation, and these features allow winds to build momentum to produce stronger winds that drive more dust into the atmosphere.

6.3.2 Anthropogenic Drivers

There are a variety of manmade sources behind the SDS that are one-third of the total natural sources; however, from the past few decades, land use has been changing thus contributing to increase in the anthropogenic drivers contributing SDS. Manmade sand/dust emission can be classified into their direct and indirect emission sources. Anthropogenic drivers, such as changes in land use pattern, agriculture activities, diversion of water bodies, and deforestation, contribute up to 25% of the present global dust generation (ESCAP 2018; UNEP, WMO, UNCCD 2016). Inadequate water management, poor farming, and grazing practices are some of the drivers cause dry conditions resulting in the appearance of SDS. The changing climatic conditions are also responsible for the generation of SDS. Several authors estimated the average contribution of the anthropogenic drivers ranging from 10 to 50% in global dust emission (Tegen et al. 2004, 2006; Mahowald and Luo 2003). The major anthropogenic factors of SDS may be highlighted as follows:

1. Overgrazing and thumping/stampede by livestock
2. Overuse of agricultural field in cultivation, prolonged farming without crop rotation, improper water impoundment, over-drafting of ground water, increased fire frequency, etc.
3. Deforestation to clear land for urbanization and agricultural practices
4. Over-exploitation of natural vegetation for domestic uses like fuel, construction material, etc.
5. Bio-industrialization

Even though there is large uncertainty about the impact of human activities on dust emission from disturbed soil, deforestation, disturbance in the hydrological cycle, and changing climate, several studies mentioned that the anthropogenic contribution to the dust emission is not negligible at the world scale (Guan et al. 2016; Huang et al. 2015; Tegen and Fung 1995). Figure 6.2 shows the percentage contribution of the different SDS emission sources.

6.4 State and Trends of SDS

Dust storms are significant climatic events for the people living in the “Dust Belt”. However, there are very few studies available on the state and trend of SDS events globally. A large temporal variation in dust emissions has also been observed. Dust events generally happen during late spring and summer season; however, there is also substantial transportation of dust particles into the South America during the winter period.

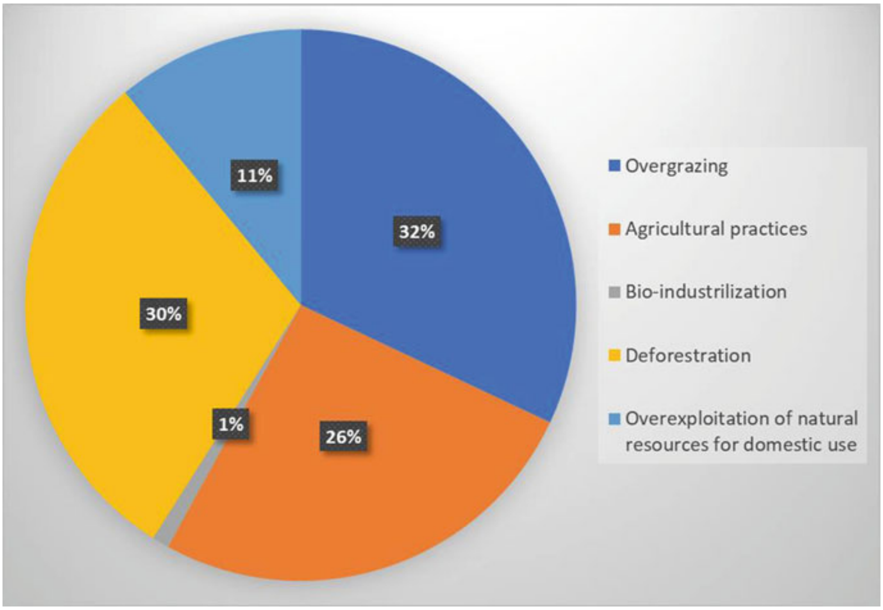

Fig. 6.2 Causes of SDS in Asia

Though it is postulated that there is substantial temporal and spatial variation in the SDS events, but there is no consistent evidence to substantiate that SDS occurrence and intensity has raised globally in recent years. Ground-level monitoring records, satellite data, and the results of dust model are used to identify the distribution and occurrence of SDS events. Though it has been observed that SDS events have increased in few parts mainly due to deforestation activities caused by the urbanization and industrialization but in few places, there are record of lesser number of SDS events due to improvement in vegetative cover. A recent study has observed that within the last few decades there are noticeable changes in the SDS pattern in Australia, Central Asia, and in the US high plains; while SDS events over Northern Africa, the Middle East, and South America have continued with similar activity. Few stations like the Sahel show a strong rising trend of great disaster, others indicate a descending trend (e.g., Mexico City) (Goudie and Middleton 2006). Several studies have conclusively established a decreasing trend of SDS activities in Northern China; however, investigation of storms in the Tengger Desert in China has revealed that the frequency of dust storms has increased significantly during 2000–2007 in comparison to 1980s (Guan et al. 2017). In the Eastern Asian countries like Mongolian People's Republic, no conclusive pattern is observed, rather different parts of the country observe differential patterns of annual dust-storm frequency. Long-term SDS frequency data for Australia show an increasing trend for the continent. Dust storm frequency in Sahelian Africa has been observed to increase sharply in the early 1970s. During the 1960s, fewer than two dust storms observed in a year that was rose through the 1970s to peak at 85 dust storm days in

1983 that continued high through the 1980s. In South Asia, Hamoun Basin which is considered as one of the dustiest areas of south Asia is been reported to experiencing an increased level of dust storm frequency over the period 2000–2004. The scientists have observed a strong correlation with current level of global dust generation and man-made dust emissions. The expansion of livestock grazing areas is considered to have contributed in the annual dust concentration by 500% in the western United States (Neff et al. 2008). Even today, crop land and rangelands are one of the major origins of SDS in North America (Lee and Gill 2015). Similarly, increasing industrial production especially mining and related operations create dust sources.

The comparative involvement of anthropogenic activity to the present levels of dust production varies from 10 to 50% (Tegen et al. 2004; Mahowald and Luo 2003). However, there are wide spatial variations in releases between natural and man-made sources. As North Africa release about 20% of its release by man-made activities but contribute about 55% of the world total release, while 75% of Australia's dust is man-made but contribute about 13% of the world man-made release. In reference to the notable contributions over the twentieth century, the data mentioned a doubling of world dust abundance in the air due to man-made activities and/or climate change. Stanelle et al. (2014) mentioned the comparative significance of changing climate and man-made land cover change for dust generation. Thus, the world yearly dust generation has raised by 25% as compared to the late nineteenth century. Approximately 56% of this variation contribute to change in climate and 40% to anthropogenic land cover change.

6.5 Geography of Dust Storms in South Asia

SDS events are common in every part of South Asia. SDS critically impacts the South Asian subregion. Since past several decades, the climatology of the Asian SDS was well documented through synoptic records and satellite data (Sun et al. 2001; Qian et al. 2002; Shao et al. 2003; Rezazadeh et al. 2013; Zhao et al. 2008). The SDS in the South Asian region are originated by pre-frontal and post-frontal winds in winter, and strong "Shamal" winds in summer. Moreover, SDS of low scale, time duration and strength are triggered by downwind regimes, sea breeze, and convection cell in topographic regions (Zarrin et al. 2011; Choobari et al. 2012). It is postulated that the increased SDS activity over the South Asian region during the El-Nino years linked with strong westerlies (Abish and Mohanakumar 2013); however, La-Nina phases are observed to be linked with the disturbance in precipitation over Indian Ocean, central and south west Asia (Barlow et al. 2002).

The bigger SDS incidences happen in the Sistan Basin in south-eastern of Iran and south-western Afghanistan, areas of southeastern of Iran, Baluchistan in Pakistan, the Thar Desert of Rajasthan in western India, the plains of Afghan Turkestan, and the Registan area of Uzbekistan. Dust originated from such areas is transported north to Central Asia, south over the Arabian Sea, and east over South-East Asia. The distribution of SDS belt in south Asia is shown in Fig. 6.3.

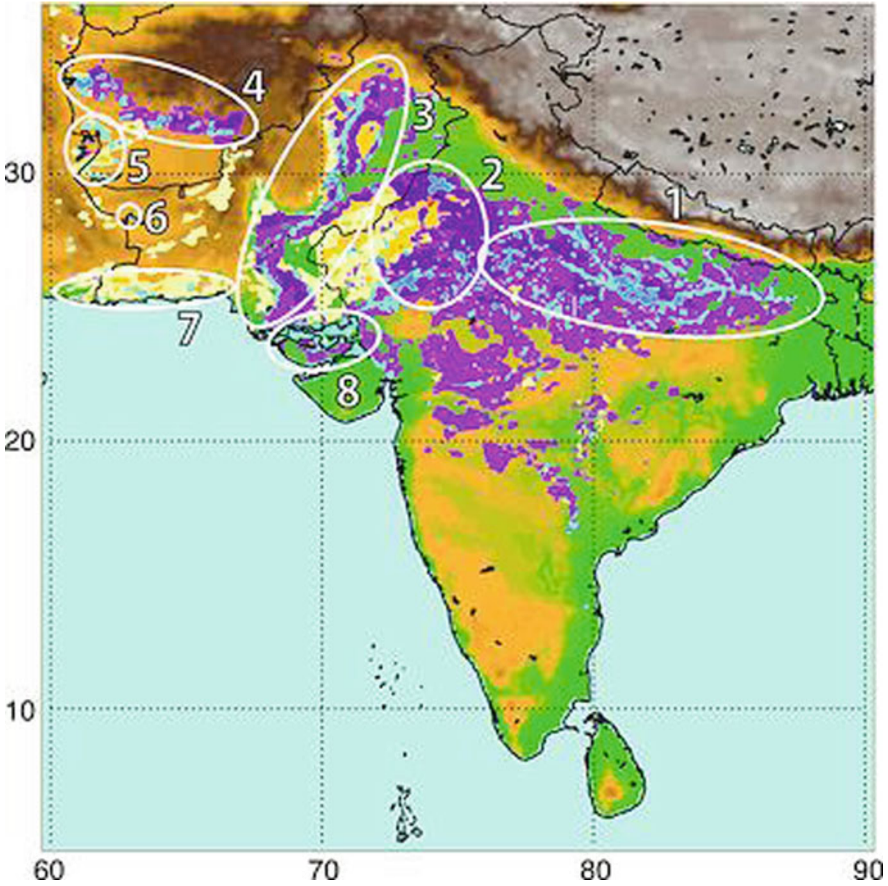

Fig. 6.3 Distribution of the SDS belts in south Asia (Adapted from: UNEP, WMO, UNCCD 2016)

6.5.1 India

Dust storms are most common in north-western India, in the arid and semi-arid states of Rajasthan, Haryana, and Punjab, but they also occur on the Ganges plain and in the northern cold arid areas of Jammu and Kashmir. In India the SDS events are regulated by farming activities and desert dust transportation from western India (Prasad et al. 2007). Maximum SDS occurrence is noticed in the Rajasthan with detected frequency beyond 70% along the seasonal Ghaggar River. The Rajasthan Desert is an important source of dust in southwest Asia. Human-induced desertification has been caused due to wind erosion and deposition of sediments in saline lake basins and agricultural areas in the Indian Plateau (Pandithurai et al. 2008). Indian SDS events are mostly seasonal in their incidence, and occur mostly in the pre-monsoon months (from April, May to June). In Rajasthan maximum dust storm frequency occurs at Ganganagar, which, with 17.0 days per annum (highest in India) and frequencies decrease south and westward, Bikaner records 8.0 per annum and Jodhpur 6.0. (Krishnan 1978) has put forward evidence indicating an increasing trend of dust storms in the Jodhpur region in association with a decreasing trend of monsoonal rainfall over a 22-year period.

6.5.2 Pakistan

Dust storms occur in all parts of Pakistan, largely during the hot season that prevails from April to June. Kureshy and Ahmad (1977) divide the country into four climatic regions that provide a good framework for an analysis of dust-raising activity in Pakistan. The subtropical coastal strip (arid marine) includes the stations of Pasni and Ormara and the Indus delta south-east of Hyderabad. The area receives less than 175 mm rainfall per annum, and dust storms occur largely from April to July. The subtropical continental plateau (extreme climate, very arid) receives less than 125 mm rainfall a year. Snead (1968) reports that, for southern Pakistan as a whole, dust storms are most frequent in the afternoon, although larger, less local storms associated with an approaching eastern depression occur at any hour of the day and sometimes at night. The Makran coast is a hyper-arid area and the important universal dust sources (Goudie and Middleton 2001).

6.5.3 Afghanistan

As per the ground-based data collection, the maximum occurrence of dust storms happens at the junction of the borders of Iran, Pakistan, and Afghanistan (Middleton 1986). The bed of Lake Hamun and the large deltaic fan of the Helmand River are identified with the dust storms as a predominant source, perhaps due to the diversion of upstream water for irrigation purpose and by risky droughts in recent years. In Afghanistan, there is a widespread man-made source in the Hindu Kush, with several rivers nourishing into the Helmand River that support agriculture activity. There is also natural source from seasonal lakes within the Sistan Basin.

6.6 SDS Hazards and Their Impacts

The impact of SDS on the environment is far reaching. One of the primary impacts of SDS on the atmosphere is its impact on local atmospheric energy balance (Singh et al. 2004). Dust particles in the atmosphere disturb the local energy balance by impacting atmospheric radiation and absorption profile of solar energy in the atmosphere. Change in energy balance disturbs local climatic condition aggravating climatic extremities (Highwood and Ryder 2014) which ultimately impact regional bio-geochemical cycle. Current research suggests that SDS also play a role in extreme weather events like altering tropical storm, escalation of cyclonic activities, or frequent drought events.

Dust storms also play a role in impacting local rainfall pattern (Creamean et al. 2013). Dust particles in the atmosphere act like a condensation nuclei for the formation of atmospheric cloud. Atmospheric dust particles disturb radiation balance which effects temperature profile of the atmosphere (Maley 1982). One of far-reaching effects of dust storm events on global climate change impact is that that the mineral dust on glaciers lowers surface albedo and faster ice melting rate (Oerlemans et al. 2009). Some researcher has observed impact of dust particles on global Ozone balance by reducing photolysis rates of ozone production (Martin et al. 2003).

SDS are also known for their impacts on the south Asian monsoon, radiative forcing, climate, and hydrological cycles (Sonwani and Saxena 2021; Kaskaoutis et al. 2017, 2018; Pandey et al. 2017). Several other studies identified the impact of SDS on aerosol physical, optical, and radiative properties over the South Asian region (Kedia et al. 2018; Bhattacharjee et al. 2007; Prasad and Singh 2007).

Apart from the several negative impacts of SDS on environment, it has some positive global impacts in terms of their transboundary movement, impact on global climate, and their impacts on biogeochemical cycling (World Bank 2019; Prospero and Mayol-Bracero 2013). Some of the major impacts of SDS events are discussed below:

6.6.1 Impacts on Ocean and Its Productivity

SDS delivers a main source of several nutrients and trace elements to the oceans (Mahowald et al. 2018). Such elements are important for all life forms and can control over marine primary production (Jickells and Moore 2015). The impact on ocean primary productivity happens mainly through the effects of dust-borne nutrients on phytoplankton. Thus, SDS is responsible for boosting primary productivity of ocean but having adverse effects on coral reefs. It is also responsible for increasing primary productivity at surface and sea bed by increasing the growth of phytoplankton (Rosenberg et al. 1983). The dust deposition on marine environment has been reported to increase the primary productivity of ocean by 6% (Jickells and Moore 2015). Similarly, trace metals, nutrients, organic constituents, and microorganism are also some other important factors deposited along with the dust and sand storm and responsible for significant changes in the coral reefs and other ecosystems globally (Hallock 2001). Macronutrients like phosphorus and nitrogen, and the micronutrient like iron play an important role in marine primary production (Jickells and Moore 2015). It was also mentioned that most of the atmospheric nitrogen (organic and inorganic) deposition to ocean comes from SDS appear to be both soluble and bioavailable. In contrary, phosphorus and iron carried by SDS are not immediately soluble in water, and therefore are not bioavailable (Jickells et al. 2005; Tagliabue et al. 2017; Okin et al. 2011).

6.6.2 Impact of SDS on Air Quality

SDS activities enhance the overall loading of the atmospheric particles that affect visibility and air quality (Verma et al. 2013; Sikka 1997). Desert dust contributes about 50% of the naturally occurring tropospheric aerosols. SDS events increase the concentration of PM2.5 and PM10 in the atmosphere which ultimately impacts general public health (Saxena et al. 2020; Sonwani et al. 2021a; Sonwani and Kulshreshtha 2016; Maji et al. 2015, 2020). Poor air quality has been linked to be responsible for 1.4% of global mortality and 2% of all cardiopulmonary disease (WHO 2006). Exposure to elevated levels of dust concentration for a prolonged period of time has been linked to premature mortality due to different cardio-respiratory diseases. Inhalation of fine dust particles exposes individuals not only to hazardous fine mineral particulates, but different bio-allergen like spores, bacteria, fungi, and potential allergens are also carried with dusts (Kellogg et al. 2004; Sonwani et al. 2022). The Global Burden of Disease Comparative Risk Assessments study published by the World Health Organization (WHO) designates indoor air pollution and ambient air pollution as the world's second- and third-largest environmental health risks factors, respectively (WHO 2014). Impacts of SDS events on air quality over the north-western parts of India and Indo Gangetic Plain (IGP) have been extensively studied (Sonwani and Kulshrestha 2019; Sonwani et al. 2021a, b).

6.6.3 Human Health Impacts

SDS events lead to increase in particulate matter concentration in the atmosphere. The elevated levels of particulate matter concentration in the atmosphere are linked to so many cardio-respiratory diseases ranging from allergic symptoms to exacerbation of asthma occurrence, surges in bronchitis cases, whereas long-term exposures have been reported to be responsible for chronic health effects like cardiovascular changes like chronic obstructive pulmonary diseases (COPD) as well as congestive heart failures (Guarnieri and Balmes 2014; Maji et al. 2017, 2018; Chen et al. 2012; Mostofsky et al. 2012; Saxena and Sonwani 2019a).

Not only concentration, the origin of dust particles plays a major role in the mechanism of health impacts. Size, shape as well as composition of the particulate are all governing factors for the mechanism of toxicity. The dust particles can vary widely in size, shape, and composition depending on the nature of parent soils, emissions as well as transport processes. Acute exposure of elevated levels of particulate matter is linked to effects like bronchoconstriction and increased asthma symptoms (Kanatani et al. 2010); whereas scientific evidences have also linked long-term exposure to diseases like cancers (Arden Pope III and Dockery 2006), and cognitive impairments (Chen et al. 2009). Accounting the health significance of ambient air pollution, the International Agency for Research on Cancer (IARC) has designated outdoor air pollution as carcinogenic to humans (Bae and Hong 2018).

6.6.3.1 Cardio-respiratory Diseases

The normal human lung consumes about 5–6 mL oxygen per minute at an esophageal temperature of 28 °C (Loer et al. 1997). Therefore, any contaminant in ambient air enters the human cardio-respiratory system easily during respiration. Particulates, once inhaled, enter deep into the respiratory system depending on size fraction. The most common respiratory diseases affected by air pollution include upper respiratory symptom (URS), lower respiratory system (LRS), bronchitis, asthma, and chronic obstructive pulmonary disease (COPD), and even cancer due to prolonged damaging effects (Saxena and Sonwani 2019b).

Particulates of size below 2.5 μm can reach up to alveoli of lungs and are capable of absorbing by blood and transported to heart. A large number of literatures have reported cardiovascular events such as stroke, myocardial infarction, arrhythmias, and sudden cardiac death due to chronic exposure to elevated levels of dust particles (Arden Pope III et al. 2004; Brook et al. 2010; Saxena and Naik 2018). Cardio-respiratory impacts of particulate matter have been reported from the literature throughout the world. Studies conducted in Europe reported an increase in mortality rate of 0.69% for 10 $\mu g/m^3$ increase in PM10 concentration (Zanobetti et al. 2003). Studies conducted in the United States reported an increase in cardiopulmonary mortality of 0.31% for 10 $\mu g/m^3$ increase in PM10 concentration (Samet et al. 2000). Studies conducted across Asia have reported an increase in mortality rate of 6% for 10 $\mu g/m^3$ increase in PM10 concentration (HEI 2010). Plausible evidences show exacerbation of cardiovascular disease with increase in particulate matter concentration. A recent global meta-analysis of vital statistics has observed an increase in cardiovascular diseases by 41% during 1990 and 2013 (Roth et al. 2015).

Literatures have established clear link of increase in hospital admission with respiratory, cardiovascular disease and increase in acute bronchitis after dust events (Saxena et al. 2021; Nogueira 2009). Studies conducted in Asian cities have observed a strong correlation of increase in emergency visit and daily hospital admissions rate with cardio-respiratory diseases after dust storms events (Otani et al. 2012, 2014). Similar observations have been reported from Italy (Sajani et al. 2011) and Spain (Jiménez et al. 2010) which have observed increase in respiratory mortality rate among the elders during Saharan dust events. Exacerbation in asthma attacks after episodic increase in particulate matter concentration has been conclusively established in so many literatures (Atkinson et al. 1999; Dockery 2001; WHO 2003). Asthma is one of the world's leading noncommunicable diseases. As per the estimates made by the World Health Organization, asthma affected an estimated 262 million people in 2019 and caused 461,000 deaths.

6.6.3.2 Valley Fever

Valley fever, also called coccidioidomycosis, is an infection caused by the fungus Coccidioides. Two Coccidioides fungi species (C. immitis and C. posadasii) cause valley fever (Williams et al. 1979). These fungi are commonly found in soil and are almost endemic in the southwestern United States and parts of Mexico and Central and South America. The valley fever is one of the fast-rising infectious diseases in the Southwestern United States. A positive correlation between dust storm events and increase in valley fever incidents has been observed by several researchers (Tong et al. 2017).

6.6.3.3 Eye and Skin Infections

Peoples leaving in arid areas often experience eye and skin infections after dust storm events. High concentration of particulate matter in the ambient air reported to cause acute effects like conjunctivitis, itchy eye, and skin infections. However, these effects are not fatal, and effects are allergic response to dust particles only (Saxena and Srivastava 2020).

6.6.4 Economic Impacts

Apart from its effects on air quality and human health impact, SDS events are also related to have both immediate and in longer term economic impacts. The direct effect of SDS event is observed on agriculture productivity due to soil erosion, loss of nutrient-rich topsoil, and crop damages due to sandblasting and burial of seedlings associated with dust storm events. Direct economic losses due to dust storm events also come from destruction of infrastructure services like transport and communication systems, buildings, roads, etc. Long-term indirect economic impacts of dust storm events are accounted for the economic loss due to chronic health problems and the disruption of global climate regulation services. It is reported that millions of tracts of agricultural land have become unfertile due to loss of top soil as well as soil pollution due to deposition of pollutants.

Continued incidence of dust storms can also result in the migration of people from the place. Some of the major SDS events and the estimated economic loss due to dust storm event in the past few decades may be noted as follows:

- US$262 million: A single massive dust storm called, Red Dawn, in Australia on 22–23 September 2009
- US$964 million: Dust events in northern China from 2010 to 2013
- US$125 million: Dust events in Sistan region, Iran from 2000 to 2005
- US$0.5 million: A dust storm in eastern Mongolia in May 2008

6.7 Climate Change and SDS Events

SDS aerosol attracts gaining attention in recent times due to their interrelation with environment, weather, and climate (Shao et al. 2011). SDS aerosol can alter global thermal balance by absorbing and scattering the incoming shortwave and outgoing longwave solar radiation (Wu et al. 2018). Mineral dust particles in the atmosphere impact weather as well as global and regional climate (Boucher et al. 2013; Nickovic et al. 2012). SDS particles act as condensation nuclei for cloud formation; clouds absorb solar radiation, which indirectly affects the energy reaching the earth's surface (Boucher et al. 2013). SDS particles also influence the growth of cloud droplets and ice crystals, thus affecting the amount and location of precipitation (Mahowald and Kiehl 2003). SDS also affects precipitation processes through connective activities due to variable temperature (Maley 1982; Tiwari and Saxena 2021).

6.7.1 Positive and Negative Forcing and SDS

Aerosol particles emitted during SDS events can be different in the size, shape, and chemical composition that determine their optical properties. Thus, the aerosol particles originated during SDS events can have positive (warming) and negative (cooling) radiative forcing of climate system (Sokolik and Toon 1996; Dey et al. 2004; Sonwani et al. 2021b). Such forcing (positive/negative) depends on extent of dust layer and local surface albedo (Tanré et al. 2003). At global level, the net annual radiative forcing for desert dust at the top of the atmosphere is negative (cooling), whereas at the regional level, it is identified with positive value (warming) that occurs over snow-covered or desert areas (Bonan 1997; Miller and Tegen 1998). Due to the dust, darker surface (ocean) absorbs more sunlight whereas brighter surfaces like snow/ice surfaces. Such SDS events play an important role in changing radiative forcing that affects global dust cycle that might play an important role in increasing past climate change (Abbot and Halevy 2010).

6.7.2 Connection Between SDS and Climate Change

High temperature, low rainfall, and strong wind speeds are important variables for the SDS origin (Guan et al. 2017). Different climatic simulation models have confirmed that the surface wind speed and precipitation are the main meteorological factors to influence the SDS formation and have strong impact on the Asian dust formation and occurrences (Zhang et al. 2003). SDS during the winter and spring season are influenced by cold air interference from north that is triggered by the Siberian high, while during summer, SDS occurrence in the Asian region is generally controlled by high pressure over the Caspian Sea (Indoitu et al. 2012). The pressure gradient between Caspian Sea High and Hindu Kush Low acts as the main governing factor affecting the SDS action over southwest Asia and the Karakum desert (Kaskaoutis et al. 2016).

6.8 Conclusion

SDS is a natural extreme atmospheric event of arid and semi-arid regions that occurs beneath the earth's surface. It is a result of strong turbulent winds in arid zone that carry dust particles to distant locations and impact air quality and atmospheric visibility. SDS events are responsible for the presence of airborne dust particles. The occurrence of SDS event depends on wind speed and susceptibility of surface materials for erosion. Thus, it transports a huge quantity of particulate matter to thousands of kilometers away from its source location. Globally, more than 150 nations are affected directly by such events, and 45 nations are identified as SDS source-areas. The areas like deserts, beaches, and other dry lake beds are most susceptible for wind erosion, hence important sources for SDS. Climatic factors directly cause dust storms, while several human-induced factors influence the impacts and frequency of SDS events. Land degradation, desertification, indiscriminate exploitation of land, and water resources are important drivers of SDS events.

SDS have significant socio-economic impacts on human health, agriculture, industry, transportation, water, and air quality. The direct impact of dust storm events is on agriculture due to loss of top fertile soil, soil erosion, and crop damages. Following the dust storm events, disruption of communication and transport services are some of the immediate effects. Dust particles in the atmosphere impact radiative balance impacting local and regional climatic balance. Several studies have also observed the impact of dust storm events with climatic change impacts. Drought intensification as well as enhanced precipitation are some of the long-term climate change impacts which are correlated with dust storm events. SDS events are also linked with health concerns, airborne dust aggravates respiratory symptoms. Inhalation of fine dust particles exposes individuals not only to hazardous fine mineral particulates, but also to harmful combinations of pollutants, spores, bacteria, fungi, and potential allergens carried along with mineral dusts. Globally, 334 million people and 14% of world's children experience asthmatic symptoms. In addition, dust storms can transport pathogens such as meningitis and valley fever (Abdussalam et al. 2013).

Thus, SDS is identified as one of the important extreme events with global importance due to their huge impacts on the economy, human health, and the environment. SDS has large-scale impact and affects a range of Sustainable Development Goals (SDGs) related to human health, productivity, agriculture, and infrastructure (transport). With increasing urbanization and land use/land cover changes and an increase in surface temperature, the frequency of similar SDS events is expected to increase in the future. To reduce the harmful impacts of SDS is identified as a priority area for achieving SDGs. With such wide transboundary impacts, managing the SDS risks requires both global and regional cooperation.

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Assessment of Heat and Cold Waves Phenomena and Impacts on Environment

7

Daphne Parliari, Christos Giannaros, and Stavros Keppas

Abstract

Extreme temperatures, either elevated or low, are known to cause adverse impacts on the natural and human environment. Increased hospital admissions and mortality rates during heat and cold waves demonstrate the severity of the problem concerning human health. Heat waves (HWs) are expected to become more severe in terms of frequency, intensity, and duration due to climate change, whereas cold events will become rarer and milder. Along with rapid urbanization and deterioration of air quality due to human activities, heat waves pose a major threat for people's well-being and quality living conditions, affecting especially the urban population. Thus, appropriate counter-measures and mitigation strategies are necessary worldwide in order to combat these effects in timely intervention. The current chapter focuses primarily on heat waves addressing in detail their definition, generation, future projection, and synergy with the urban heat island (UHI) effect and air pollution in cities, as well as their harsh impacts on several sectors and the approaches for mitigating these effects. A part of this chapter is also devoted to cold waves, while a case study concerning the interplay between extreme temperatures, thermal comfort, and air pollution during a significant HW episode that occurred in Greece is presented.

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Keywords

Heat waves · Cold waves · Air quality · Human health · Urban heat island · Climate change

7.1 Introduction

From ancient until current times, weather and climate directly affect people's lives on a daily basis. Fringe events particularly, such as floods, droughts, tornadoes, and heat waves, may induce disproportional impact on human societies, as infrastructure can be significantly devastated, economy and health are affected, and loss of life is frequent (World Meteorological Organization—WMO 2016). Even though an extreme episode would normally be as rare as the 10th or 90th percentile of a probability density function estimated from observations (Cubasch et al. 2013), in recent years, natural and climate hazards are becoming more frequent, as well as more severe under the influence of climate change (IPCC 2014). This is particularly true for heat waves, as research findings show a rise in the frequency, intensity, and duration of extreme temperature events (Fischer and Schär 2010), which will also be evident in the future. In contrast, occasional but milder cold wave events are expected to occur in future years (IPCC 2014). HWs can result in increased mortality and health-related risks, agricultural losses, wild fires, and power shortage (WMO 2016; Jain et al. 2021). Rapid urbanization, urban heat island effect, and poor air quality work synergistically with high temperatures prevailing during a heat wave, thus exacerbating the adverse impacts on urban residents (World Health Organization—WHO 2016).

Considering the above, it becomes evident that it is essential to better understand the physical characteristics of HWs and their association with the UHI effect and air pollution in cities. Most importantly, it is urgent to develop counter-measures and strategies that alleviate these combined effects and improve living conditions in urban agglomerations (Voogt 2004), but also integrated heat action plans that can provide guidelines for the management of heat as a hazard (McGregor et al. 2015). The aforementioned exigent necessity is reflected on the present chapter, which primarily aims to present key points on heat waves, including their definition and generation mechanisms, and highlight their severe impacts on environment and human health. Particular attention is given to the synergy between heat waves, air pollution and UHI effect, as well as to the future projections of this detrimental combination, along with their adverse repercussions. Mitigation and adaptation actions are also presented in the current chapter, focusing on heat-health warning systems, implemented by many countries worldwide. Moreover, cold waves and their impacts on environment are investigated. The present chapter attempts to summarize the existing scientific knowledge concerning major environmental problems arising from heat and cold waves, and present a concise overview of the most important aspects, in order to better understand the importance of effective adaptation for the human well-being, especially in urban areas.

7.2 Heat Waves

7.2.1 Defining Heat Waves

Although heat waves are among the most damaging climate extremes, there is no global, standard definition of them (Giannaros 2018). Generally, a HW can be described as a period of abnormally hot weather over a region that usually lasts from few days to few weeks (WMO 2016). However, the standards for determining the extreme warming at a place depend primarily on the local climate features. This fact is reflected on the diversity of the definitions in different countries or regions. The National Meteorological Services (NMSs) around the world have adopted their own standards for issuing HW advisories. These standards mainly involve the application of absolute temperature thresholds for a given number of days. In Greece, for example, a heat wave is defined when a daily maximum temperature greater than 38 °C is recorded for 3 days in sequence (Giannaros 2018). Other approaches for determining a HW may involve the application of different measures of heat and the use of relative exceedance thresholds. For instance, the National Weather Service (NWS) in the United States (US) apply the daytime heat index (incorporating temperature and humidity) to issue early warnings (Barcena-Martin et al. 2019), while the 95th percentile of summer maximum temperature is used in Belgium (WMO 2016). In overall, characterizing quantitatively a heat wave event in terms of meteorological conditions should consider four factors: severity, geographical extent, magnitude, and duration (WMO 2016), while percentile-based thresholds are necessary for the statistical robustness of any HW definition (Kiktev et al. 2003). A recent attempt to integrate these elements into a HW definition was realized by Giannaros et al. (2019), who utilized the IPCC's TX90p index for extreme temperature (Hartmann et al. 2013). Based on this index, a HW day is defined when the daily maximum temperature is higher than the 90th percentile of the reference period that spans from 1961 to 1990. Giannaros et al. (2019) applied the TX90p index to the temperature data over three meteorological stations across Greece and defined a HW episode when at least three successive HW days were identified at the same time over all three stations.

Beyond the meteorological perspective of heat waves, another aspect that cannot be disregarded lies on the impacts of HWs on human health. Matzarakis and Nastos (2011) point out that, although a heat wave is a meteorological event, its assessment should include reference to the impacts on humans. Therefore, the definition and analysis of HWs should always evaluate the human sensation of heat, contributing to the decision-making for the prevention and protection of people. In this direction, determining the links between extreme hot weather conditions and morbidity and mortality is necessary, especially when targeting vulnerable groups of people. Heat-related epidemiological studies assist the incorporation of the public health risk into HW definition indices (Metzger et al. 2010; Williams et al. 2012) and the development of heat-health warning systems (Michelozzi et al. 2010). Nori-Sarma et al. (2019) indicated the crucial importance of various heat wave definitions versus health effects for the provision of necessary tools to the policymakers, in order to implement effective heat wave warnings.

7.2.2 Generation of Heat Waves

7.2.2.1 Atmospheric Characteristics

Large-scale atmospheric circulation is considered as the factor that primarily affects surface temperature. Heat waves and warm spells have been related to the development of anticyclonic anomalies in various regions across the globe (Meehl and Tebaldi 2004; Maheras et al. 2006; Chen and Lu 2015; Lu and Chen 2016; Luo and Lau 2017). Surface air temperature may increase due to various reasons, such as the adiabatic heating and increasing solar radiation due to subsidence in an anticyclonic regime (Zaitchik et al. 2006; Loikith and Broccoli 2012; Chen and Lu 2015), the horizontal airflow via temperature advection (Ziv et al. 2004) or through the mechanism of katabatic winds (Ágústsson et al. 2007; Fig. 7.1).

Depending on the region, sometimes more than one particular atmospheric circulation patterns can cause a heat wave (e.g., Harpaz et al. 2014), while even regions within a few hundreds of kilometers may be affected by a heat wave under significantly different circulations (e.g., in Iberia; García-Herrera et al. 2005). In addition, in some cases, typical synoptic conditions for a region during summertime may be determinant for the occurrence of a HW. As an example (Harpaz et al. 2014), in southeast Mediterranean Sea, heat waves over the eastern Mediterranean region can be mostly affected and regulated by the mechanism of temperature advection rather than the prevailing subsidence due to dominant northeasterly winds (etesians; e.g., Poupkou et al. 2011; Dafka et al. 2020), which usually blow during summertime.

According to Stefanon et al. (2012), there are six dominant circulation patterns, which can lead to the occurrence of a HW over different regions in Europe. A ridge centered in west Russia can cause heat waves in this region (e.g., Russian heatwave of summer 2010; Grumm 2011). Within this case, a secondary maximum of

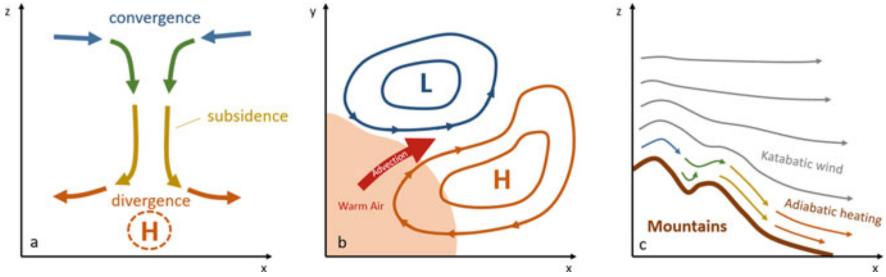


Fig. 7.1 Schematic representation of the mechanisms of (**a**) subsidence in an anticyclone, (**b**) horizontal warm air advection, and (**c**) katabatic wind, which may lead to and/or enhance a heat wave

geopotential heights over the eastern Atlantic Ocean affects western Iberia with high temperatures. If a ridge is located over Poland, then a heat wave occurs in regions of Eastern Europe and around the Baltic and Black Sea. In contrast, a region of enhanced geopotential heights over France is associated with HWs in central Europe and Iberia (e.g., August 2003; Fink et al. 2004). In case of an enhanced ridge over the North Sea and British Isles, high temperatures occur over northwest Europe and southern Scandinavia (e.g., summer 1976), while if this ridge is located over Scandinavia, northern Europe is affected. Finally, there is another common circulation pattern, which is a case of a wide, but weak, positive anomaly of geopotential heights over central-east Europe. This pattern has been associated with high temperatures in Iberia and Turkey. Under this pattern, warm air is advected via southerlies caused by the low-pressure system in the Atlantic Ocean.

Although the previously mentioned patterns are fairly typical for the European continent, according to Harpaz et al. (2014) and García-Herrera et al. (2005), there are various circulation patterns that may lead to a HW occurrence in eastern and western Mediterranean Sea. In particular, according to Harpaz et al. (2014), there are three main circulation patterns associated with heat waves in eastern Mediterranean. During the tropical pattern, tropical air mass is transported from south. The subtropical pattern occurs when the subtropical high intensifies from North Africa toward the east Mediterranean. Last, the baroclinic pattern is associated with an enhanced mid-latitude disturbance, while the east Mediterranean is affected by a ridge-inducing subsidence. Moving to the western of the Mediterranean Sea, García-Herrera et al. (2005) suggest that extreme temperatures are usually observed in Iberia when the high-pressure system of Azores enhances and extends further to the west linking with the system of high pressure over west Mediterranean. The example of Iberia is an illustration of the variation of circulation patterns in a limited region that may lead to a heat wave. Although extreme heat may reach Madrid when anticyclone of Azores is further to the west over the Atlantic, Lisbon may experience a HW when the center of the same anticyclonic system is located in northeastern regions.

Hu et al. (2019) detected two circulation patterns that lead to heat waves in south and north side of central Africa. HWs in southern parts have been associated with a positive anomaly in vertical velocities at 500 mb in both the south side of central Africa and northeast Africa/Saudi Arabia regions, which implies an anticyclonic regime there. Both subsidence and warm advection from the north seem to be the mechanisms contributing to a heat wave over the area. In contrast, HWs in northern parts of central Africa are related with the occurrence of a depression in North Africa and central/east Mediterranean causing southerlies, which advect warm air from the Sahara.

Moving to North America, Loikith and Broccoli (2012) found that the warmest 5% of days (for a period of ~50 years) in south-central regions are associated with an extensive region of positive anomalies of geopotential heights at the level of 500 mb over the south-eastern states. Regarding South America, Cerne and Vera (2011) showed that 73% of the heat waves in subtropical South America develop when South Atlantic Convergence Zone (Cerne et al. 2007) is active. A ridge over

Argentine and Chile is associated with an active convergence zone and a HW in the wider area of northern Argentina. An extreme heat episode under similar conditions occurred in February 2003.

In Australia, there are two key atmospheric circulations, each of them relating to a heat wave over different areas (Pezza et al. 2012). In particular, an anticyclone centered at an area between southeast Australia and New Zealand favors a HW in the eastern parts of the continent, while an elongated anticyclone centered over the south Australian coastline allows warm air advection toward the west. In both cases, the anticyclone causes a flow from the inland to peripheral regions.

In eastern Asia, Lu and Chen (2016) distinguished between days with high maximum temperatures (called Extreme Heat—EH) and nights with high minimum temperatures (called Tropical Nights—TN). Each of these types occurs under different synoptic conditions. EH cases occur when a cyclonic system over northeast China allows warm air to be advected from the inland to the coast, while TN cases are present when an anticyclonic system located at a similar position blocks any cyclonic system to pass through, but advects moisture from the eastern maritime area. In addition, Chen and Lu (2015) conducted a more comprehensive study about the heat waves in eastern China highlighting, between others, the impact of westerlies blowing from the mountains to the east (foehn; Speirs et al. 2010; Takane and Kusaka 2011) increasing the temperature further.

Areas of the north and central India located far from the coastline are usually affected by a HW when a ridge at 500 mb is present over northern India and Pakistan. The main mechanism that causes a heat wave in this case is the subsidence and adiabatic heating over the region. According to Ratnam et al. (2016), this type of circulation is associated with an anomalous blocking system in northern Atlantic Ocean resulting in a cyclonic anomaly in northwest Africa. Next, this generates Rossby waves close by the entrance of the African Jet Stream, which maintains the heat wave in India. Another atmospheric pattern that affects mostly eastern parts of this country is linked with an extensive cyclonic system in eastern Asia and western Pacific Ocean.

Finally, focusing on central Asia, heat waves in July may be favored by a positive anomaly over this region at 500 mb. Again, in this massive continental region, the dominant mechanism of the temperature increase is the air descent in the lower troposphere, which leads to clear skies, increased solar radiation, and adiabatic heating. Such a circulation pattern can explain more than 40% of warm spells/heat waves in Eastern Europe and northwest Asia.

Besides the synoptic atmospheric conditions, several regional land-atmosphere interactions and characteristics, such as soil moisture, have a governing role in the generation and development of HWs. Various studies have shown that extreme HWs in summer are preceded by droughts in spring, which are associated with rainfall deficiencies during the winter (e.g., Diffenbaugh et al. 2005; Fischer et al. 2007; Zampieri et al. 2009). The spring soil moisture deficit propagates during the summer strengthening the sensible heat fluxes due to limited evapotranspiration. As a result, heat wave temperatures are enhanced. Moreover, the increased sensible heating assist the growth of the planetary boundary layer (PBL), leading to higher heat entrainment from above the PBL (Miralles et al. 2014). Furthermore, the development of clouds is inhibited by the dry and hot conditions, resulting in rainfall deficiency and, consequently, in a greater demand for evapotranspiration, which further dries out the soil and, in turn, enhances the temperatures increase (Vautard et al. 2007). Other important factors contributing to the shaping of HWs include the atmospheric water vapor content and anomalies in sea surface temperarure (Giannaros 2018).

7.2.3 Climate Change and Heat Waves

There is a significant uncertainty about the characteristics of future climate. One of the reasons is the uncertainty on the human activities in the future. Therefore, there are various scenarios considering different volumes of greenhouse gases emissions until 2100. Four different scenarios, which are called Representative Construction Pathways (RCPs), are used. The RCPs are labeled according to the possible radiative forcing that they represent in the year 2100 (2.6, 4.5, 6, and 8.5 W m^{-2} corresponding to 490, 650, 850, and >1370 ppm) (e.g., Moss et al. 2008; Taylor et al. 2012; Jubb et al. 2013; Rogelj et al. 2012).

In general, climate change is expressed by increase in temperature around the most regions of the world. It seems that more frequent extreme events, such as heat waves, will be part of this change in the future. In a “business as usual” scenario (RCP8.5) until 2100, 3-day HWs are anticipated to be significantly strengthened in intensity (by 3 °C in daily minimum temperature), duration (by more than 5 days), and frequency (by 25–30%) in parts of north America and Europe (Meehl and Tebaldi 2004). Such a change of the climatology of summer may impact on people losses, failure of crops, and significantly decreased discharge in many rivers (Beniston 2004).

The 2003 HW in Europe may provide an insight of the course of summers in the late twenty-first century (Beniston 2004). Summer of 2003 had been the hottest since 1540. This conclusion comes up not only from the meteorological observations (e.g., the average maximum temperature of the summer 2003 in Basel of Switzerland exhibited a positive anomaly of 6 °C), but also from the noticeable changes in rivers and crops in Europe by the end of that summer. A summer in Europe in the latter period of the current century is expected to present increased average of maximum temperatures by 4–6 °C comparing to the present, with 40–60 more days of temperatures >30 °C in an annual basis and the occurrence of 3–4 heat waves per year on average based on the RCP8.5 (Beniston 2004). Under the RCP4.5 scenario, the impact of the climate change on heat waves is estimated to be roughly halved (Lhotka et al. 2018).

Looking at the heat waves in a global scale, it seems that they will increase in frequency, duration, and intensity. Under the “business as usual” scenario and the trend of increasing temperature, extreme events will increase in frequency and heat waves, which are considered as extreme today (e.g., extreme heat waves in USA (1980; Livezey 1980; Applegate et al. 1981; Karl and Quayle 1981; Jones et al.

1982), Europe (2003; Beniston 2004; Stott et al. 2004; Fouillet et al. 2006), and Russia (2010; Dole et al. 2011; Otto et al. 2012)), will be the normality in the future. It is noticeable though that the frequency of HWs will rise in a much more significant rate during the later decades of the twenty-first century (Russo et al. 2014). According to the IPCC report (Stocker et al. 2013), under high-emissions scenarios the current rate of 1 extreme heat wave event per 20 years will increase in case to 1 event per 2 years by the end of the twenty-first century. Additionally, it seems that the maximum increase of $T_{\max}$ of an extreme event will occur in central Europe and northern America exhibiting, by the end of the century, values 7–9 °C larger than the $T_{\max}$ of an extreme heat wave at the present.

7.2.4 Urban-Scale Aspects of Heat Waves

The urban micrometeorology is significantly complicated, as the presence of buildings of various heights and different densities, various structure materials, and green areas locally differentiate the near-surface meteorological conditions. An urban area usually presents higher temperatures than the surrounding areas due to the materials that the buildings are made of and the anthropogenic heat (Oke 1967; Kim 1992; Shahmohamadi and Etessam 2011). An extra factor that is involved in the microclimate of a city is the pollution produced by it. Both the complicated structure and the pollution can add extra charge under a heat wave condition.

7.2.4.1 Heat Waves and Urban Heat Island Effect

The adverse impacts of HWs are more evident in cities due to the urban heat island (UHI) phenomenon and the greater population density. UHI denotes the higher temperatures observed in urban environments compared to their rural surroundings (Giannaros et al. 2018). Today, more that 50% of the world's population is living in urban areas, while this proportion is expected to reach up to 68% by 2050, with the most urbanized regions being the Northern America, Latin America and the Caribbean, Europe and Oceania (United Nations 2018). The combined effects of climate change, fast urban development, and UHIs induce an important health concern for the urban residents.

UHI effect is considered to be the most illustrative environmental problem emerging from local climate changes induced by humans (Giannaros et al. 2018). Its causation is primarily associated with changes in the surface characteristics due to replacement of the natural environment by artificial materials (e.g., asphalt and concrete). These changes alter the surface energy budget (SEB) due to the artificial facets having high heat capacity storage and the low vegetation coverage resulting in limited evaporative cooling. SEB is also modified by the enhanced production of anthropogenic heat (Founda and Santamouris 2017), while the complicated geometry of streets of buildings introduce modifications in the near-surface air flow (Laaidi et al. 2012).

UHI is a local phenomenon demonstrating different characteristics depending on time and place (Fig. 7.2) (Giannaros and Melas 2012) found that UHI in

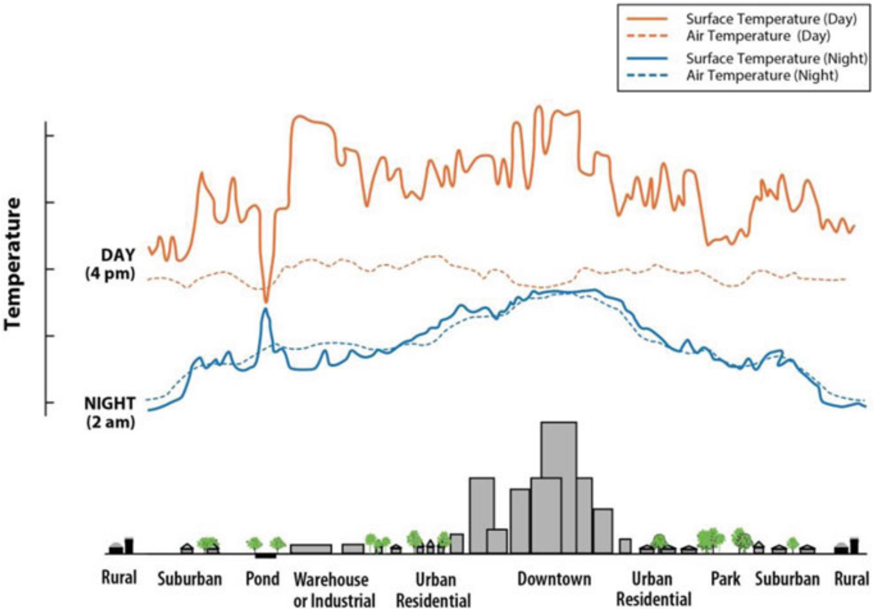


Fig. 7.2 U.S. Environmental Protection Agency (2019). Illustration of the impact of different land uses to the air and surface temperatures of a city. www.usgs.gov/media/images/urban-heat-islands

Thessaloniki, Greece, is primarily a nighttime effect, with maximum values ranging between 2–4 °C and 1–3 °C during the warm and cold period of the year, respectively. The city of Athens in Greece is also characterized by a strong UHI effect, with intensity up to 4 °C during the night (Giannaros 2013). The summertime UHI intensity in Beijing, China, ranges from 4 to 6 °C between the urban core of the city and the suburbs and from 8 to 10 °C between the city center and outer suburban areas. In Johannesburg, South Africa, the temperature in the city center was found to be higher than 11 °C compared to the suburban valleys during the dry season. The London UHI is primarily evident during the night hours, with its intensity being equal to around 0.7–0.8 °C at noon and rising to 2.5–3.0 °C after sunset. In Melbourne, Australia, UHI intensity can range from a mean of 2–4 °C, with daily peaks as high as 7 °C (Tzavali et al. 2015).

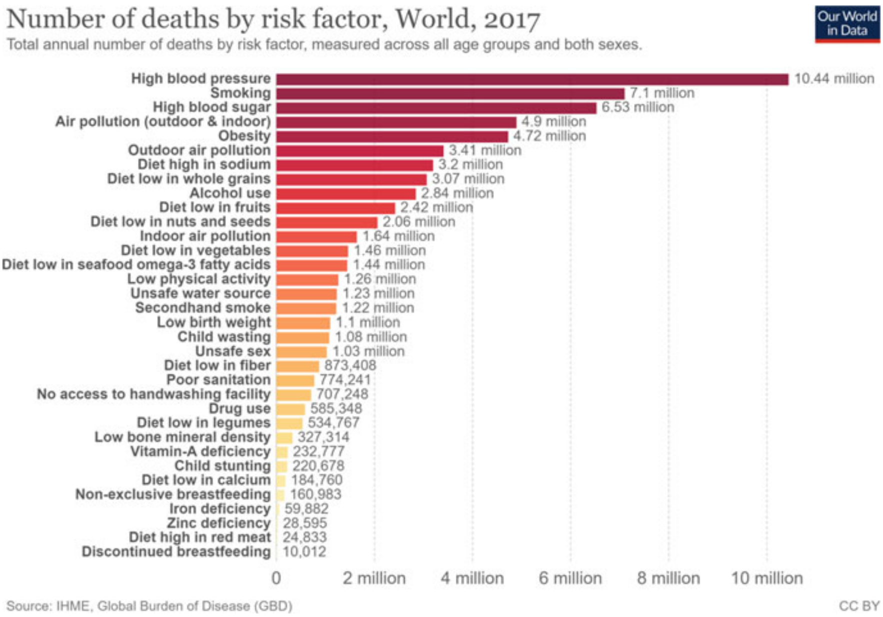
Extreme heat in urban areas is intensified by the interaction of UHIs and heat waves. Founda and Santamouris (2017) investigated five heat waves events in Athens, Greece, during the summer of 2012. They showed that the mean UHI intensity increased by up to 3.5 °C during the studied HWs compared to the summertime normal conditions. Furthermore, Zhao et al. (2018) reported higher UHI intensities (0.4–2.8 K) during HWs than during normal days, after investigating interactions between UHIs and HWs for 50 cities in the United States. A case study conducted for Szeged, Hungary, showed that nocturnal UHI was 2–3 times stronger in the HW period compared to normal summer periods (Unger et al. 2020), while positive synergy between UHI and HW events were also reported for Washington in US (Li and Bou-Zeid 2013).

The elevated temperatures resulting from interaction between UHIs and HWs have been linked to increased mortality rates. Tan et al. (2010) showed that UHI in Shanghai, China, enhances the intensity of heat waves. In turn, the increased exposure to extreme heat results in adverse effects on the human health of urban residents. More specifically, the heat-related excess mortality was significantly higher in the urban areas of the city compared to the surrounding suburbs. This outcome was particularly evident for the two extreme heat waves in 1998 and 2003 (Tan et al. 2010). Moreover, Heaviside et al. (2016) concluded that UHI in the West Midlands in the United Kingdom (UK) contributed 50% approximately to the total heat-related mortality during the 2003 European HW. Laaidi et al. (2012) also studied the heat wave that occurred in August 2003 in Europe by assessing the impact of UHI on mortality in Paris. They highlighted that the exposure to high nighttime temperatures over several days during the HW increased the probability of death for elderly people living in urban areas.

7.2.4.2 Heat Waves and Air Quality

Air pollution, both ambient (outdoor) and household (indoor), has become one of the major concerns affecting life quality in modern societies (Saxena and Srivastava 2020; Saxena and Sonwani 2019). Especially, outdoor air pollution is considered the biggest environmental risk to health, as it is responsible for around three million deaths each year, mainly from non-communicable diseases (WHO 2016). It is characteristic that for 2017, accumulative air pollution (indoor and outdoor) was the fourth most important risk factor for the total annual number of deaths globally, as illustrated in Fig. 7.3.

Pollutants observed in urban agglomerations are in higher concentrations than in rural areas due to the emissions caused by human activities (Williams et al. 2008; Kalisa et al. 2018; Saxena and Naik 2018). During heat waves, the air masses remain stagnated, trapping pollutants at layers of the troposphere near the surface (Tressol et al. 2008). In addition, tall buildings in cities may trap pollutants as they stop/decelerate air movement. Several studies have shown that the already enhanced concentrations of NO_2, O_3, and PM_{10} within urban areas increase under high temperature, increased solar radiation, and the absence of significant winds. O_3 is a secondary pollutant in the cities, which means that it is not directly emitted, but is formed on hot days by the influence of solar radiation and the presence of NO_x (Yin et al. 2019; Saxena et al. 2019; Archibald et al. 2020). A recent study conducted in Birmingham, UK, showed that the levels of O_3 increase by more than 50% under elevated temperatures during heat waves (Kalisa et al. 2018). Pollutants such as NO_2 and PM_{10} are produced in cities by vehicle emissions and road transport-related emissions and other human activities. However, secondary formation is again favored by increased temperatures (e.g., Vardoulakis and Kassomenos 2008; Papanastasiou et al. 2015). Particularly for NO_2, its concentration increases by 120% for temperatures higher than 35 °C. Also, it is worth mentioning that emissions of pollutants on hot days may be further increased by behavioral changes (e.g., enhanced air-conditioning and use of cars).


Number of deaths by risk factor, World, 2017

Total annual number of deaths by risk factor, measured across all age groups and both sexes.

Source: IHME, Global Burden of Disease (GBD)

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Fig. 7.3 Total global annual number of deaths by risk factor, measured across all age groups and both sexes (Data published by Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2017 (GBD 2017) Results. Seattle, United States: Institute for Health Metrics and Evaluation (IHME), 2018. http://ghdx.healthdata.org/gbd-results-tool)

Considering the increasing concern about the health impacts induced by the climate change, especially in cities, the study of the synergistic effects of air pollution and extreme heat conditions on health is of great importance. An early study by Katsouyanni et al. (1993), which focused on the deadly heat wave of July 1987 in Greece, showed that the greater mortality recorded in Athens compared to other urban and rural areas of the country was probably associated with the increased air pollution that characterizes the city. Concerning the more recent heat wave of 2003 in Europe, Filleul et al. (2006) demonstrated that the excess risk of deaths linked to the combined effects of ozone and temperature ranged in France from 10.6 to 174.7%, in Le Havre and Paris, respectively. This outcome highlights the enhanced risk in highly urbanized areas during heat waves due to the synergy between poor air quality and elevated temperatures. Further, Analitis et al. (2014) investigated the relationship among daily mortality, meteorological, and air quality data from 1990 to 2004 in nine European cities. They found a 54% increase in mortality for people aged 75–84 years during HW episodes characterized by high ozone concentrations, compared to low ozone days. Similar findings were demonstrated during the HW episodes with high PM10 days, when daily deaths were increased 106% in the 85+ year age group. Chen et al. (2018) studied the impact of urban air pollutants and temperatures on the total and cardiovascular mortality in eight European cities and showed overall positive feedbacks between air pollution and mortality, which were generally stronger during days characterized by high temperatures. In particular, an increase of 10,000 particles/cm^3 in particle number concentration during days with elevated temperatures corresponded to a 2.51% increase in cardiovascular mortality. Similarly, Shaposhnikov et al. (2014) suggest that at temperature $\leq$18 °C mortality rate is +0.43% increasing to +1.44% at the temperature near 30 °C in the city of Moscow.

7.2.5 Impacts of Heat Waves and Mitigation Strategies

Heat waves affect severely the natural and human environment, including human health, energy demand, infrastructure, and forests (Zuo et al. 2015).

7.2.5.1 Human Health

HWs deteriorate the human thermal comfort conditions. This fact may result in a significant increase in morbidity and mortality because of diseases associated with the cardiovascular and respiratory systems (Giannaros 2018). Several studies across the world have clearly connected elevated temperatures with excess in mortality rates. A characteristic example is the severe heat wave of 2003 in Europe, when over 70,000 people died (Robine et al. 2008). Concerning non-fatal health effects of heat waves, Semenza et al. (1999) showed that during the July 1995 HW in Chicago, hospital admissions were higher by 11% than average and 35% more than expected for patients aged 65+ years. Dehydration, heat stroke, and heat exhaustion were among the major treatments (59%), especially for people with underlying medical conditions. Moreover, according to Theoharatos et al. (2010) more than 140 emergency department visits related to heat exhaustion and heatstroke were reported by the National Health’s Operational Center in Attica, Greece, during June 2007 HW that affected severely the capital of Greece.

According to Giannaros et al. (2018), enhanced susceptibility to heat-health impacts is evident for particular vulnerable groups, such as children, elderly, and people having pre-existing cardiovascular or respiratory diseases or other medical conditions (e.g., diabetes). Urban residents are also susceptible to heat-related health issues. Several studies highlight that death rates during heat waves are often much higher in cities encumbered to the rural areas (Conti et al. 2005; Gabriel and Endlicher 2011; Heaviside et al. 2016; Matzarakis et al. 2009). This is because of the interplay between HWs and the urban heat island effect, as already analyzed in the previous Sect. 7.2.4, exacerbating the thermal load on people living in urban areas. Especially, the nighttime UHI leading to increased nocturnal temperatures in the urban cores has a critical damaging effect on human health, as the urban residents are deprived of the sense of thermal relief (Giannaros 2013).

7.2.5.2 Energy Sector and Infrastructure

Higher energy demand is induced during HW events due to the increased need for cooling. This fact can lead to power shortages and even outages, while it also results in a greater release of greenhouse gases, since the major sources of the electricity production are the fossil-fueled and nuclear power plants. This environmental side effect, apart from leading to the deterioration of air quality and to consequent worsening of the associated health problems, has a positive interaction with the elevated temperatures that introduces further increase for energy consumption in order to meet the cooling needs. High temperatures during a HW can also have significant impacts on the energy generation, transmission, and distribution (Giannaros 2018).

Given the complexity of urban infrastructure and the interaction between its elements, increased temperatures especially during prolonged periods of time cause problems and malfunctions (e.g., damages on rail tracks and roads). Additionally, extremely high temperatures may affect significantly artificial materials in buildings. Some characteristic examples are the expansion stress (e.g., in concrete), issues with protective finishes, stress in large sections of insulated glass units, and damage to durability of coatings due to ultraviolet radiation (Zuo et al. 2015). According to the Institute for Sustainable Resources (2010), HWs may also induce major effects on the electricity infrastructure, while air transportation and telecommunications are less vulnerable to extreme heat.

7.2.5.3 Other Aspects

According to Unal et al. (2013) and Westerling and Cayan (2006) HWs are highly associated with wildfires. In particular, during dry heat waves, the significant declination of relative humidity increases the development probability of disastrous wildfires (Pezza et al. 2012), like the devastating bushfires in Australia that burned more than 12.35 million acres of land and caused 25 deaths in 2019. Water services are also significantly affected by heat waves, as water usage is enhanced during HW periods, while the water infrastructure problems may arise due to extreme heat (Zuo et al. 2015). Moreover, the elevated air temperatures contribute to the deterioration of water quality. Eutrophication, increased concentrations of major elements, and warmer temperatures in water are evident during HW events (van Vliet and Zwolsman 2008). Agricultural and livestock productivity are also decreased in the course of heat waves (Smoyer-tomic et al. 2003). Potential impacts of HWs also affect the natural environment, forestry agriculture, and tourism (McGregor et al. 2007). Last, but not least, HWs affect the mental health of humans. The heat stress induced by extreme high temperatures exacerbates pre-existing mental disorders and affects sleeping leading to fatigue and lack of concentration (Zuo et al. 2015), while there is evidence that hot weather is associated with crime, aggressive behavior, and domestic violence (McGregor et al. 2007).

7.2.5.4 Mitigation Strategies

Due to the growing severity of the elevated temperatures and the consequent adverse impacts on human health and environment, several strategies and measures have been established in order to attenuate these effects. Nevertheless, proposed solutions should take into consideration that heat waves act synergistically with UHIs, air quality, rapid urbanization, and the growing percentage of elderly people. People living in urban environments are exposed to higher risks associated with heat waves, as UHI effect makes the cities warmer than their surrounding non-urban areas.

According to Akbari and Kolokotsa (2016), the mitigation technologies to counteract the urban warming effects follow major approaches. The first approach aims at increasing solar reflectance (e.g., cool roofs and pavements). It contains measures aiming to keep urban surfaces cool by decreasing the absorption of the solar radiation with the use of materials characterized by high solar reflectance and high thermal emittance. In this framework, Morini et al. (2016) investigated the effect of albedo change in urban temperatures for the area of Terni, Italy. Their results demonstrated that when the albedo was increased from 0.2 to 0.8 for roofs, walls, and roads in the whole urban area, a decrease of the daytime and night-time urban temperature by up to 2.5 °C followed. The second approach aims at increasing evapotranspiration, using technologies that favor urban greenery and water availability (e.g., green walls). For instance, Li (2014) highlighted that green roofs had a substantial effect in reducing the UHI intensity during a HW episode occurred in Baltimore-Washington in June 2008. Other urban heat mitigation actions may include improved ventilation in urban areas by assisting cold air drainage flows, especially at night (Gabriel and Endlicher 2011).

A comprehensive study concerning the effectiveness of heat mitigation measures was presented by Silva et al. (2010). They investigated the impacts of increasing the overall emissivity, percentage of vegetated area, thermal conductivity, and albedo in the urban area of Phoenix, Arizona, USA, to human health vulnerability associated with extreme heat-related events from 2002 to 2006. According to their findings, the albedo strategy had the strongest influence on temperature followed by increasing thermal conductivity and vegetated area, whereas increasing emissivity was the least effective. The most important outcome of their study was that the combination of the studied mitigation approaches led to a 48% reduction in annual heat-related emergency service calls.

Another way to categorize extreme heat mitigation measures is according to their time frame. Short-term measures include actions in a more immediate scale (e.g., heat-health warning advisory), while long-term strategies require more time to be introduced and implemented (e.g., construction of green parks). Heat-Health Warning Systems (HHWSs) are extremely important for the short-term mitigation measures. Since the severe heat wave that stroke Europe in 2003, causing more than 70,000 deaths, interest on HHWSs has raised significantly and most of concerned countries have established a type of heat-health action plan to protect their population. A HHWS aims at reducing heat-related impacts on human health, especially during hot conditions, by combining meteorological forecasts and public health actions (Koppe et al. 2004). Through HHWSs, decision-makers and the general public can be warned about extreme hot weather and obtain advice on how to avoid associated adverse health outcomes. Although HHWS can vary significantly as they are based on area-specific information depending on local populations, systems, human and technical resources and heat–health associations, there are some universal characteristics for such application. Among these is the consideration of local meteorology, demographics and urban structure, thresholds associated with heat-health outcomes and nomenclature that is easily understood by the public, local stakeholders, and decision-makers (McGregor et al. 2015).

As there is no global definition of HWs (see Sect. 7.2.1), there is also a variety of methods to define the weather-health relation which acts as "action trigger" for issuance of warnings. According to McGregor et al. (2015), current HHWSs incorporate three broad categories of heat situations that affect human health. The most common of them is the single—or few—parameter method, where the exceedance of one or more variables above a certain threshold triggers a respective warning. Different countries use different metrics and methods to achieve the most effective result on national or regional levels. For example, Belgium, France, Greece, and UK use Temperature, Australia and Italy apply Apparent Temperature, while Humidex is implemented by USA and Airmass by Italy and China. In any case, the first step for building a NHWSS is selecting the proxies which best depict heat-health relation and setting the thresholds that are either correlated to the consequences or depend on climatological fringe values. Then, thresholds initiate a system of scaled warnings that are often related to specific recommendations. The dissemination of the alerts addresses both general public and vulnerable groups, informing them about the severity of the event and providing advice on health impacts (Casanueva et al. 2019).

Italy was one of the first countries to establish HHWS that is covering the vast majority of urban agglomerations and it is operational for almost 17 years. The Italian system combines mortality data and meteorological variables to detect conditions connected to an increase in daily mortality. The heat-health-related risk is classified from low (<20% excess in mortality) to high (≥20% excess in mortality). This HHWS is based on two pillars: the air mass-based approach, and the relationship between mortality and maximum Apparent Temperature. A series of conditions, based on the two approaches mentioned earlier, must be combined interactively in order for Level 1 and Level 2 warnings to be issued while Level 3 warning corresponds to three continuous days of Level 2 (Michelozzi et al. 2010).

A recent example of HHWS is implemented in the framework of the project LIFE ASTI "Implementation of a forecasting system for urban heat island effect for the development of urban adaptation strategies" (https://lifeasti.eu/). Based on the approach of the Italian system, urban-specific relationships between maximum apparent temperature and daily mortality of vulnerable population groups were extracted for the involved cities (Thessaloniki and Rome). In the second stage, HHWS was developed and implemented to issue differential alerts at high spatial and temporal resolution during the warm period of the year. The results from this effort will conclude to the improvement of the decision-making of local policy-making authorities in the integration of heat prevention plans.

Last, but not least, improved education and public awareness also play an important role when adapting to heat, especially regarding sensitive groups. According to the US Environmental Protection Agency, local policy-making authorities should disseminate information about conceivable risk factors, symptoms of overdone heat exposure, and recommend advice on remedy. Particular attention must be given to vulnerable groups, namely infants, outdoor workers, pregnant women, elderly people, as they must be specifically taken into consideration in information campaigns utilizing more active approaches, such as a tandem system, home visits, and regular phone calls (Matthies et al. 2008).

7.3 Cold Waves

According to WMO (2016), a cold wave is defined as "*unusual cold weather characterized by significant temperature decrease that remains below certain thresholds for at least two consecutive days during the cold season*". A cold wave is usually linked to an incursion of very cold air that is displaced to lower latitudes, or it is enforced by long radiative cooling under clear sky conditions (WMO 2016).

Cold-related mortality is a public health concern that affects many areas of the world and cannot be ignored. A study by Analitis et al. (2008) on the impact of low temperatures on mortality using data from 1990 to 2000 for 15 European cities revealed increase of the daily amount of deaths from natural causes with 1 °C decrease in temperature. The respective increase for cardiovascular, respiratory, and cerebrovascular deaths was found to be 1.25% (Analitis et al. 2008). In a different aspect of the association of cold weather and its impacts on human health, Hajat et al. (2004) associated low temperatures and an increase in consultations about lower respiratory tract infections made by elderly people (65+ years) over a 10-year period, 1992–2001, for 16 selected locations. Furthermore, a study conducted by Keatinge and Donaldson (1997) linked winter temperatures with mortality resulting from ischemic heart, cerebrovascular, and respiratory disease. In particular, increases in all types of mortality were depicted with 1 °C fall in temperature. Fu et al. (2018) also investigated the mortality attributed to cold ambient temperatures in India using national data for 2001–2013 and proved that medium low temperatures showed higher attributable risk than extremely low.

As regards connection of winter-related mortality and air pollution, several studies have been published. Low temperatures significantly enhanced the acute mortality effects of ozone in Suzhou, China. According to Chen et al. (2013), the connection of ozone and daily mortality in winter was much stronger than during summer, both for total and for cardiovascular mortality. Interestingly, O_3 was more distinctly associated with cardiovascular mortality than total mortality.

Results published by Cheng and Kan (2012) revealed significant association between PM10 and extreme low temperatures, not only for non-accidental mortality but for cause-specific also. On cold days, an increase of 10-μg/m^3 in PM10 corresponded to a 0.40% increase in total mortality, while similar behavior was demonstrated by O_3. As indicated in Peterson et al. (2014), pollutants can be ensnared by inversions related to cold air near the surface and warmer air in higher altitude. Therefore, it is evident that low temperatures are directly linked to increased air pollution and compromised air quality, consequently.

In a wider context, cold spells can induce severe impact on several aspects of environment and life. In a research conducted by Morignat et al. (2018) it was found that prolonged exposure to cold temperatures showed a 23% increase in female cattle mortality, and the mortality risk increased with the duration and the severity of the exposure.

Añel et al. (2017) investigated a possible connection between cold waves and power production and consumption. The energy network is exceptionally stressed and power blackouts are very likely to happen during winter; the accumulation of snow, freezing rain, and ice can cause significant damage to airlines, control towers, and power transmission lines.

In the cold wave that stroke the United States and Canada in January 1998 (Chang et al. 2007), 120,000 km of power lines were destroyed and four million people experienced days with no heating and electricity. 100,000 inhabitants were forced to evacuate their residences, several were injured, and 23 lost their lives. Bridges, highways, railroads, train services, and subway systems were completely destroyed. People living in the affected areas had to boil water for up to 48 h as the water supply was damaged; dairy farms, maple syrup producers, and millions of trees were ruined. The total economic cost reached US$1 billion in the United States and US$1.5 billion in Canada (Jendrizky 1998).

Future projections of cold waves show a negative trend. For example, in Europe, current cold extremes tend to gradually disappear. As a consequence of the diminishing occurrence of moderate cold waves in many parts of the world, the number of attributed fatalities will decline strongly. Feyen et al. (2020) demonstrated that European population exposed annually to extreme cold is expected to lower from ten million in the baseline scenario to five million at 1.5 °C global warming scenario. Similarly, Forzieri et al. (2017) showed that European people exposed to cold waves and deaths because of cold waves will rapidly decrease from the reference period to 2011–2040 (−6% and −16% respectively), 2041–2070 (−64% and −76% respectively), and 2071–2100 (−97% and −97% respectively).

7.4 Case Study of Heat Wave

Air quality is directly affected by elevated temperatures during a heat wave period, as discussed in detail in Sect. 7.2.4.2. The current study presents a characteristic case for the city of Thessaloniki, Greece, located in South-East (SE) Mediterranean. In the summer of 2007, the SE Mediterranean and Balkans were affected by three heat waves, during which record-breaking temperatures were recorded in several weather stations in Greece (Founda and Giannakopoulos 2009). The present case study focuses on the July 2007 event, investigating the relationship between air temperature and pollutants. The thermal comfort conditions during the examined episode are also assessed using an appropriate index.

The study area is the city of Thessaloniki in northern Greece, the second largest city of the country accommodating 800,000 inhabitants approximately. It is built along the north-east coast of the Thermaikos Gulf and as a result, its climate is

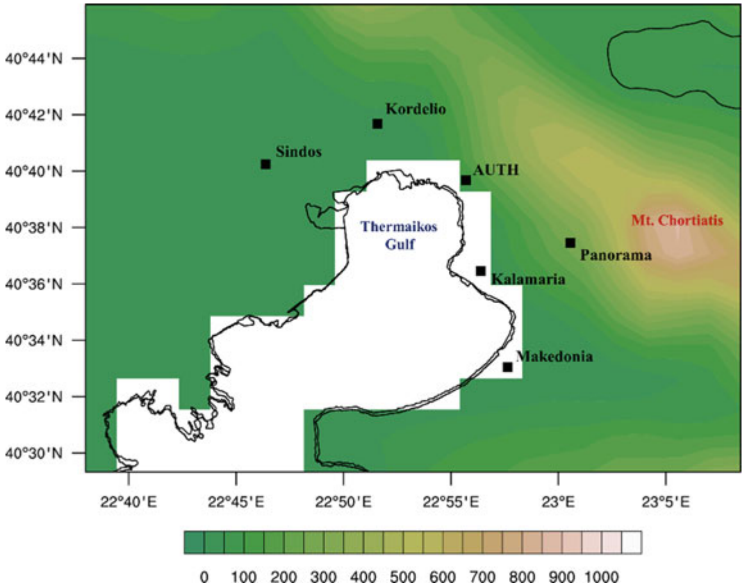

Fig. 7.4 Topography of Thessaloniki with the locations of the weather stations and identification of the main geomorphological features. (Adopted from Giannaros 2018)

directly affected by the sea. The flat area of the city in the West is dominated by the industrial zone of Sindos, whereas Hortiatis Mountain (1200 m) is located in the East. Thessaloniki's climate can be described as Mediterranean with hot and dry summers and mild and wet winters.

The city of Thessaloniki was affected by a severe HW from July 22 to July 25, 2007, according to Giannaros et al. (2018). The approach he followed for identifying this heat wave was based on the extreme temperature index, TX90p, provided by IPCC (Hartmann et al. 2013). The observational data for the study period were collected from five ground-based weather stations (Fig. 7.4) operated by the Region of Central Macedonia (RCM). In particular, time series of air temperature and relative humidity, wind speed and direction, and pollutants (O_3, NO_2, PM_{10} according to availability) were obtained for the period 20–28 July 2007.

Based on the temperature and humidity measurements, Thom's Discomfort Index (DI; Thom 1959) was computed in order to assess the thermal stress during the examined heat wave. Table 7.1 presents the DI classes and the corresponding effects on human thermal sensation.

Figure 7.5 shows the temporal evolution of temperature, air pollutants, and DI from July 20 00Z to July 28 00Z. A gradient rise of temperature is evident from July 22 (the starting day of the HW), while a significant decrease in temperature is observed after the 26th of July. The maximum daily values of temperatures were recorded on July 24 and 25, exceeding and reaching up to 42 °C in the highly (AUTH, Kordelio, Kalamaria; Fig. 7.5a–c) and semi-urbanized (Panorama;

Table 7.1 DI classes and the corresponding thermal discomfort conditions

Class number	DI (°C)	Discomfort conditions
1	$\mathrm{DI} < 21$	No discomfort
2	$21 \leq \mathrm{DI} < 24$	Less than half of the population feels discomfort
3	$24 \leq \mathrm{DI} < 27$	More than half of the population feels discomfort
4	$27 \leq \mathrm{DI} < 29$	Most of the population feels discomfort
5	$29 \leq \mathrm{DI} < 32$	Everyone feels severe stress
6	≥ 32	State of medical emergency

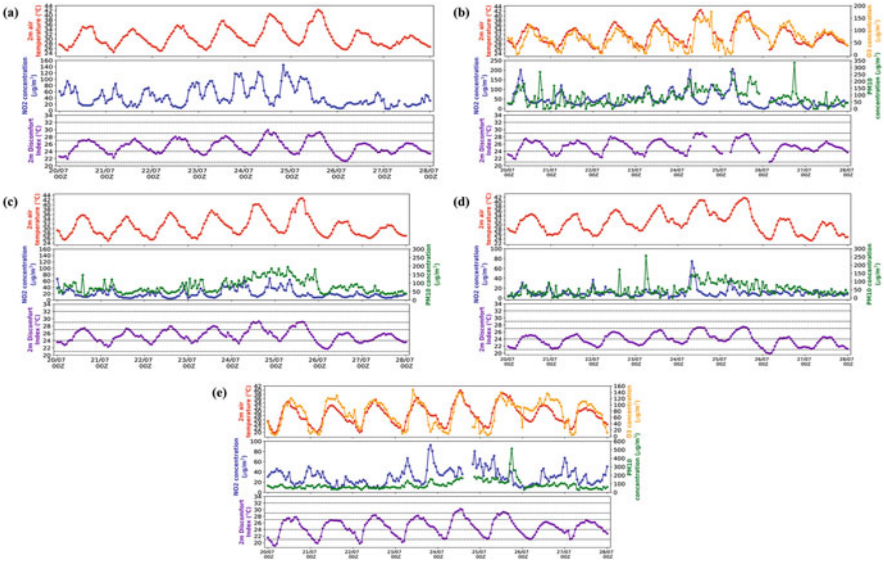

Fig. 7.5 Temporal evolution of air temperature, pollutants, and DI from July 20 00Z to July 28 00Z over (**a**) AUTH, (**b**) Kordelio, (**c**) Kalamaria, (**d**) Panorama, and (**e**) Sindos in Thessaloniki, Greece

Fig. 7.5d) areas of the city, respectively. The excess warmth during these days led to maximum DI values that ranged from 29 to 32 °C in AUTH, Kordelio, and Kalamaria (Fig. 7.5a–c). Thus, all population in the urban core of the city experienced severe heat stress. In Panorama (Fig. 7.5d), DI was also increased in the course of the HW, maintaining, however, its levels below 29 °C due to the low relative humidity values in the area (not shown). Interestingly, although the lowest daily maximum temperature among the examined sites was recorded in the semi-rural station of Sindos, the highest DI maximum value was observed in this location (Fig. 7.5e). This could be attributed to the fact that Sindos area is frequently exposed to high relative humidity values. Especially during the examined episode, the analysis of the wind field in Sindos (not shown) demonstrated south winds from the sea, which were amplified by 2–3 m/s in the afternoon hours, thus, possibly carrying high levels of humidity that pushed DI values higher than other areas.

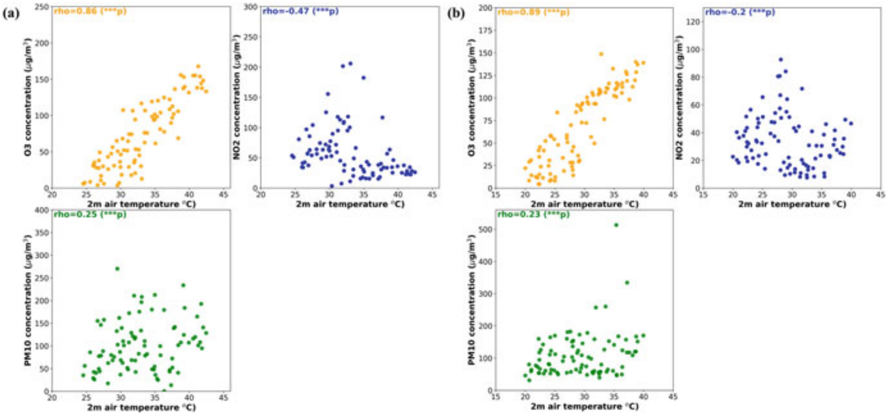

Fig. 7.6 Air temperature against O_3, NO_2, and PM10 concentration over Kordelio (**a**) and Sindos (**b**) during the examined HW episode. Rho values indicate the Spearman correlation coefficient with statistical significance (*p* value) being symbolized as ***p (<0.001; 99.9% confidence interval)

Nevertheless, during the night hours, DI values in Sindos decrease significantly (≤24 °C) revealing that the local population experiences a vital heat relief, in contrast to the urban residents, especially in AUTH and Kordelio. This fact highlights the importance of the UHI effect and its role in deteriorating the human thermal comfort conditions.

Concerning air quality, higher concentration of NO_2 is evident in the urban sites (AUTh, Kordelio; Fig. 7.5a, b) due to emissions from traffic congestion, especially in the morning rush hours. The highest values of PM_{10} are also observed in areas with enhanced human activities, including the city's urban core (Kordelio, Kalamaria; Fig. 7.5b, c) and suburbs (Panorama; Fig. 7.5d). O_3 concentrations follow the temperature's daily cycle in both urban (Kordelio; Fig. 7.5b) and semi-rural (Sindos; Fig. 7.5e) areas of the city, with maximum O_3 coinciding with the peaks in the temperature, as O_3 formation is favored by heat and sunlight. The two variables are strongly correlated, as the values (0.86 and 0.89; statistically significant at the 99.9% confidence interval) of the nonparametric Spearman coefficient (rho) indicate in Kordelio and Sindos (Fig. 7.6). PM10 concentrations also increase as the temperature elevates during the examined HW period. This is due to the formation of secondary aerosols induced by the warmer weather conditions. Figure 7.6 demonstrates a weak positive correlation (statistically significant at the 99.9% confidence interval) between PM10 and air temperature, with Spearman coefficient varying from 0.23 (Sindos; Fig. 7.6b) to 0.25 (Kordelio; Fig. 7.6a). On the contrary, the Spearman coefficient values when NO_2 and temperature are examined reveal a negative correlation (statistically significant at the 99.9% confidence interval) between the two variables, which is more profound in the urban site (Kordelio; rho $= -0.47$; Fig. 7.6a). This finding indicates that NO_2 promotes the formation of O_3 during the mid-day, when the highest temperatures during the HW were observed.

The above outcomes are in satisfactory agreement with previous studies (e.g., Theoharatos et al. 2010; Kalisa et al. 2018), which reported that high levels of pollutants were much more prevalent during prolonged heat waves. Such findings are important to the establishment of long-term prevention measures in HW emergency plans and urban planning, considering the human thermal comfort and the synergistic impacts of extreme heat conditions and poor air quality.

7.5 Conclusions

Heat waves pose a major threat to people's well-being. Their constantly increasing frequency and duration due to climate change and their synergy with air pollution and UHI effect cause adverse impacts on environment and human health. Urban populations in areas most in danger, as in the South-East Mediterranean, are already experiencing the unpleasant consequences concerning thermal comfort conditions and the overall view of their everyday performance. Heat-related mortality is under thorough investigation in recent years in order to define ways to understand and analyze the effect, as the scientific community worldwide is eager to assist policy-making authorities who wish to protect and provide guidelines to the general public and vulnerable groups. Heat-health warning systems are a valuable tool for this endeavor. Further effort should be continuously put to enrich and sophisticate HHWS through high-quality and accurate scientific services and products.

Cold waves can also pose threat to human health and environment as low temperatures are related to increased mortality and damage in infrastructure. Nevertheless, as global temperature is rising, number and duration of cold spells are expecting to decrease even in the colder parts of the planet. Therefore, with no intention to underestimate their importance, attention has been moved to the investigation of heat wave events and their impact worldwide. Extended research and collaboration with key policy-making entities is essential for the provision of suitable guidelines, advisory, and overall protection of urban populations and vulnerable groups of citizens.

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Intense Biomass Burning Over Northern India and Its Impact on Air Quality, Chemistry and Climate

8

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and Chandrima Chakrabarty

Abstract

The provinces of Punjab, Haryana and western Uttar Pradesh in northwest Indo-Gangetic Plain (IGP) produce two-thirds of India's food grains, and are widely known as the "breadbasket" of India. This "breadbasket" accounts for roughly a quarter of the total annual fire events observed over India, and hence is a regional hotspot for biomass burning. The enormous amount of aerosols and trace gases, emitted largely from extensive post-harvest crop residue burning in autumn (October–November) and spring (April–May), along with events of wildfires, and domestic consumption of biofuels, unfurls its influence along the length of the IGP under the prevailing meteorological conditions. The elevated levels of pollutants, primarily generated from intense post-monsoon biomass burning over northwest IGP, under the influence of unfavourable meteorological conditions, contribute significantly to the episodes of extreme pollution over the regions downwind of northwest IGP. The downwind region of intense biomass burning experiences high values of particulate matter, including black carbon, organic carbon, ozone, volatile organic compounds and other ozone precursors, resulting in an intense photochemistry and an adverse air quality. Furthermore, excessive smoke aerosols in the atmosphere exert a strong surface cooling, but an overall atmospheric warming, thereby changing the regional radiative balance.

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Keywords

Biomass burning · North India · Extreme events · Aerosols · Trace gases · Haze · Radiative forcing · Air pollution · Air quality · Tropospheric chemistry

8.1 Introduction

Biomass burning is defined as combustion of vegetation, either living or dead, and it can be both natural and anthropogenic (Levine 1991; Bond et al. 2004). While wildfires are the natural sources of biomass burning, the anthropogenic or human-induced sources include burning of crop residue or grassland for the purpose of changes in land use. Combustion of biomass is one of the key sources of atmospheric trace gases and aerosols (Crutzen and Andreae 1990; Saxena et al. 2021). Across the globe, the events of biomass burning have demonstrated significant impacts on the environment, land cover, atmospheric chemistry, human health, radiative forcing and climate (Saxena and Srivastava 2020). Figure 8.1 gives an overview of the sources and impacts of biomass burning emissions.

A bulk of the Earth's biomass burning comes from the tropics—primarily the South American and Southeast Asian forests. It is mainly governed by various factors such as lightning, topography and weather. For instance, the tropical phenomenon of El Niño–Southern Oscillation (ENSO) is largely responsible for

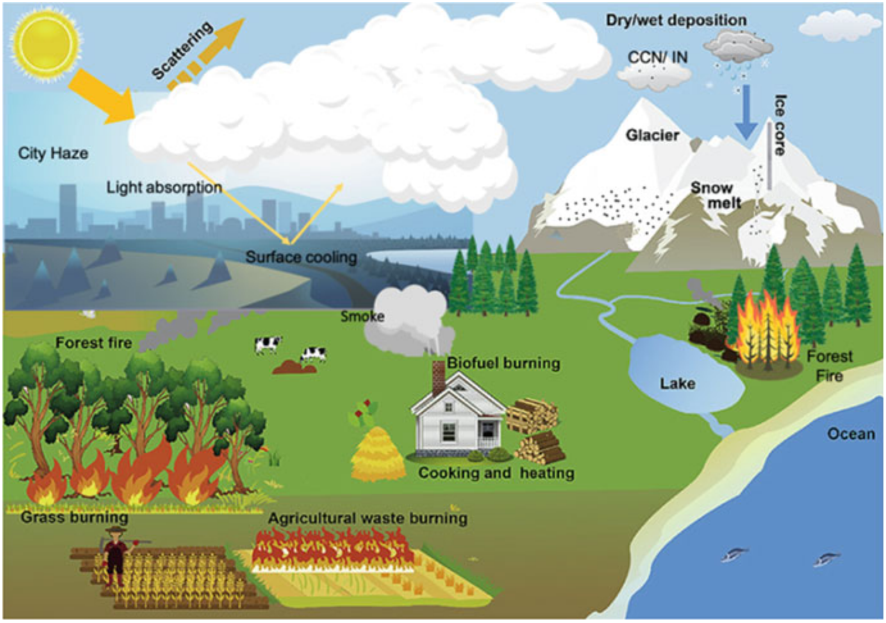

Fig. 8.1 An overview of the sources and impacts of biomass burning emissions (modified from Wan et al. 2019)

imposing drought conditions over Southeast Asia and India (Siegert et al. 2001). Droughts enhance the dry conditions over a forested/vegetated land, making it conducive for the occurrence of fire. Natural fires triggered by lightning also contribute significantly to the total biomass burning (Andreae 1991). Besides natural factors, a major chunk of biomass burning in the tropics comes from changes in land use and clearing of land which are both human induced. Burning of agricultural waste to clear land for the next crop is a part of the agricultural practices in India, and in many other countries in South and Southeast Asia (Vadrevu et al. 2019). In the Eastern Ghats and north-eastern India, agricultural practice like slash-and-burn (jhum cultivation) is very common, which leads to fires and ignition of biomass (Prasad et al. 2002; Prasad et al. 2003).

In the recent past, there have been several instances where anthropogenic interventions have accelerated the pace of biomass burning emissions in the atmosphere. For instance, the episode of out-of-control biomass burning in Indonesia in 1997, for agricultural purposes, which continued for 5 months, posed an overwhelming environmental threat for itself as well as its neighbouring countries (Brauer and Hisham-Hashim 1998; Fang et al. 1999). Climate change-induced extreme hot and dry conditions led to unprecedented fires over millions of hectares of forest in Australia in Balwinder-Singh et al. 2019 (Boer et al. 2020; Yu et al. 2020; Jain et al. 2021). Also, anthropogenic climate change has been held responsible for an increase in intense forest fire events in western North America (Williams et al. 2019; Goss et al. 2020). These processes of biomass burning release an enormous amount of particulate matter (PM) in the atmosphere, including smoke particles, resulting in deterioration of air quality, along with land-cover changes worldwide (Sonwani and Saxena 2021). In north-western Brazil, an increase in premature deaths due to extreme biomass burning was reported owing to rise in fire events from 2016 to Balwinder-Singh et al. 2019 in the Amazon rainforest (Nawaz and Henze 2020). Apart from that, aerosols emitted from biomass burning have also decreased the amount of sunlight touching the Earth's surface, causing a positive radiative forcing of $+0.04 \pm 0.07$ W m^{-2} globally (Forster et al. 2007). These changes are alarming since it directly impacts Earth's temperature and climate, which is a matter of major global concern (Seiler and Crutzen 1980; Crutzen and Andreae 1990; Levine et al. 1995).

South Asian countries of India and China witness severe seasonal episodes of biomass burning like wildfires as well as fires resulting from agricultural crop burning and forest conversion during the boreal spring (Gautam et al. 2013; Shi et al. 2014; Chen et al. 2017). Recently in 2017, it was reported that India generated 488 Mt. of total crop residue, of which ~24% was burnt in agricultural fields. This led to release of an enormous amount of particulate matter having a size of ≤ 2.5 μm (PM2.5; 824 Gg), elemental carbon (EC; 58 Gg) and organic carbon (OC; 239 Gg). In addition to this, 211 Tg of greenhouse gases equivalent to carbon dioxide (CO_2) was also released into the atmosphere (Ravindra et al. 2019c).

The Indo-Gangetic Plain (IGP) covers a vast geographical area in South Asia, and covers 20% of the geographical area in India. This region is a very important agroecological zone, producing 42% of the total food grains and holding almost

40% of India's total population (Tripathi et al. 2007). In terms of aerosol-induced health impacts, this region has regularly recorded poor air quality resulting from biomass burning, and is expected to be one of the most vulnerable areas (Gautam et al. 2007; Apte et al. 2015; Bikkina et al. 2019; Sonwani et al. 2021). A large part of this problem is attributed to open crop burning in the agriculture-dominated regions of Punjab and Haryana, in northwest India (Singh et al. 2014). India's capital city, Delhi, sits in the northern IGP, and is one of the world's most densely populated cities. It experiences severe winters and lies close to the states of Punjab and Haryana. The wind pattern over these regions associated with smoke generated from biomass burning extensively affects the air quality and climate (Chen et al. 2017). Severe worsening of air quality was witnessed in the Indian capital city of Delhi in 2016 and 2017, due to emissions from excessive crop burning events in North Indian states of Punjab and Haryana, together with emissions from celebration of festivals under unfavourable meteorological conditions (Singh et al. 2014; Chauhan and Singh 2017; Kanawade et al. 2020).

In this chapter, we therefore review the status of excessive biomass burning emissions over the IGP, and their impacts. Section 8.2 describes the sources of biomass burning with depiction of intense biomass burning. Section 8.3 illustrates extreme biomass burning episodes, Sect. 8.4 provides a description of the elevated levels of trace gases and aerosols generated as a result of biomass burning, followed by their impacts in Sects. 8.5, and summary in Sect. 8.6.

8.2 Major Sources of Intense Biomass Burning in Northern India

India is one of the well-known agricultural nations in the world. It accounts for 18% of the total biomass burning in Asia (Hao and Liu 1994; Streets et al. 2003; Taylor 2010). Nearly 12 million hectares of land in the IGP region is harvested for wheat and rice, with a common practice of rotation of rice and wheat crops (Badarinath et al. 2009a). The harvesting techniques generate a large volume of agricultural residues such as rice and wheat straws, in the field, which needs to be eliminated before the next crop planting. Open burning is one of the most convenient and inexpensive ways to eliminate the agricultural waste; therefore, a quarter of the generated agricultural crop residue is burnt in open fields in India every year (Ravindra et al. 2019a, b, c). The major sources of biomass burning can also be seen in Fig. 8.1.

Wildfires, caused by both natural and anthropogenic activities, are another major source of biomass burning in North India. Forest fire burns 32–61 $\mathrm{Tg \cdot year^{-1}}$ annually, while agricultural fire over India burns 116–289 $\mathrm{Tg \cdot year^{-1}}$ (Venkataraman et al. 2006). Approximately 61% of the forest area in India, which is predominantly covered by deciduous trees, is vulnerable to fires (FSI 2015). Owing to activities such as shifting cultivation practices, controlled burning, deforestation and firewood burning, these forest fires are mainly anthropogenic in origin (Bahuguna and Upadhay 2002; Chand et al. 2007). However, the spatial coverage and damage due to these forest fires are also determined by local and regional weather patterns (air temperature, wind speed and prolonged droughts).

Unlike wildfires and crop residue burning, which are largely a seasonal phenomenon, domestic biomass burning for energy production constitutes a continuous input of trace compounds into the environment. Use of biofuel such as fuelwood, charcoal and non-woody biofuels like dung cakes, primarily for cooking, heating or lighting especially in the rural areas, contributes to emissions of particulate matter and trace gases (Venkataraman et al. 2010; Pandey and Tyagi 2012; Bhattacharya and Nanda 1992; Aggarwal et al. 2009; Metz 1991; Singh et al. 2010). However, domestic biomass burning events are very scattered, which is one of the main reasons for sparse availability of its information.

8.3 Extreme Biomass Burning

Figure 8.2a illustrates the logarithm of annual fire counts averaged over 17 years (2002–2018) over India based on MODIS (MODerate resolution Imaging Spectrometer) fire detection. MODIS on board Terra and Aqua satellites is one of the instruments popularly used for fire counts data which has a spatial resolution of 1 × 1 km^2. Fire event is a form of thermal anomaly and is detected from both brightness temperature at 4 μm and difference between brightness temperatures at 4 and 11 μm (Giglio et al. 2003). The fire pixels having detection confidence >30% (confidence class: nominal and high) are used (Jethva et al. 2019) here to generate fire count map. It is observed that nearly 200–500 fire events occur every year over most of the grids (0.25 × 0.25°) in northwest India (i.e. mainly states of Haryana, Punjab and some parts of western Uttar Pradesh). The total number of counts over this small region (marked by a magenta box in Fig. 8.2a) accounts for 26% of the

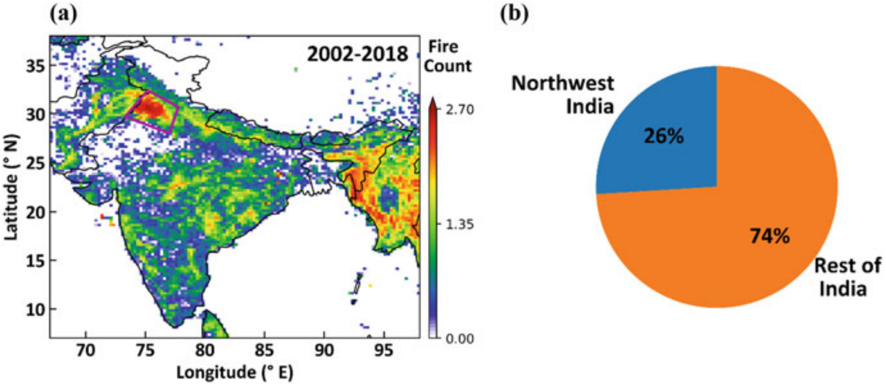

Fig. 8.2 (**a**) Annually accumulated fire counts (in log scale) over India gridded at 0.25° × °0.25°, averaged during 2002–2018 based on MODIS fire event detection. (**b**) Pie chart represents relative contribution of fire counts from northwest India (i.e. mainly states of Haryana, Punjab and some parts of western Uttar Pradesh, marked by a magenta box)

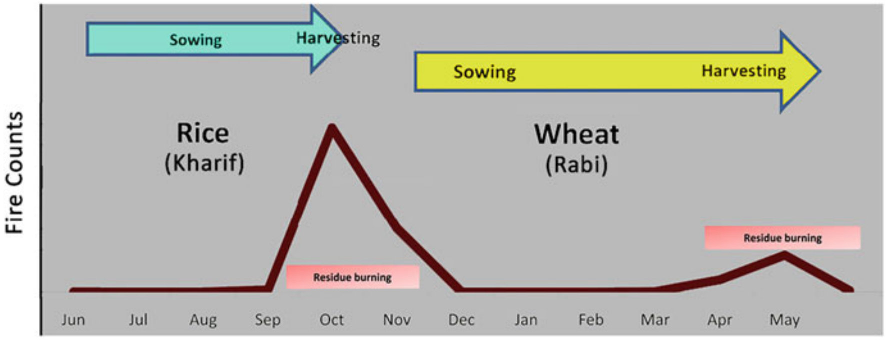

Fig. 8.3 Schematic of seasonal pattern of fire counts over northwest along with depiction of agricultural practice (modified from Vadrevu et al. 2011)

total fire counts over India (pie chart in Fig. 8.2b). Hence, biomass burning over northwest India is more extensive (Sharma et al. 2011; Kaskaoutis et al. 2014) as compared to the rest of India, and therefore represents the regional hotspot over northern India. It should be noted that since fire counts are obtained from the counts of pixels where fires are detected, the total number of counts over a grid or a region depends upon pixel resolution of the observing satellite.

In northwest India, the provinces of Haryana, Punjab and western Uttar Pradesh produce two-thirds of the food grains of India, and are commonly referred to as the “breadbasket” of India (Jethva et al. 2019). Wheat and rice are the two principal crops grown over this region. The sowing time of Kharif crop (rice) is July–August, while that of Rabi crop (wheat) is November–December. The residue generated from rice paddy is burned in post-monsoon (autumn) months of October and November, whereas the residue from wheat crop is burned in the pre-monsoon (spring) months of April and May (Vadrevu et al. 2011; Singh and Kaskaoutis 2014). The two agricultural seasons, and the associated crop residue burning over this region, are pictorially shown in Fig. 8.3 (modified from Vadrevu et al. 2011). The two prominent peaks in fire counts, indicating extreme biomass burning, are observed during both autumn and spring, where autumn peak is significantly higher than that of spring.

Crop residue burning events during spring and autumn for the years 2002 and 2018 are shown in Fig. 8.4. The autumn peak in fire count is clearly more intense than the springtime peak, during both 2002 and 2018. The seasonally accumulated MODIS-detected fire counts over 0.25° × 0.25° grids are over 100 during spring, while it reaches values as high as 300 during autumn over northwest India. The crop residue burning during autumn of 2018 is also much higher than that of 2002. This is due to an increase in rice production over the years, with a linear trend of 0.18 million tonnes per year and an associated increase in crop residue burning, leading to a statistically significant trend of 500 fire counts per year (Jethva et al. 2019; Vadrevu et al. 2019). Singh et al. (2020b) have estimated 29.9 Mt. of crop residue burned in Punjab and Haryana during 2017–2018, which resulted in an emission of

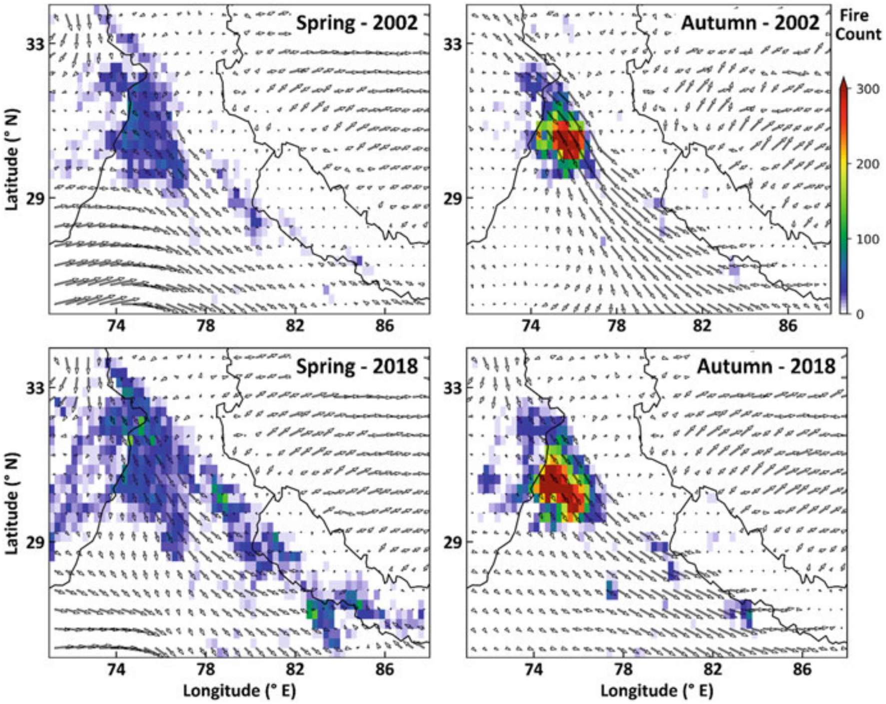

Fig. 8.4 Seasonally accumulated fire counts gridded at 0.25° × 0.25° for spring (March–May) and autumn (October–November) during 2002 and 2018 along with synoptic winds (black arrows) at 900 hPa

194.1, 235.8, 12.3, 63.4 and 0.11 Gg of PM2.5, PM10, EC, OC and polycyclic aromatic hydrocarbon (PAH), respectively. High fire counts over north as well as northwest India have also been reported from emission inventories like EDGAR (Emission Database for Global Atmospheric Research) and GFED (Global Fire Emissions Database) during the post-monsoon season (Sarkar et al. 2018). Also, a shift towards mechanized and advanced techniques of cultivation systems has contributed significantly to the increase in crop residue (Sharma and Prasad 2008; Kumar et al. 2015; Manjunatha et al. 2015). While cereal straws, woody stalks and sugarcane leaves are typically burned over western IGP (Venkataraman et al. 2006), crop residues are commonly used as fodder and domestic fuel in eastern IGP, which explains lower emissions from eastern IGP (Vadrevu and Lasko 2015). The mean synoptic winds (from the fifth ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis—ERA5) over North India are north-westerly during both the seasons with small differences (Fig. 8.4). Burning of crop residue contributes to enormous amount of trace gas emissions and aerosol loading over the IGP (Badarinath et al. 2006, 2009a; Ram et al. 2012; Jain et al. 2014; Kaskaoutis et al. 2014; Vijayakumar et al. 2016; Liu et al. 2018). The pollutants emitted from open crop residue burning can travel thousands of kilometres downwind, spanning the full IGP area from west to east (Kaskaoutis et al. 2014), as can be seen from the wind direction over the IGP (Fig. 8.4). The local emissions due to burning, coupled with meteorological conditions, worsen the air quality across the entire Indo-Gangetic basin (Ram et al. 2016).

Wildfires also contribute to the high aerosol loading over the IGP during both spring and autumn. The dominant fire seasons are the pre-monsoon and post-monsoon months, which account for more than 45% and 24% of total annual fire counts, respectively. The North Indian state of Uttarakhand has an extended forest area and typically exhibits forest fire activity during February to June, with a spike in May and June (FSI 2015). Widespread forest fires near the foothills of the Himalayas have impacts on severe air quality and climate, since it releases a substantial amount of greenhouse gases and pollutants (Crutzen and Andreae 1990; Andreae and Merlet 2001; Duncan et al. 2003). Episodes of violent forest fires in northern India have been reported in 2016 and 2018 (Jha et al. 2016; Srivastava and Kumar 2020; Yarragunta et al. 2020). Such events have been reported to degrade air quality, and also propagate its impact vertically up to a depth of ~6.5 km in the troposphere (Yarragunta et al. 2020).

8.4 Biomass Burning-Induced Elevated Levels of Aerosols and Trace Gases

The amount of trace constituents emitted from biomass burning depends upon the type of biomass, its moisture content and its burning conditions such as ambient temperature, humidity and local wind speed (Seinfeld and Pandis 1998). The incomplete combustion of biomass releases a variety of particulate matter/aerosols such as carbonaceous aerosols, and trace gases such as carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and non-methane hydrocarbons (NMHCs); (Andreae and Merlet 2001; Saxena and Naik 2018). It also releases CO_2 and methane (CH_4), which are the major drivers of the Earth's radiation balance. The trace gases and aerosols modulate the chemistry of the atmosphere that has impacts on air quality, at both local and regional scales. Some of the trace gases are precursors of ozone (O_3), and also aerosols, via the process of gas-to-particle conversion (Saxena et al. 2020). O_3 is an important source of OH radical, which plays a central role in atmospheric chemistry (Seinfeld and Pandis 1998). Interestingly, the influence of the emitted gases is not limited only to the place of biomass burning, but gets transported over longer distances under the influence of the prevailing meteorological conditions. Vertical transport of trace gases due to convection also changes the chemistry and composition of the upper troposphere (Roy et al. 2017; Girach et al. 2020).

Table 8.1 Biomass burning-induced elevated PM2.5 concentrations at a few stations over the IGP during crop residue burning period

Observational sites	PM2.5	Observation period	References
Delhi (28.6° N, 77.2° E)	>200 μg m^{-3} (~3.5 times above NAAQS of daily mean)	October–November, 2012	Bisht et al. (2015)
	~150–250 μg m^{-3} (~4 times above NAAQS of daily mean)	October–November, 2011	Tiwari et al. (2013)
Patiala (30.2° N, 76.3 ° E)	123.1 ± 25.5 μg m^{-3} (~2 times above NAAQS of daily mean)	October–November, of 2007–2009	Agarwal et al. (2012)
Amritsar (27.16° N, 78.08° E)	178.4 ± 83.8 μg m^{-3} (~3 times above NAAQS of daily mean)	October–November, 2016	Ravindra et al. (2019b)
Kanpur (26.5° N, 80.3° E)	189 ± 82 μg m^{-3} (~3 times above NAAQS of daily mean)	October–November, 2008	Ram et al. (2012)
Chandigarh (26° N, 76° E)	191.1 μg m^{-3} (~3.5 times above NAAQS of daily mean)	October–November, 2015	Ravindra et al. (2020)

8.4.1 Particulate Matter (PM)

Biomass burning is one of the chief sources of fine particulate matter, PM2.5. Open biomass burning contributes to 9–13% of ambient PM2.5 as per the estimation made during 1995–2000 (Venkataraman et al. 2006). The cities of Delhi and Chandigarh, located in the northwest IGP, have reported 7–20% and 8% contribution to ambient PM2.5 from biomass combustion, respectively (Chowdhury et al. 2007). Analysis of observations obtained from a number of satellites and ground-based measurements post-2010 revealed increased episodes of crop residue burning in northern and northwestern regions of India. Simultaneously, emissions from active fire events have been reported to increase by 83–106% for Punjab compared to anthropogenic emissions based on the data from GFED4 and Fire Inventory from NCAR (FINN; Singh et al. 2020a).

The National Ambient Air Quality Standards (NAAQS) for annual and 24-h averaged PM2.5 over India are 40 μg m^{-3} and 60 μg m^{-3}, respectively. Table 8.1 accounts for biomass burning-induced elevated levels of PM2.5 observed over a few stations located in the IGP during crop residue burning period, where the PM2.5 concentrations are at least two times above the annual NAAQS. A multi-city campaign across the IGP during post-monsoon period of 2016 revealed an average PM2.5 concentration as high as 148.2 ± 20 μg m^{-3}. Amritsar had the highest average PM2.5 concentration of 178.4 ± 83.8 μg m^{-3}, whereas Chandigarh recorded the lowest PM2.5 concentration of 112.3 ± 6.9 μg m^{-3}. Rohtak and Sonipat recorded PM2.5 concentration values in between these two, 158.4 ± 79.8 and 156.5 ± 105.3 μg m^{-3}, respectively. The daily average values over these locations were several times higher than the standard quality of national air for 24 h (Ravindra et al. 2019b). Recently, Chandigarh reported very adverse PM2.5

levels (191.1 μg m^{-3}), which were 3.5 times higher than the NAAQS for 24 h during October–November 2015 (Ravindra et al. 2020). Increased number of fire counts and PM2.5 concentrations as severe as >100–150 μg m^{-3} were also observed during October–November 2012 over the IGP from MODIS satellite (Kaskaoutis et al. 2014). Over Delhi, the maximum value of PM2.5 on a daily scale is highly variable, and it depends on the transportation of air mass via meteorological parameters from source to sink (Beig et al. 2020). On events of typical air pollution, fire emissions contributed as much as 50–75% (80–120 μg m^{-3}) to PM2.5 concentration in Delhi, thereby emphasizing the importance of both external transport and local emissions to PM2.5 pollution in Delhi (Kulkarni et al. 2020). During post-monsoon season, the impact of biomass burning on PM2.5 is higher over Delhi, as compared to fossil fuel burning (Tiwari et al. 2013). A recent study from both model and observations estimated that 7–78% of Delhi's maximum observed PM2.5 changes can be related to crop residue burning in the upwind states (Cusworth et al. 2018). Paddy crop burning in the post-monsoon season of 2012, along with long-range transport of smoke, elevated the aerosol loading over the length of IGP.

Episodes of extreme pollution over the region downwind of northwest IGP including Delhi result from extensive crop residue burning emissions, besides local emissions, under unfavourable meteorological conditions, such as shallow boundary layer and low ventilation coefficient (Ojha et al. 2020; Sembhi et al. 2020). In line with this, stagnant atmospheric conditions led to an extreme event of pollution over Delhi during 1–7 November 2016, with PM2.5 concentrations shooting up to 1294.5 μg m^{-3} (Kanawade et al. 2020). PM2.5 concentration over Delhi has earlier showed a high annual mean of 122.3 ± 90.7 μg m^{-3} in 2011, with values ranging from ~150 μg m^{-3} to as severe as ~250 μg m^{-3} during post-monsoon of 2011 (Tiwari et al. 2013). Agricultural burning during 2012 reported critically high PM2.5 concentration with values >200 μg m^{-3} over Delhi. Severely high values of 500 μg m^{-3} (>10 times NAAQS) were also reported on certain days (Bisht et al. 2015). The mean $PM_{2.5}$ concentration over Delhi during the post-monsoon of 2016 was 571.9 μg m^{-3}, which was ~38–60% higher than that of the previous years (Kanawade et al. 2020). The regional chemistry-transport simulations estimated ~20–60% of PM2.5 over western IGP (74–82°E) due to biomass burning over the region during autumn (Ojha et al. 2020).

8.4.2 Carbonaceous Aerosols

Incomplete combustion of biomass results in emission of carbonaceous aerosols, which are short-lived (with a lifetime of maximum 2 weeks; Bond et al. 2007, 2013a, b). It constitutes a prominent fraction of PM2.5, with key components being OC and black carbon (BC), and can be transported over long distances along with the wind (Lelieveld et al. 2001). EC is similar to BC but is measured by thermal technique, in contrast to light absorption technique for BC measurement (Andreae and Gelencsér 2006). After greenhouse gases, BC is the dominant light-absorbing species and the second major contributor to global warming (Jacobson 2002; Husain

Table 8.2 Biomass burning-induced high concentrations of BC aerosols during post-monsoon over a few stations located in the IGP

Observational sites	Post-monsoon BC concentration	Observation period	References
Patiala (30.2° N, 76.3 ° E)	>20 μg m^{-3}	October–November of 2008	Kharol et al. (2012)
	10–15 μg m^{-3}	October–November of 2009–2011	Shaik et al. (2019)
Delhi (28.6° N, 77.2° E)	~18–20 μg m^{-3}	October–November of 2012	Bisht et al. (2015)
Kanpur (26.5° N, 80.3° E)	~10–12 μg m^{-3}	October–November of 2007–2011	Kanawade et al. (2014)
Delhi (28.6° N, 77.2° E)	13.7 μg m^{-3}	October–November of 2006	Bano et al. (2011)
Gorakhpur (26.75° N, 83.38° E)	18 ± 15 μg m^{-3}	October–November of 2013–2015	Vaishya et al. (2017)

et al. 2007). It contributes to 25–50% of CO_2 warming globally (Forster et al. 2007; Ramanathan and Carmichael 2008; Jacobson 2010). On the other hand, OC illustrates scattering effect, and leads to negative radiative forcing (Liousse et al. 1996). The composition of aerosols over India has a large portion of BC (Mitra 1999; Dickerson et al. 2002; Guazzotti et al. 2003). A recent study reported that BC constituted nearly 6% of the total PM2.5 mass concentration (Tiwari et al. 2013). In India, a large population of both rural and urban households use solid biofuels (Venkataraman et al. 2010) which leads to emission of a large amount of BC. Emission from residential biofuels like wood, crop residue and dung is another source of atmospheric BC (Venkataraman et al. 2005).

Biomass burning over India contributes to approximately 33% of the total BC concentration in the atmosphere (Venkataraman et al. 2006). Seasonal influxes of crop residue from Punjab and Haryana also contribute significantly to BC loading (Tiwari et al. 2009, 2015; Srivastava et al. 2012; Bisht et al. 2015; Sharma et al. 2018). During post-monsoon or early winter, biomass sources contribute ~28% to the aerosol loading over the central IGP, whereas during pre-monsoon or monsoon, the contribution from biomass sources lowers to ~16% (Vaishya et al. 2017). The BC concentration reaches high values during October–November (emission from bio- and fossil fuel combustion), while it remains low during the months of April–May over the IGP (Bano et al. 2011; Kanawade et al. 2014; Singh et al. 2014; Prabhu et al. 2020). Table 8.2 accounts for biomass burning-induced elevated BC concentrations observed during post-monsoon over a few stations located in the northwest/central IGP. The northwest IGP station of Patiala reported higher concentration of BC ranging between 7 and 11 μg m^{-3} during post-monsoon of 2010–2012 than that during reported pre-monsoon/monsoon. This is significantly contributed by the emissions from post-monsoon agricultural biomass burning (Sharma et al. 2017). During 2009–2011, high concentrations of BC over Patiala during post-monsoon (10–15 μg m^{-3}) were observed, which also indicated the influence of crop residue burning practices (Shaik et al. 2019). Moreover, Patiala also reported extremely high values of BC concentration during post-monsoon of 2008 owing to crop residue burning, where the BC concentration values were above 7–20 μg m^{-3} (Kharol et al. 2012; Sharma et al. 2012). A recent study during 2013–2016 revealed that post-monsoon BC values are higher (~10 μg m^{-3}) as compared to the other seasons (~2–6 μg m^{-3}) over Patiala, which is attributed to biomass burning (Bansal et al. 2019). Monthly variation of BC over Gorakhpur during 2013–2015, in central IGP, showed a post-monsoon high and a monsoon low (Vaishya et al. 2017). Post-monsoon dominance of biomass burning was also observed over Kanpur during 2007–2011 (Kanawade et al. 2014). The elevated levels of BC were also in line with satellite-derived aerosol optical depth (AOD; Sharma et al. 2012).

The densely populated city of Delhi, in the northwest IGP, experiences almost a quarter (~22%) of its BC from biomass burning (Bisht et al. 2016). It was reported that large-scale post-harvest crop residue in nearby areas contributes to high loading of BC over Delhi during winter and autumn (Bikkina et al. 2019). While mean BC concentrations were 6.3 and 4.9 μg m^{-3} during summer and monsoon, respectively, over Delhi, post-monsoon season reported a very high value of 17.4 μg m^{-3} (Sharma et al. 2018). Daily mass concentration of BC over Delhi varied from as low as 0.9 to as high as ~12 μg m^{-3} during October–November 2011 (Tiwari et al. 2013). Extreme biomass burning in the post-monsoon season of 2013 also resulted in high concentration of BC over Delhi (Liu et al. 2018). Agricultural burning during 2012 reported critically high BC concentration with values reaching ~20 μg m^{-3} over Delhi (Bisht et al. 2015). Unlike open biomass burning during spring/autumn over northwest India, the wintertime small-scale biomass/biofuel burning contributed ~22% over Delhi during 2015–2016 (Bisht et al. 2016). It should be mentioned here that meteorological parameters (e.g. shallow boundary layer, stagnant conditions, synoptic winds) play a key role in the variability of atmospheric BC concentration (Safai et al. 2008; Tiwari et al. 2013). A study by Tyagi et al. (2020) showed that 2016 reported high values of BC as compared to 2017, which was partially due to variability in meteorological parameters.

OC is another key component of carbonaceous aerosols which constitutes a significant proportion of the PM2.5 mass. Recently, Andreae (2019) has compiled the emission factors, and provided a global estimation of the amount of trace gases and aerosols emitted from biomass burning. Aerosols generated from biomass burning include higher amount of OC, BC or EC and potassium (K), and these species and/or their ratios with other aerosol components are indicators of biomass burning activity (Andreae 1983). The OC/EC ratios are often used to find out the relative dominance of biomass versus fossil fuel burning. While OC/EC less than 2 indicates the dominance of fossil fuel burning emission, values greater than 5 suggest the dominance of biomass burning (Seinfeld and Pandis 1998; Bisht et al. 2016). Over the IGP, urban sites show higher OC/EC ratios ranging between 2.4 and 14.5 (mean $= 7.8 \pm 2.4$), which is largely indicative of the contribution from biomass burning sources (wood-fuel and agriculture waste), whereas rural sites show a lower OC/EC ratio (range: 2.1–4.0, mean $= 3.1 \pm 0.6$) indicating dominant contribution from coal-fired industries (Ram and Sarin 2010). Potassium being higher in biomass, K/EC ratio was seen to be higher (average ratio ~0.80) during autumn over Patiala in the downwind of crop residue burning (Rastogi et al. 2016). In line with higher K/EC ratios, the higher OC/EC ratio (7.5 ± 1.3) observed during autumn at a high-altitude site, Nainital, over central Himalayas, indicates the contribution from both organic aerosols and transported aerosols which were emitted from western IGP biomass burning (Ram et al. 2010a).

The high OC and EC levels were observed during the winter season and low during the monsoon season (Singh et al. 2016). A year-long study of carbonaceous aerosols studied at an urban and rural site in the IGP showed average OC and EC concentrations of 25.6 and 13.7 μg m^{-3}, respectively, at the urban site, while at the rural site, OC and EC concentrations were 29.6 and 12.8 μg m^{-3}, respectively. But exceptionally high values of OC and EC observed during November were indicative of the impact of post-harvest large-scale open biomass burning. The concentration of OC observed over Delhi in 2011–2012 varied between 14.1 ± 4.3 μg m^{-3} and values as adverse as 38.1 ± 17.9 μg m^{-3} (Srivastava et al. 2014). Kanpur, located in the IGP, witnessed a three- to fourfold increase in the OC concentrations during winter predominantly due to biomass burning (wood fuel and agricultural waste) emission in 2007–2008. The relatively high OC/EC ratio supports that emissions from biomass burning are overwhelming for the particulate OC in the IGP (Ram et al. 2010b). The mass concentrations of EC ranged between 3.8 and 17.5 μg m^{-3} during October–November (paddy residue burning emission), whereas it remained low during December–March (2.3–8.9 μg m^{-3}; emission from bio- and fossil fuel combustion) and April–May (2.0–8.8 μg m^{-3}; wheat residue burning emission; Singh et al. 2014).

8.4.3 Ozone

The air masses sampled over Delhi, Agra, Mohali, Pantnagar, Dehradun and Nainital trace back to the region of biomass burning (Haryana–Punjab) based on the analysis of air mass trajectories and synoptic winds during spring as well as autumn. Due to higher solar insolation over northern India during spring as compared to that in autumn, photochemistry is more intense during spring over this region in the presence of precursor gases emitted from burning biomass. Correspondingly, the amount of photochemical build-up of O_3 depends on the amount of precursor gases and the available solar insolation. Biomass burning-induced enhancement of noontime O_3 is observed to be in the range of 7 ppbv (10% over Mohali) to ~32 ppbv (72% over Delhi). Table 8.3 shows noontime O_3 enhancement over different sites highlighting the heterogeneity in O_3 enhancement due to the influence of northwest biomass burning. It is worthwhile to note that the enhancements in O_3 estimated over Delhi, Agra and Mohali are with respect to that in the preharvest period, whereas over other sites, O_3 enhancements are with respect to low-fire-activity period. The springtime maximum O_3 of 39.3 ± 18.9 ppbv over Pantnagar (29.0° N, 79.5° E, 231 m amsl), a semi-urban site in the IGP, is also influenced by Haryana–Punjab crop residue burning (Ojha et al. 2012). Similarly, biomass burning influence is

Table 8.3 Biomass burning-induced noontime O_3 enhancement in the downwind regions of Haryana–Punjab

Observational sites	Noontime surface O_3 background values	Noontime surface O_3 enhancement	Observation period of O_3 enhancement	References
Delhi (28.4° N, 77.1° E)	~44 ppbv (preharvest period)	31.7 ppbv (~72%)	September–October 2015	Kumari et al. (2018)
Agra (27.2° N, 78.1° E)	~ 52 ppbv (preharvest period)	17.3 ppbv (~33%)	September–October 2015	Kumari et al. (2018)
Mohali (30.7°N, 76.7°E; 310 amsl)	66 and 68 ppbv preharvest period of spring and autumn, respectively	19 ppbv (29%) and 7 ppbv (10%)	Spring and autumn of 2011–2013	Kumar et al. (2016)
Dehradun (77.9° E, 30.3° N, 600 amsl)	51–59 ppbv (low-fire-activity period)	21–29 ppbv (~35–56%)	May 2018	Ojha et al. (2019)
Nainital (79.5° E, 29.4° N, ~2 km amsl)	56 ± 11 ppbv (low-fire-activity period)	19 ppbv (~34%)	April–May 2007–2009	Kumar et al. (2011)
	–	4–18%	April–May 2009–2011	Sarangi et al. (2014)

observed to be infused with other anthropogenic emissions over Kanpur (26.46° N, 80.33° E, ~125 m amsl) leading to springtime maximum O_3 (Gaur et al. 2014). While in situ observations are limited, model simulations can provide biomass burning contribution at synoptic scale with effective delineation of other processes, such as changes in meteorological conditions. The regional chemistry transport model, Weather Research and Forecasting coupled with chemistry (WRF-Chem), simulated daytime O_3 enhancement of about 1–7 ppb (4–10%) over IGP and foothills of Himalayas during April and May (Jena et al. 2015). Note that this enhancement is corresponding to an average over daytime (9:30–17:30 local time), and hence it is lower in magnitude as compared to the noontime (peak values) enhancements shown in Table 8.3. It is interesting to note that noontime O_3 enhancement is higher (over Mohali and Nainital) during spring as compared to that during autumn mainly due to higher availability of solar insolation intensifying the photochemistry.

A large number of forest fire events (April–May 2016) occurred in the foothills of north-western Himalayas (Uttarakhand state), which led to 9–11% enhancement in surface O_3 as inferred from WRF-Chem simulations (Yarragunta et al. 2020). Copernicus Atmosphere Monitoring Service (CAMS) combines a suite of observations with a state-of-the-art data assimilation and forecasting system. CAMS captures the variability of noontime O_3 with very good agreement (correlation coefficient of 0.86; Ojha et al. 2019) with springtime observations in the

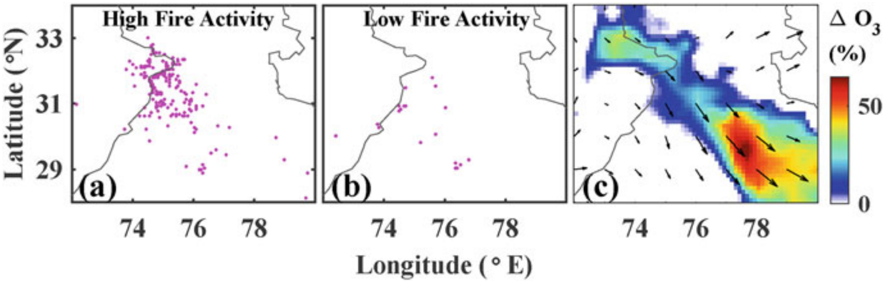

Fig. 8.5 Fire event locations during high (11 May 2018) and low (3 May 2018) fire activity (**a**, **b**). The percent enhancement (i.e. ΔO_3) in CAMS-simulated noontime surface ozone (**c**) between the high and low fire activities. Synoptic wind (black arrows) at 900 hPa during May 2018 is overlaid in figure (**c**)

downwind of northwest IGP. However, there exists significant bias and hence CAMS is utilized here to show the relative enhancement in noontime O_3 on a regional basis. As a representative case, Fig. 8.5a, b shows fire event locations during high and low fire activity for 2 days (11 and 3 May 2018) over Haryana–Punjab region. To illustrate the O_3 enhancement in the downwind of biomass burning, the relative difference in noontime O_3 on the subsequent day of high and low fire activity is taken and represented in Fig. 8.5c. Synoptic wind (from ERA-5 reanalysis) is superimposed over the change in surface O_3 (i.e. ΔO_3). The O_3 enhancement is in the range of 10–65% over northern India caused by biomass burning during spring. The maximum O_3 enhancement is in the downwind of the source region of precursor gases. Significant amount of NO over the source region would titrate O_3 compensating the O_3 produced from other precursors such as NO_2. Titration reaction NO + O_3 adds up NO_2 and due to shorter lifetime of NO (a few minutes; Seinfeld and Pandis 1998), higher magnitude of NO_2/NO ratio in the downwind would lead to en route photochemical production of O_3 along the transport pathways, besides the contributions from other precursors.

The intense biomass burning over northern India influences not only the surface-level composition and chemistry but also the boundary layer as well as free tropospheric chemistry. Mean vertical profile of O_3 for the high- and low-fire-activity periods during spring over central Himalayas (Nainital, which is considered to be the regional representative site for northern India; Kumar et al. 2011) and Doon Valley (Dehradun; foothills of Himalayas) is shown in Fig. 8.6. The crop residue burning over northwest IGP leads to enhancement in noontime O_3 by 35–56% (21–29 ppbv) over Dehradun (Ojha et al. 2019) and ~ 30% (19.9 ± 4.6 ppbv) in 2–4 km altitude range over Nainital (Ojha et al. 2014).

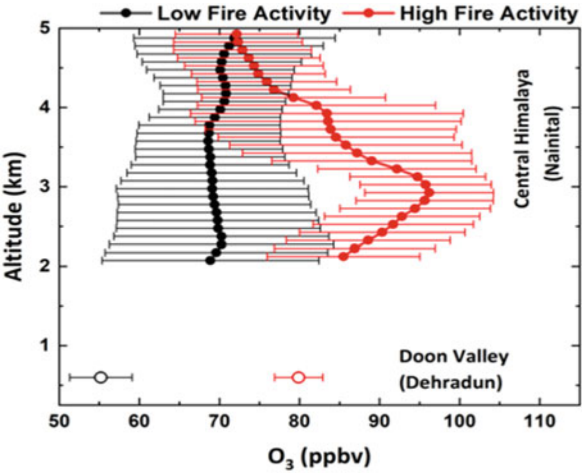

Fig. 8.6 Ozone vertical profiles along with standard deviations (error bars) during high (red) and low (black) fire activity periods of spring over two nearby sites, Nainital (filled circles) and Dehradun (hollow circles), over Himalayas. Observations are adapted from Ojha et al. (2014, 2019)

8.4.4 Ozone Precursors

Whereas O_3 has been studied more extensively, the studies on precursors of O_3 (CO, NO_x, VOCs, etc.) are limited due to their sparse in situ measurements. CO showed enhancement by 187 ppbv over Agra, and up to 300 ppbv over Delhi, during biomass burning during post-harvest period, as compared to preharvest period, during autumn of 2015. CO levels were observed to be 204–1313 and 1060–2080 ppbv over Delhi and Agra, respectively (Kumari et al. 2018). However, NO_x did not show any significant variation in pre- and post-harvest periods at both the sites mainly due to shorter lifetime of NO_x as well as influence of local emissions (predominant emission of NO_x from vehicular source). Crop residue burning event (10–12 May 2018) over northwest IGP during pre-monsoon caused enhancement of CO, NO_x and O_3 by 86, 21 and 15%, respectively, over Agra. The peak values of CO, NO_x and O_3 were observed to be 1406, 115 and 91 ppbv, respectively, during this event (Kumari et al. 2020). Satellite observations showed surface CO higher than 300 ppbv during a severe air pollution episode (1–7 November 2016) over Delhi (Kanawade et al. 2020). High-altitude station over central Himalayas experienced the enhancements of CO by 26–117 ppbv (15–76%) and NO_y by 246–1375 pptv (35–51%) due to biomass burning during spring of 2009–2011. This led to CO and NO_y levels up to 1300 ppbv and 8000 pptv, respectively (Sarangi et al. 2014).

The observations of volatile organic compounds (VOCs) at Mohali showed massive increase by a factor of 3 with respect to baseline levels in the biomass burning plume during springtime (May 2012). This led to elevated levels reaching 100 ppbv for methanol, 50 ppbv for the sum of acetone and propanol, 30 ppbv for acetaldehyde, 7 ppbv for acetonitrile, 5 ppbv for isoprene and 20 ppbv for each of the aromatics, 80 ppbv NO_x, 50 ppbv SO_2 and 2000 ppbv CO (Sinha et al. 2014). Over the same location, the elevated concentrations of acetonitrile, benzene, toluene, C8 aromatics and C9 aromatics were 1.62 ± 0.18 ppb, 2.51 ± 0.28 ppb,

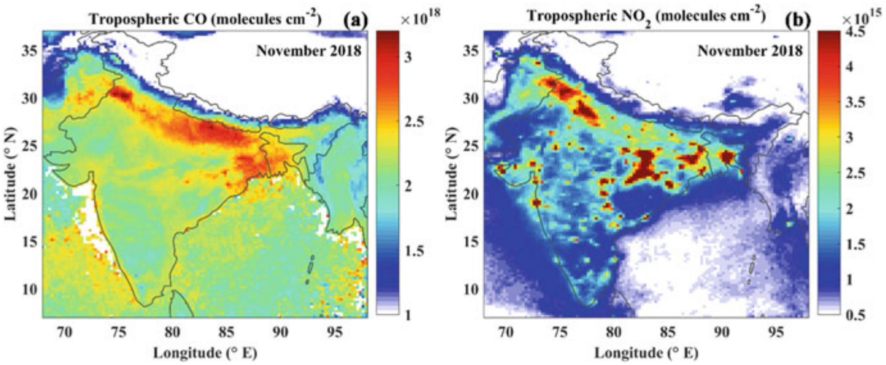

Fig. 8.7 Mean tropospheric columnar (**a**) CO and (**b**) NO_2 (0.25° × 0.25°) for November 2018 as observed by TROPOMI satellite. The data with quality assurance value higher than 0.5 are considered

3.72 ± 0.41 ppb, 2.88 ± 0.30 ppb and 1.55 ± 0.19 ppb, respectively, during the post-harvest periods, which were roughly 1.5 times higher than their annually averaged concentrations (Chandra and Sinha 2016).

Model simulations showed that the forest fire events over the foothills of Himalayas during spring season caused 34–52% enhancement in CO and 32–52% enhancement in NO_x over Dehradun (Yarragunta et al. 2020). Satellite observations for these events showed an increase in CO by 60–125 ppbv in the upper troposphere, 925–700 hPa (Srivastava and Kumar 2020). Average background and fire-impacted tropospheric column NO_2 over Dehradun were observed to be $1.7 \times 10^{15} \pm 5.0 \times 10^{14}$ molecules cm^{-2} and $3.0 \times 10^{15} \pm 8.5 \times 10^{14}$ molecules cm^{-2}, respectively (Srivastava and Kumar 2020). Figure 8.7 shows monthly mean tropospheric columnar CO and NO_2 gridded at 0.25° × 0.25° during November 2018 (as representative of post-monsoon) as observed by Tropospheric Monitoring Instrument (TROPOMI) aboard Sentinel-5 Precursor satellite (Veefkind et al. 2012). Extensive biomass burning over the northwest IGP creates hotspots of CO and NO_2 with the elevated levels above 2.7×10^{18} and 3.5×10^{15} molecules cm^{-2}, respectively (Fig. 8.7). Due to shorter lifetime of NO_2, the influence of emission remains in the close vicinity of source as can be seen from the figure. However, due to relatively longer lifetime of CO, spread from the source region is larger. The biomass burning CO hotspot (northwest IGP) represents highest values as compared to other parts of the Indian region.

IGP experiences extreme pollution episodes frequently during post-monsoon and winter leading to elevated levels of trace gases and aerosols. An extremely high CO level up to 10 mg m^{-3} (~8700 ppbv) was observed during November 2017 over IGP, including the cities of Delhi, Agra, Kanpur, Lucknow, Patna and Kolkata. Dekker et al. (2019) showed that residential and commercial combustion was a much more important source of CO pollution than the post-monsoon crop burning during this episode, which is in contrast to what media suggested and some studies on aerosol emissions found. Besides the elevated emissions, unfavourable meteorological parameters caused extreme levels of pollution over the IGP (Dekker et al. 2019). Similarly, recent studies (Kanawade et al. 2020; Ojha et al. 2020; Sembhi et al. 2020) emphasized on the role of meteorology to cause extreme pollution episodes over Delhi and IGP.

8.5 Impacts of Intense Biomass Burning

8.5.1 Air Quality

The large amounts of gaseous (CO_2, CH_4, CO, O_3, NO_x, VOCs) and particulate (PM2.5, BC, OC, EC) pollutants emitted into the atmosphere from extensive crop residue burning episodes over northwest India severely affect the local and regional air quality (Singh and Kaskaoutis 2014; Jethva et al. 2019). The highly polluted air over northern India has an adverse impact on atmosphere, crop, ecosystem and human health. The 2016 report of the World Health Organization listed Delhi and other cities in IGP amongst the highly polluted cities in the world. Every year, high levels of suspended particulate matter, contributed from the stubble burning smoke plumes, blanket the IGP causing severe haze pollution. These pollutant particles under conducive meteorological conditions also contribute to the formation of fog or smog over the northern and central India (Jenamani 2007; Ghude et al. 2017; Wang and Chen 2019). Low-intensity winds (< 5–6 m s^{-1}) and shallow boundary layer favour persistent fog conditions, while prevalence of BC particles leads to smog (smoke + fog) formation.

Delhi, the national capital region (NCR), is affected by intense pollution episodes associated with agricultural fire emissions from northwest India (Cusworth et al. 2018; Liu et al. 2018; Bray et al. 2019; Ravindra et al. 2019c; Beig et al. 2020; Kanawade et al. 2020 and references therein). While NAAQS for PM2.5 is 60 μg m^{-3} (daily average), the WHO standard for safe PM2.5 levels is 25 μg m^{-3}. During the October–November–December, over Delhi, the daily averages of PM2.5 concentrations are in the range of 100–200 μg m^{-3}, i.e. approximately an order higher than the safety standard, while occasionally exceeding 500 μg m^{-3}. The intense haze episode during October–November 2016 over IGP yielded exceptionally high concentrations of PM2.5 (440 ± 265 μg m^{-3}, 2-week average) at Delhi (Jethva et al. 2019), with the PM2.5 mass concentrations increasing to ~563 μg m^{-3} during 1–7 November 2016 (Kanawade et al. 2020). Severe smog during this episode reduced air visibility to about 5 km and less (Sawlani et al. 2019). Analysing contributions of upstream agricultural burning to pollution in Delhi, Liu et al. (2018) noted that for per unit rise in fire radiative power within the upwind region, PM10 increases by 16.34 μg m^{-3} while visibility decreases by 0.155 km. Amongst several other severe air pollution episodes over Delhi, the event of 28 October–5 November 2019 is particularly noticeable since the PM2.5 concentrations exceeded 900 μg m^{-3}, even for a 6-h average period (Takigawa et al. 2020). Satellite observations showed that these severe pollution events occur at a much larger spatial scale and are attributed to the outflow of stubble burning smoke plumes aided by atmospheric winds (Kanawade et al. 2020; Takigawa et al. 2020). The percentage contribution of large-scale post-harvest open burning to severe haze pollution in Delhi has been observed to be ~42 ± 17% (Bikkina et al. 2019). Furthermore since 2010, delayed timing of agricultural waste combustion activity in the Punjab area might have led to a gradual rise in the severity of smog episodes over Delhi in the recent years (Sawlani et al. 2019). Transport of crop residue burning of carbonaceous aerosols by north-westerly winds across IGP, particularly during the non-monsoon season, results in poor air quality over rural areas in Lumbini, located at east-central IGP (Chen et al. 2020a).

The NAAQS for 8-h average O_3 is 100 μg m^{-3} (~50 ppbv at normal temperature and pressure—NTP). Limited observations of 80 days in the Doon Valley show that MDA8 (maximum of 8-h running mean O_3 values) index frequently (47 days) crosses the WHO guideline value (50 ppbv) during spring (Ojha et al. 2019). It was also observed that O_3 exceeds the NAAQS standards on 40% and 53% of the days over Delhi and Agra, respectively (Kumari et al. 2018), during the post-harvest period. The site of Mohali experiences elevated O_3 crossing 8-h average NAAQS limit for 62% of days (451 days out of 2 years of observations; Kumar et al. 2016). 307 events of O_3 exceeding 180 μg m^{-3} (i.e. 1-h O_3 NAAQS limit) were also observed during the polluted springtime over Mohali. In addition, the annual average concentrations of benzene, a class A carcinogen, exceeded the annual exposure NAAQS limit of 1.6 ppb at Mohali, whereas annual exposure to isocyanic acid was close to 1 ppb (Chandra and Sinha 2016). Unlike intense biomass burning during spring/autumn, wintertime biomass burning influences ambient VOC composition over Delhi during fog days with $\geq$30% decrease in acetaldehyde, toluene, sum of C8 aromatics (e.g. xylenes) and sum of C9 aromatics (e.g. trimethyl benzenes) and 20% increase in acetonitrile and benzene. The lower temperatures during fog tended to cause an emission feedback from enhanced open biomass burning within Delhi for warming (Hakkim et al. 2019).

The deterioration of air quality by gaseous and particulate pollutants emitted from the stubble burning is a threat to public health and affects the lives of over 900 million people residing in the IGP (Singh and Kaskaoutis 2014; Jethva et al. 2019). The emitted particles travel downstream to urban areas with high population density and combine with local emissions and meteorology to produce dense haze/fog/smog episodes. This results in a drastic reduction in visibility and severely affects day-to-day life of the residents of the North Indian urban conglomerates and surrounding rural areas. In the recent years, implementation of policies regarding groundwater conversation has resulted in a shift in the crop residue burning period to a narrow window in the late fall with a 39% increase in maximum fire activity during unfavourable environmental conditions, further aggravating the poor air quality of the region (Balwinder-Singh et al. 2019). Exposure to hazardous levels of respirable fine particulate matter released from agricultural waste burning over northwest India is a consequential threat to public health. The adverse effects of aerosol emissions from crop residue burning are pronounced on respiratory health (Chakrabarti et al. 2019; Sonwani et al. 2022) and child health over northwest India (Singh Balwinder-Singh et al. 2019). However, elevated levels of trace gases like benzene and isocyanic acid have the potential to enhance risks for cardiovascular diseases and cataracts (Chandra and Sinha 2016). Furthermore, biomass burning emissions after aging processes go through photochemical reactions with hydroxyl radicals to produce secondary organic aerosols, which is another concern for researchers owing to its harmful impact on health (Cheng et al. 2013; Bosch et al. 2014; Dumka et al. 2017).

8.5.2 Chemistry

The rate of change of O_3 calculated during the O_3 build-up hours (08:00–11:00 LT) is referred to as O_3 production rate here. It is reported to be 8.6, 8 and 8 ppbv h^{-1} over Delhi, Agra and Mohali during the preharvest period of post-monsoon (Kumar et al. 2016; Kumari et al. 2018). These rates are higher as compared to other urban (Ahmedabad) and rural (Gadanki) sites likely due to enhanced biogenic emissions during these seasons. Biomass burning intensified the production rate by 3.4, 4.5 and 1.2 ppbv h^{-1} reaching to 12, 12.5 and 9.2 ppbv h^{-1}, respectively, during the post-harvest period of autumn. The increase in the production rate is observed to be 39%, 56% and 15% over Delhi, Agra and Mohali, respectively, due to upwind biomass burning. Similarly, the higher production rate (~9.6 ppbv h^{-1}) was observed over Dehradun during May month as compared to that (~9.6 ppbv h^{-1}) during March 2018 (Ojha et al. 2019). It is worth noticing that this enhancement in production rate is partially due to changes in meteorological conditions (e.g. higher solar radiation and temperature during May as compared to March). Sensitivity simulations using the photochemical box model as well as global chemistry transport model showed that O_3 chemistry is NO_x limited over a semi-urban site, Pantnagar (29.0° N, 79.5° E, 231 m amsl), influenced by biomass burning over Haryana–Punjab. In contrast, box model simulations suggested VOC-limited O_3 chemistry over Delhi during November (Chen et al. 2020b). This suggests the heterogeneity of chemistry over nearby locations. While the rate of change of O_3 is studied well in the downwind of crop residue burning, observations of such changes in precursor gases are sparse over northern India. The rate of increase in surface CO was found to be 45 ppbv·day^{-1} in the downwind of a widespread forest fire episode (April–May 2016) over Himalayas (Srivastava and Kumar 2020).

Variety of VOCs emitted from biomass burning influences the chemistry of the region which is inferred from the OH reactivity. The OH reactivity is observed to increase from 28 to 64 s^{-1} (~120%) at Mohali in the downwind of crop residue burning over northwest IGP (Kumar et al. 2018). There is no missing OH reactivity when air masses are not influenced by biomass burning; however, missing OH reactivity increased to 40% at Mohali under the influence of crop residue burning, highlighting the presence of unmeasured compounds (Kumar et al. 2018). O_3 levels up to 100 ppbv would cause higher level of OH radicals which could oxidize the precursor gas and enhance the secondary formation of aerosols. Extensive measurements as well as model-based estimation of OH concentration and reactivity are required over northwest India to better understand the changes in chemistry in the downwind of biomass burning.

8.5.3 Climate and Weather

Pollutants emitted from biomass burning have a prominent impact on global and regional climate. A large amount of trace gases and aerosol particles produced from forest fires, burning of fuelwood and agricultural waste influence Earth's radiative budget (IPCC 2013; Bond et al. 2013a, b), and are key contributors to changes in the hydrological cycle and climate (Robock 1991; Penner et al. 1992; Randerson et al. 2006; Keywood et al. 2013; Tosca et al. 2013; Liu et al. 2014). On a global scale, human-induced forest fires for land acquisition may account for up to 20–60% of the global warming caused by CO_2 emitted from fossil fuel combustion (Crutzen and Andreae 1990). The smoke aerosols produced directly, and as secondary products, from biomass burning alter the atmospheric radiative balance by absorbing, scattering and reflecting solar radiation (direct effect; Fadnavis et al. 2020). The particles also act as cloud condensation nuclei (CCN) and ice nuclei (IN) and impact cloud optical and microphysical properties (indirect effect; Cattani et al. 2006; Koren et al. 2008). Aerosols emitted from biomass burning have significantly different characteristics while acting as CCN. The mean CCN activation ratio (at a supersaturation of 0.46) was observed to be highest (>0.7) at high-altitude station, Nainital, during autumn which is attributed to the contribution of biomass-burning aerosols to CCN formation at high supersaturation conditions (Gogoi et al. 2015). In addition, the optical properties of smoke aerosols are constrained by the burning conditions; consequently, depending on the vertical variation of smoke plumes, they alter cloud cover, albedo and precipitation efficiency (Kaskaoutis et al. 2014). Owing to their short lifetime and heterogeneous distribution, the biomass burning aerosols primarily impact regional climate. Although the global mean radiative forcing from biomass burning is estimated to be 0.0 (-0.2 to 0.2) W m^{-2} (IPCC 2013), the BC particles in smoke plumes strongly absorb incoming solar radiation resulting in heating of the lower to middle atmospheric layers influencing the vertical temperature profile and reducing surface radiation (Hansen et al. 1997; Ackerman et al. 2000; Krishnan and Ramanathan 2002; Randerson et al. 2006; Ramanathan and Carmichael 2008). Deposition of BC on snow and ice also affects climate by lowering surface albedo and melting snow/ice (IPCC 2013). Over South Asia, absorbing carbonaceous aerosols has a profound impact on the regional hydrological cycle through changes in atmospheric heating, cloud cover and rainfall, and is strongly linked to the vertical distribution of the aerosols and background environmental conditions (Ramanathan et al. 2005; Lau et al. 2006; Li et al. 2016).

8.5.3.1 Impact on Aerosol Characteristics and Radiative Forcing

The paddy residue burning during post-monsoon season (October–November) produces very high values of AOD (>1) and an increase in angstrom exponent value (>1.2), indicating elevated concentrations of fine-mode particles during the

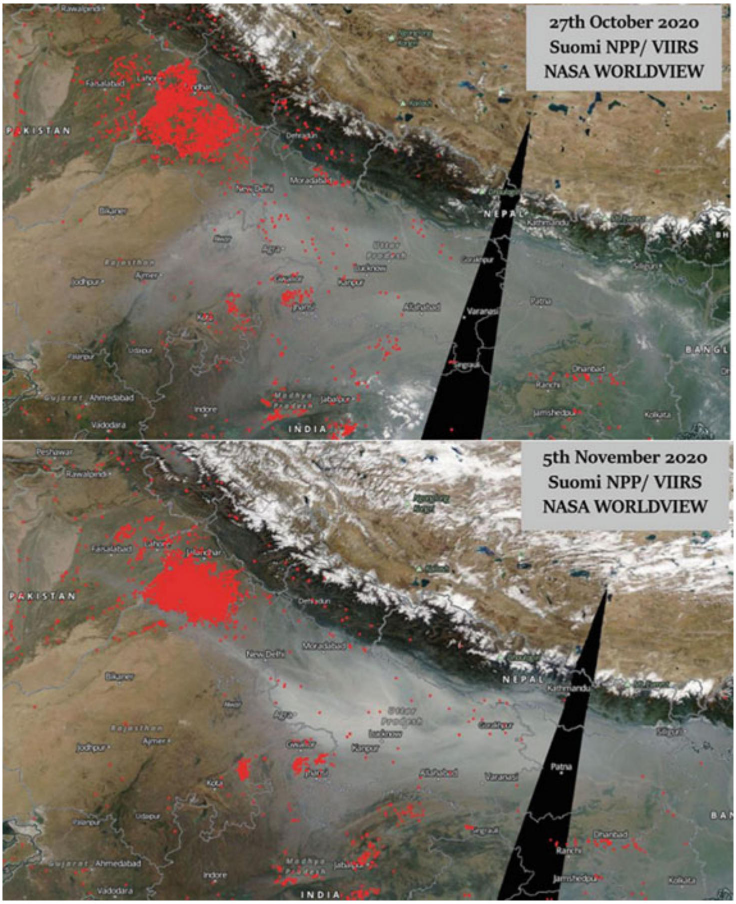

Fig. 8.8 Agricultural fires and smoke plumes over northern India on 27 October 2020 and 5 November 2020 as observed from Suomi NPP/VIIRS (image generated using NASA worldview)

biomass burning activity over northwest India (Sharma et al. 2010, 2011, 2017; Kharol et al. 2012; Kaskaoutis et al. 2014). In the recent years (2003–2017), during the post-monsoon months there has been a 4% rise in crop burning activity over Haryana–Punjab which resulted in 8%, 9% and 11% increase in AOD, absorbing AOD and aerosol index, respectively (Shaik et al. 2019). Figure 8.8 shows a snapshot of intense agricultural crop waste burning activity (red dots) predominantly over Haryana–Punjab region. The associated dense smoke plumes (in white) are also seen to spread in the downwind region along the length of the IGP during post-harvest season of 2020.

Sharma et al. (2010) noted a 21% increase in aerosol loading over Patiala for October 2007 compared to October 2006. Also, Sharma et al. (2011) observed very high AOD of ≈2.65 (at 500 nm) in October 2008 compared to ≈1.71 in November 2009, signifying intense crop residue burning during the rice harvest season of 2008.

The study also noted that the substantial variations in the daily BC mass concentration resulted in single scattering albedo (SSA) value ranging from 0.76–0.88 during highly turbid days to 0.95–0.97 for less turbid days. Analysing the aerosol properties during the post-monsoon crop residue burning season of 2016 over several locations spread across IGP, Kaskaoutis et al. (2014) noted that the AOD increase over Patiala has a greater influence on the angstrom exponent values (increase) and fine-mode radii (decrease) compared to the fine/coarse ratio (increase), indicating an additional contribution of newly formed soot particles from rice harvest fires. The shortwave radiative forcing (RF) estimates over Patiala (Sharma et al. 2010, 2011, 2017) during the biomass burning periods of October–November show large reductions in the surface shortwave radiation, varying from -57.2 to -212.1 W m^{-2} for highly turbid days. The shortwave RF at the top of the atmosphere (TOA) varied from 0.17 to -47.67 W m^{-2}. The considerable reduction in the surface forcing results in a strong atmospheric aerosol RF in the range of 43–164.4 W m^{-2}, suggesting the predominance of absorbing aerosols from paddy residue burning. The strong surface cooling and large atmospheric warming result in an atmospheric heating rate of 1.7 ± 0.6 K day^{-1} over Patiala during the post-monsoon season (Sharma et al. 2017). The BC-induced elevated atmospheric heating results in increased air temperatures at mid-tropospheric (700 hPa) level over the region (Kharol et al. 2012). WRF-Chem simulations for 2013 over Punjab also yield similar results, with carbonaceous aerosols from open biomass burning producing strong reduction of shortwave radiation at the surface resulting in a negative change in the surface temperatures (Singh et al. 2020a).

Transport of smoke particles from Punjab biomass burning region via low-intensity north-westerly winds strongly influences the accumulation of fine particulate matter over New Delhi (Bisht et al. 2015). The high atmospheric RF (~60–70 W m^{-2}) due to BC from the post-monsoon extreme crop residue burning events contributes to the large positive RF (~18 W m^{-2}) at TOA over Delhi, resulting in high atmospheric heating rates (1.9–2.0 K day^{-1}). Furthermore, transport of smoke aerosols from the biomass burning hotspots over northern India occurs in the downwind direction, across the entire IGP extending from east to west, to central peninsular India, north-eastern Arabian sea and occasionally onto Bay of Bengal (Badarinath et al. 2009a, 2009b; Mishra and Shibata 2012; Kaskaoutis et al. 2014; Das et al. 2015; Singh et al. 2018; Shaik et al. 2019). During the intense biomass burning season of 2012, satellite observations revealed thick smoke plumes in the lower troposphere (below ~2–2.5 km) spreading across the entire IGP (Kaskaoutis et al. 2014). As the vertical profiles of crop residue burning aerosols show an exponential decay with height, Mishra and Shibata (2012) obtained scale heights for smoke aerosols in the range of 1.25–1.66 km. Although predominantly biomass burning smoke plumes are trapped inside the planetary boundary layer, in some cases it extends vertically up to 2–3 km (Shaik et al. 2019). Air mass trajectory analyses from the province of Punjab (Kaskaoutis et al. 2014) showed the transport of the smoke-laden plumes by the north-westerly winds predominantly along western and eastern IGP, and sometimes across central India and northeast Arabian sea. Figure 8.9 shows 5-day forward trajectories, obtained from HYSPLIT (Hybrid

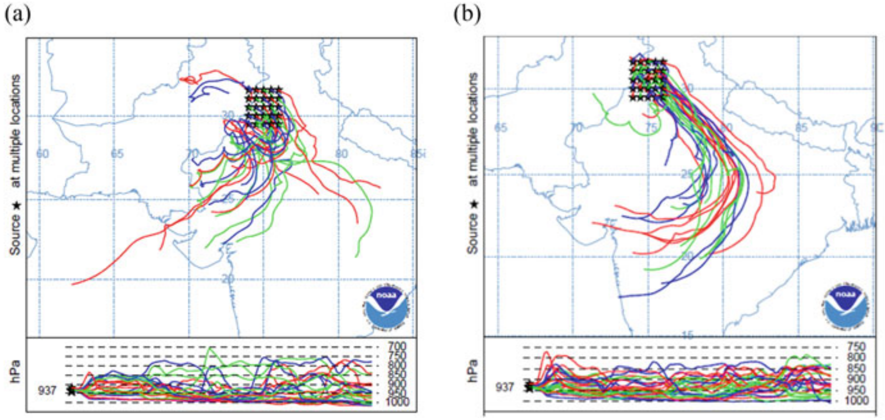

Fig. 8.9 5-Day forward air mass trajectory pathways and their travelling heights originating at a matrix, 29.5–31.5°N, 74–76°E (marked by stars), located over Punjab during (**a**) 27 October 2020 and (**b**) 5 November 2020

Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Rolph 2003), originating from a matrix located over Punjab (29.5–31.5° N, 74–76° E) during the recent biomass burning events of 27 October 2020 and 5 November 2020. The altitude of the start point of the trajectories was fixed at 937 hPa (~500 m). The Global Forecast System (GFS) meteorological fields including the model vertical wind velocities were used for calculating the forward trajectories. Under the prevailing meteorological conditions on both the days, biomass burning plumes spread across north/north-western India, and also propagate vertically up to an altitude of 750 hPa. Singh et al. (2018) investigated the transport of extreme biomass burning emissions (October–December) of 2016 and observed the predominance of absorbing aerosols with a low smoke plume height (<1.5 km) across IGP. Owing to the vertical transport, significant enhancement in absorbing aerosol loading is observed in the free troposphere during spring (Nair et al. 2016; Gogoi et al. 2019). Radiative forcing estimates that the biomass burning-dominated period caused a significant increase in atmospheric RF (135 W m^{-2}) and very high atmospheric heating rates (4.3 K day^{-1}) over Varanasi in comparison to the non-dominating period (56 W m^{-2}, 1.8 K day^{-1}; Singh et al. 2018). Long-range transport of biomass emission aided by circulation patterns and environmental conditions across central India resulted in large deficit in surface solar radiation (-107.81 W m^{-2}) over south-central India (Badarinath et al. 2009a). Although northwest IGP is the hotspot for biomass burning, considering several weeks of burning activity and large-scale transport of emissions through prevailing winds, the smoke plumes have significant implications on regional climate through changes in aerosol RF and cloud modifications.

8.5.3.2 Impact over Himalayan Region

Light-absorbing aerosols get transported and lifted to the high mountains over northern India and are deposited on glaciers and snow, affecting the snow albedo over Himalayas (Fadnavis et al. 2020). Deposition of absorbing aerosols on snow decreases the surface albedo resulting in increased absorption of shortwave radiation enhancing the surface snowmelt. Crop residue burning emissions from northwest India and Himalayan forest fire emissions are known to be the sources of carbonaceous aerosols over various sites located across the Himalayan region (Kumar et al. 2011; Srivastava et al. 2012; Vadrevu et al. 2012; Sahai et al. 2013; Sarkar et al. 2015; Kant et al. 2020; Prabhu et al. 2020). Furthermore, You et al. (2016) showed that smoke plumes from intense biomass burning episode over the northern India can be lifted onto upper tropospheric levels and can get transported and deposited at high-altitude glaciers over the Tibetan Plateau. The springtime biomass burning over northern India during 2007–2009 resulted in significant enhancements in surface BC (~145%), 550 nm AOD (150%) and ozone (~34%) at Manora Peak, Nainital, located in the central Himalayan region (Kumar et al. 2011). Wavelength dependence of the BC observations shows that significant contribution of BC at Manora Peak occurs from biomass burning and is transported by air masses from the west and northwest sector onto central Himalayas (Srivastava et al. 2012). The northern Indian biomass burning-induced shortwave RF shows large reduction of surface solar radiation (-27 W m^{-2}) compared to TOA (-8 W m^{-2}) in high-altitude regions of the central Himalayas (Kumar et al. 2011). The surface cooling leads to an increase in atmospheric RF (19 W m^{-2}), thus enhancing the lower atmospheric heating rate by 0.8 K day^{-1}. The radiative changes caused by the transport of biomass burning aerosols to the central Himalayan atmosphere may produce enhanced shortwave absorption above clouds and have an impact on the monsoon precipitation.

8.6 Summary

The IGP is a very important agroecological region which holds nearly ∼40% of India's total population. The northwest IGP, comprising Haryana, Punjab and west Uttar Pradesh, produces two-thirds of India's food grains, and is commonly referred to as the "breadbasket" of India. The total number of annual fire counts over northwest IGP accounts for ~26% of total fire counts over India, manifesting that biomass burning over Haryana–Punjab region is more extensive as compared to the rest of India, and hence represents the regional hotspot over northern India. The most prominent source of biomass burning over this region is post-harvest crop residue burning, while other important sources of biomass burning include wildfires and biofuel combustion. The agricultural waste generated, as a result of rice and wheat harvesting, is burnt during post-monsoon/autumn (October–November) and pre-monsoon/spring (April–May) seasons, respectively. However, significantly high fire counts are observed in post-monsoon which is indicative of intense biomass burning events occurring predominantly during these months. Burning of biomass releases a variety of particulate matter/aerosols such as carbonaceous aerosols, and trace gases such as CO, NO_x, SO_2 and NMHCs. Intense biomass burning under unfavourable meteorological conditions (e.g. shallower boundary layer and lower ventilation coefficient) contributes significantly to the extreme pollution episodes during late post-monsoon season over the downwind region of northwest IGP. Elevated levels of ambient PM2.5 ($>120\ \mu g\ m^{-3}$), BC ($>10\ \mu g\ m^{-3}$), OC/EC ratios (>5) and O_3 (>45 ppbv) and its precursors (NO_x, CO, VOCs, etc.) are observed mostly during post-monsoon crop residue burning season. However, in contrast, O_3 is higher during pre-monsoon biomass burning as compared to that during post-monsoon owing to higher solar insolation. Biomass burning also impacts the chemistry of region, as can be seen from the higher O_3 production rates and increased OH reactivity over a region under the influence of biomass burning.

The excessive emission of trace gases and particulate matter causes severe air pollution incidences over the province of Punjab and adjoining areas, particularly the NCR. The stubble burning smoke plumes get transported horizontally as well as vertically under the influence of the prevailing circulation patterns and environmental conditions, thereby affecting the entire IGP region. In situ measurements, supplemented with space-based observations, air mass trajectory analysis and chemistry-climate modelling over northern India, have unravelled the impacts of biomass burning on atmosphere. The biomass burning-induced trace gases and aerosol particles, coupled with regional meteorology, have a significant impact on air quality, chemistry as well as weather and climate of a region. Notably, the light-absorbing BC and CCN forming OC aerosols from the thick smoke plumes have a profound impact on circulation and precipitation patterns, glacier melt and atmospheric heating over the South Asian region. With a projected rise of surface temperatures over the Himalayan region by the end of the twenty-first century, the climate community is striving to constrain any significant snowmelt and glacier retreat over the Himalayas, and also to limit the global temperature rise to 1.5 °C. For this, a massive reduction in carbon dioxide and short-lived climate forcers (methane, ozone and aerosols: particularly carbonaceous aerosols) is necessary, in order to bring about a sustainable climate over the South Asian domain. Since crop residue burning continues to play a crucial role in the problem of seasonal air pollution, effective alternative solutions through coordinated public and private actions need to be implemented to reduce stubble burning, along with more sustainable agricultural management practices. This will include educating the farming community and empowering them with technical and socio-economical assistance. Shared socio-economic pathways (SSPs), as described by the climate change research community, have indicated that socio-economic factors will affect the amount of greenhouse gas emissions. It suggests that a sustainability-focussed world will lead to quick reduction of emissions beyond those agreed in the Paris Agreement.

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atmosphere-monitoring. The smoke plume images embedded with fire events were obtained from Suomi NPP/VIIRS NASA worldview imageries (https://earthdata.nasa.gov/earth-observation-data/near-real-time/hazards-and-disasters/smoke-plumes). NOAA Air Resources Laboratory (ARL) is acknowledged for the HYSPLIT model and READY website (https://www.arl.noaa.gov/hysplit/hysplit/).

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Rising Extreme Event of Smog in Northern India: Problems and Challenges

9

Ashima Sharma and Renu Masiwal

Abstract

What makes *Air Pollution dangerous?*—it causes untimely death of innocent people, oblivious of the threat, and what did they do?- they breathed! Yes, that's it. The victims are unsuspecting and at exposure of an inopportune risk. Annually, nearly 1.67 million Indians were killed due to air pollution, while so many more were endangered with some disease, allergies, health troubles, etc., due to the toxic air they breathed. Even though it is a silent killer, it is no more invisible. A noxious smog is seen hanging in the air every winter, dooming the once bright sunlit winter days, with its gloomy grayish-brown tint. Suspended particles in air scatter the sunlight away from the surface and what might appear as winter *fog* is actually the fatal *smog*, an intense blow to our fundamental right to breathe in a clean air. The critically impacted states include those in North India, such as Haryana, Punjab, Uttar Pradesh, and Delhi. The present chapter gives an overview of the challenges behind the increasing trend of smog events across Northern India. It seeks to deliver an understanding of the question of why the northern part of our country is becoming the pollution center of the world and intends to link the plausible causes and impacts for the rising extreme events of smog.

Keywords

Smog · Air quality · Air pollution · Northern India · Human health

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9.1 Introduction

In the very words of Theodore Roosevelt, knowing more about the past makes one better prepared for the future. On the same lines, a thorough understanding of the historical smog events, across the globe, is henceforth necessary to be able to link the sequence of their occurrence with the current reality of Indian cities.

It was in 1905 that a London physician named Harold Des Veaux coined the term *smog*. It was a combination of the two otherwise not very destructive entities, *smoke* and *fog,* and used to describe a condition wherein natural fog is contaminated by smoke. Very soon, in 1909, the term smog was for the first time used to describe a dangerous 5-week-long pollution episode in Glasgow, Scotland. The number of reported deaths was at least 2–4 times the normal number during pre-smog days. By 1925, Shaw and Owens had already published a comprehensive work on urban air pollution problems, wherein the smoke problem in big cities was discussed in detail.

In 1939, as the Second World War started, Los Angeles (LA) was about to witness what would be remembered in history as one of the world's most talked about air pollution episodes. In 1943, as a thick smog enveloped their city, the residents believed that it was some kind of a chemical attack prompted by the Japanese. No other reason was acceptable to the residents because the air in LA was extremely clean. However, this fog made their eyes burn and noses run. Only later, in the 1950s it was realized that this was a consequence of the emissions of their vehicles and factories. Investigations led by a scientist, A.J. Haagen-Smit, at the California Institute of Technology, brought about an understanding that ozone (O_3) was a major ingredient of this haze (Haagen-Smit 1952). An apparent tipoff was an unusual increase in the number of cases of cracking of rubber during this smog event, a phenomenon related to ozone attack. He studied that the gases from the exhaust fumes of vehicles and industries release volatile organic compounds (VOCs) and nitrogen oxides (NO_X), which photochemically oxidize to generate O_3 (Fig. 9.1). LA had also seen large-scale immigration during wartime and early adoption of automobiles in the city made it a forerunner in automobile retailing. It was this incessant emission flux from vehicles and industries, plus a geography that supported trapping of air pollutants, that caused the "*photochemical smog*" or the "*oxidizing smog.*" Currently, many cities in Mexico, USA, and Brazil are facing the same type of photochemical smog.

However, in the mid-twentieth century, the air pollution problem traversed continents and another most talked about smog event came into the limelight—*the Great Smog of London*. Although owing to coal burning, the polluted fog was prevalent in London since the thirteenth century, but with continued development, the situation progressed to worsen further. King Edward I had to pass a law in the fourteenth century to ban coal burning (Gaffney and Marley 2009). This is known to be the first legislation for reducing smog pollution and resultant human exposures. During the seventeenth century, soot deposition due to coal burning and its consequent effects on the buildings also attracted attention and concern of King James I (Chen et al. 2007).

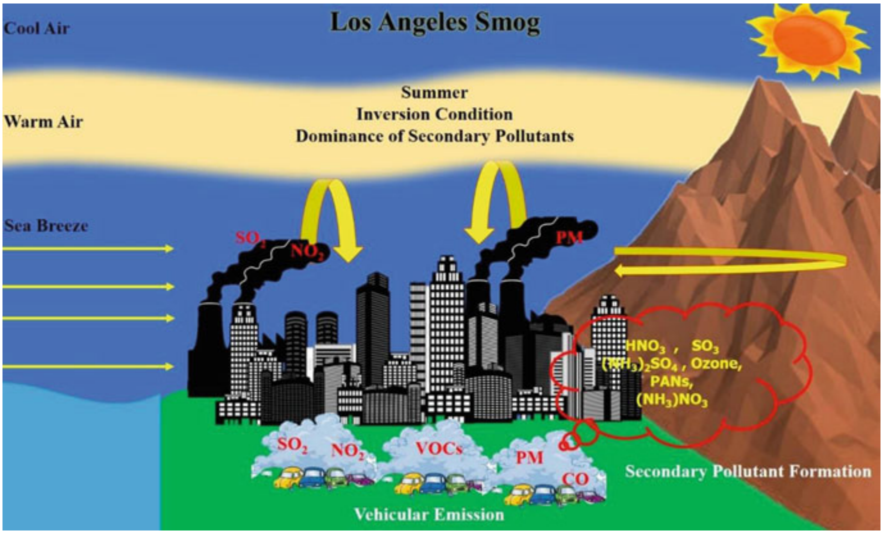


Fig. 9.1 A schematic diagram explaining factors responsible for Los Angeles type photochemical smog and formation of major chemical components

In 1661, King Charles II asked John Evelyn Esquire to assess and report London's deteriorating quality of air attributable to combustion of coal. He reported horrid smoke concealing the buildings of London, fouling people's clothes, tainting the water bodies, causing acid rain, and leading to premature mortality, especially in kids (Evelyn 1772).

Industrialization in the 1700s made the air of even poorer quality. The possibility of these smoggy occurrences was attributable to the particulate release from coal burning that would attract water droplets in the atmosphere, producing dark clouds, an accompanied haze, and impaired visibility. However, nothing was done to curb the menace of these regular smog events, and in December 1952, the great smog manifested when inversion conditions (low winds and a shallow boundary layer caused by winter season) ensured none of the pollutants dispersed (Polivka 2018). Visibility conditions were extremely impaired to an extent that there were reports that people could not even see their own feet while walking on road. The 5-day-long event led to more than 12,000 fatalities. This type of smog was the *sulfurous or reducing smog*, characterized by high concentrations of sulfur dioxide (SO_2) and particulate matter (Fig. 9.2). Ultimately, the Clean Air Act was passed in 1956, which did improve public health conditions in London (Brazell 1970). At present, urban areas in China, Egypt, and India are examples of urban centers with London-type smog (Davis 2002).

Similarly, many such smog events have been observed in Meuse River Valley, Belgium (1930), St. Louis, Missouri (1939), Donora Pennsylvania (1948), New York, USA (1963), etc. (Firket 1936; Zimmer and Nemery 2017). These

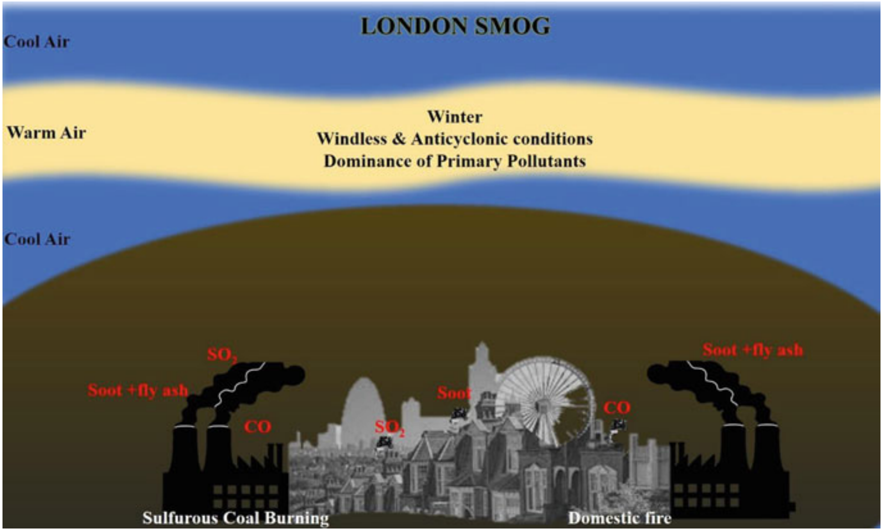


Fig. 9.2 A schematic diagram explaining factors responsible for London-type sulfurous smog and formation of major chemical components

smog events served as major catalysts to create awareness and air quality regulations.

History repeats itself if lessons are not taken, and so is the case with air pollution. Increasing haphazard development, urbanization, population and several such factors are now causing a continuous decline in the air quality with similar such situations now recurring over the Indian cities. In regard to PM_{10} pollution, World Health Organization (WHO) enlisted some 100 cities around the world, out of which 37 Indian cities were included (Guttikunda et al. 2014). Sharma et al. (2019) reported that while in 1998, the national standards for ambient air were being breached in only 27% of India's districts, however, in 2010, air quality of nearly 45% of districts was exceeding the standards. They also wrote about WHO reports stating that nine cities out of top ten most polluted ones were in India, with the national capital Delhi, the most polluted in terms of PM_{10}. Majority of these cities are in Northern region of our country, and hence, for people living here, clean air is now a distant dream. Regular smog events are indicative of an impending crisis.

This chapter aims to understand the reasons behind this increasing trend of smog events across North India. It is extremely vital that we should have concrete answers to the question of why is the northern part of our country becoming the pollution capital of the world. Perhaps the answer lies in increasing population, urbanization, vehicular growth, industrial and economic expansion, or uncontrolled constructions releasing tonnes of dust. The geography of the Indo-Gangetic plain and meteorological parameters cannot be ruled out as major inherent disadvantages. This chapter intends to link these plausible causes for the rising extreme events of smog in Northern India.

9.2 North-India's Crowning Glory or Not?

The north is among the largest region in India comprising nearly 30.7% of the total national land area. Jammu and Kashmir, Himachal Pradesh, Rajasthan, Punjab, Haryana, Delhi, Uttar Pradesh, and Uttarakhand are major component states and/or union territories. More than 368 million people currently inhabit North India (Census 2011). The region's importance can be accessed from the fact that all together it contributed almost 26% to the national GDP in the financial year 2013. The installed capacity of power utilities in the North Indian states is reported in Table 9.1. The flourishing sectors of this region are IT, hydropower, and infrastructure. The economic growth of the northern region sometimes outperformed the growth in the rest of the country. The northern region is also rich with natural resources that offer opportunities for the development of several sectors such as solar power, hydropower, and mineral resources. All this offers opportunities for the development of industries in this region and scope to export and generate revenue. Continual infrastructure development in the region by major investments in the sector of rail, power, road, and technology is also a marked advantage in this part of the country (Table 9.2). Punjab, Haryana, and Uttar Pradesh have high agriculture production, which not only supports the national food demand but also supports the growth of agro-processing industries and power generation.

The extensive north-central region of the Indian subcontinent is the Indo-Gangetic Plain (IGP). It extends from the west to the east—including the Indus River Valley, the Ganga River, and the Brahmaputra River Valley. Encompassing an area of 2.5 million km^2, which is nearly 20% of the national geographical area, this fertile plain spreads majorly across north and east India. Silt and alluvium deposition by the numerous rivers originating from the Himalayas in the north makes the region very fertile. It makes it a vital agricultural and ecological hub, contributing nearly 42% to the total production of food grains in the country (Vadrevu and Lasko 2018). Rice and wheat are the main crops grown here, with others like sugarcane, maize, and cotton. This also makes IGP densely populated, with approximately 500 million residents. Undoubtedly, IGP is one of the most developed regions of our country, in terms of literacy, GDP, installed power capacity, telecom services, industries, agriculture, and much more. The key urban characteristics of cities of IGP are shown in Table 9.3.

However, when it comes to air pollution, the IGP region pretty much stands out as the most polluted region of the country. According to a 2018 report by the WHO, stating the list of the world's most polluted cities based on fine $PM_{2.5}$, 9 of the 10 cities were located in the IGP. Reasons are aplenty, several brick kilns still work with old combustion technology, numerous coal mines and large thermal power plants, landlocked cities that offer negligible pathway for the pollutants to disperse, intense post-harvest crop residue burning activities that results in a high amount of air pollution load over the IGP, high population density, regional-level dust sources such as the Thar Desert, meteorology, and lack of effective dispersion owing to the Himalayas (Bray et al. 2019; Raatikainen et al. 2014). Numerous studies (Gaur et al. 2014; Ravindra et al. 2019; Singh et al. 2020) identified the following major sources of air pollution over northern India vehicles, manufacturing, industries, construction, road dust, open waste burning, fossil fuel combustion, and indoor and outdoor biomass burning.

Table 9.1 Installed capacity (in MW) of power stations in Northern India (as on 31.08.2020) (Source: http://cea.nic.in/reports/monthly/installedcapacity/2020/installed_capacity-08.pdf)

	Thermal				Nuclear	Hydro	RES MNRE	Total
States/union territories	Coal	Lignite	Gas	Total				
Delhi	4406.35	0	2115.41	6521	102.83	723.09	226.93	7574.62
Haryana	8660.57	0	685.61	9346.18	100.94	2312.02	537.98	12,297
Himachal Pradesh	151.69	0	62.01	213.70	28.95	2812.88	960.85	4016.38
Jammu and Kashmir	523.42	0	304.07	827.49	62.98	2321.81	204.92	3422.27
Punjab	8327.47	0	414.01	8441.48	196.85	3809.12	1604.85	14,322.27
Rajasthan	10,862.57	1580	824	13,267.47	556	1939.19	9755.6	25,519
Uttar Pradesh	18,690	0	549	19,239.78	289.48	3396.53	3350.46	26,276
Uttarakhand	461.17	0	519.66	980.83	31.24	1876.89	662.37	3551.33
Chandigarh	40.17	0	15.03	55.76	8.01	101.71	42.94	208.42
Total	53,439.79	1580	5781.26	60,801.05	1620	20,044.77	17,346	99,812.72

Table 9.2 North India and its Glory (Source: https://assets.kpmg/content/dam/kpmg/pdf/2014/10/Northern-India-Heralding.pdf)

States	Geographical area (sq. km)	Population (million)	GDP (%)	No. of administrative division	Population density per sq. km	Literacy rate (%)	Installed power capacity (MW)	Telecom (wireless subscribers) (million)	No. of airport	Sectors Industries (I) Agriculture (A) Service (S)
Chandigarh	114	1.1	–	–	9258	86	116.34	–	1	I-14% A-0.45% S-85%
Delhi	1483	16.8	15.86	11	11,297	83.6	7840.74	42.7	2	I-9% A-1% S-90%
Haryana	44,212	25.4	13.50	21	573	75.6	8288.69	21.2	6	I-27% A-15% S-28%
Himachal Pradesh	55,673	6.9	3.17	12	123	82.8	4007.22	7.2	3	I-38% A-19% S-43%
Jammu and Kashmir	222,236	12.5	3.05	22	124	68.7	2587.71	8.1	3	I-23% A-20% S-57%
Punjab	50,362	27.7	11.62	22	551	75.84	8389.14	31.3	3	I-29% A-21% S-50%
Rajasthan	342,239	68.6	16.45	33	200	67.06	15,175	52.9	6	I-25% A-29% S-46%
Uttar Pradesh	240,928	199.6	31.44	71	829	67.6	14,401.52	126.8	6	I-21% A-22% S-57%

(continued)

Table 9.2 (continued)

States	Geographical area (sq. km)	Population (million)	GDP (%)	No. of administrative division	Population density per sq. km	Literacy rate (%)	Installed power capacity (MW)	Telecom (wireless subscribers) (million)	No. of airport	Sectors Industries (I) Agriculture (A) Service (S)
Uttarakhand	53,483	10.1	4.90	13	189	78.8	2640.3	–	1	I-38% A-10% S-52%

Table 9.3 Key urban characteristics of cities of IGP (Source: Guttikunda, S. K., Goel, R., & Pant, P. (2014). Nature of air pollution, emission sources, and management in the Indian cities. *Atmospheric Environment*, *95*, 501–510)

City	Build-up area (km^2)	Population	Population density (per hectare)	% Households with a motorized two wheelers	% Households with a four wheelers	% Households with a non-gas cookstove	PM_{10} (μg/m^3)	SO_2 (μg/m^3)	NO_2 (μg/m^3)
Delhi	669	16,314,838	244	39%	21%	9%	260.1 ± 117.1	6.5 ± 4.2	51.1 ± 17.2
Jammu	123	651,826	53	48%	25%	13%	118.2 ± 37.4	8.2 ± 4.4	12.7 ± 3.4
Ujjain	33	515,215	156	40%	6%	26%	78.4 ± 42	10.9 ± 3.4	11.9 ± 3.1
Amritsar	90	1,183,705	132	50%	15%	21%	188.7 ± 24.2	14.8 ± 2.2	35.1 ± 3.1
Chandigarh	115	1,025,682	89	47%	26%	27%	79.9 ± 32.6	5.8 ± 0.5	15.4 ± 7.8
Ludhiana	167	1,613,878	97	50%	19%	19%	251.2 ± 21.9	8.4 ± 2.3	36.2 ± 7
Agra	129	1,746,467	135	48%	12%	27%	184.1 ± 95.9	6.6 ± 3.5	20.8 ± 12.1
Allahabad	71	1,216,719	171	54%	11%	26%	165.3 ± 70.7	3.6 ± 1	23.7 ± 15.9
Firozabad	21	603,797	288	25%	4%	40%	195.6 ± 78.2	21.6 ± 4.8	32.1 ± 4.9
Kanpur	150	2,920,067	195	11%	3%	42%	211.5 ± 25.3	7.5 ± 1.2	31.3 ± 4.9
Lucknow	240	2,901,474	121	52%	15%	20%	200.4 ± 28.4	8.4 ± 1	36.1 ± 2.6
Varanasi	102	1,435,113	141	40%	7%	29%	125.3 ± 8.4	17.2 ± 0.7	19.6 ± 0.7

This trend of air pollution is widely reported in the Indian capital Delhi and its surrounding National Capital Region (NCR). As India's largest urban agglomeration and second largest in the world, Delhi–NCR has approximately more than ten million registered vehicles, which are the greatest source of pollution here (Peshin et al. 2017). More than 70,000 trucks cross Delhi roads polluting the air with its diesel exhaust. In addition, poor public transport, ever-increasing population, continuous construction and demolition activities, millions of vehicles contaminating the air with their emissions, etc., are all the preliminary anthropogenic reasons for the prevalence of smog in this region. Balakrishnan et al. (2019) reported highest mean $PM_{2.5}$ over Delhi in 2017, followed by Haryana, Uttar Pradesh, Bihar, etc., all with mean values exceeding 125 μg/m^3.

9.3 Smog Events over Northern India

North India has changed a lot, with respect to demography, urbanization, economy, and environmental pollution. Major sources of air pollution here include brick kilns, industries, coal burning, electricity production, construction, vehicles, suspended road dust, biomass burning, crop stubble burning, and generators. Indoor air pollution, majorly caused by burning biomass such as wood, dung cakes, charcoal, and agricultural waste for cooking or heating purposes, also remains a challenge (Sonwani and Saxena 2022; Tiwari and Saxena 2021; Saxena and Naik 2018).

The past decade has been very hard on Northern India in terms of air pollution. The escalating number and intensity of the smog events over the north are not only influenced by the emissions but also influenced by the weather conditions, growing population, industrial activities, open waste disposal and burning, high energy demands, inherent topography of the North Indian plains, etc. (Bhaskar and Mehta 2010). For example, the northwesterly winds from Punjab and Haryana are one of the causative factors that bring in pollutants emanating from the burning croplands to Delhi–NCR (Saxena et al. 2021). Similarly, reduced wind speeds are also responsible for the surface stagnancy of air pollutants and their coalescing onto the water vapor (Fig. 9.3). Ambient air water vapor undergoes condensation when solid particles are present as they serve as condensation nuclei (Kumar and Goyal 2014). More or less, the reasons can be clubbed together as anthropogenic (urbanization and industrialization) and natural causes as is described in the chart below:

- **Urbanisation**
  - Overpopulation
  - Increase in number of vehicles
  - Poor waste management
  - Poor agricultural pratices
- **Industrialization**
  - High demand of power
  - Increased industrial activites
- **Natural Causes**
  - Topography
  - Meteorology

The regular occurrence of smog events is now being observed almost on an annual basis, particularly after the monsoonal months, and during winters. Table 9.4 lists few studies across different regions of Northern India showing the severity of the situation.

Delhi has been experiencing repeated smog events since the last few years, almost on an annual basis. In the year 2014, smog intensified in Northern India, especially over Delhi–NCR, due to low wind speeds, causing pollutant build-up and visibility dropping to just 1100 m. Agricultural fires in Punjab and Haryana were detected by NASA's satellite imagery, were considered the most dominant factor enhancing pollution in the region, as the winds emanating from these burning croplands, eventually reached Delhi, from the northwestern side (Sawlani et al. 2019; Takigawa et al. 2020). Even major rice-producing districts in Punjab such as Patiala and Ludhiana recorded very high air pollution levels (Rana et al. 2019; Chawala and Sandhu 2020).

In 2015, smog was back during the post-monsoon months, blanketing the city and reducing visibility down to about 200 m. An AQI of 372 was recorded over New Delhi, which indicated that the citizens breathed hazardous air. Possible reasons were local-scale coal and biomass fires lit on the street by homeless poor, traffic emissions, temperature inversions, and the lack of wind. As the most widely celebrated festival of India, Diwali, came, the pollution breached WHO recommended levels on the festival's night, by almost 40 times. The fingers were

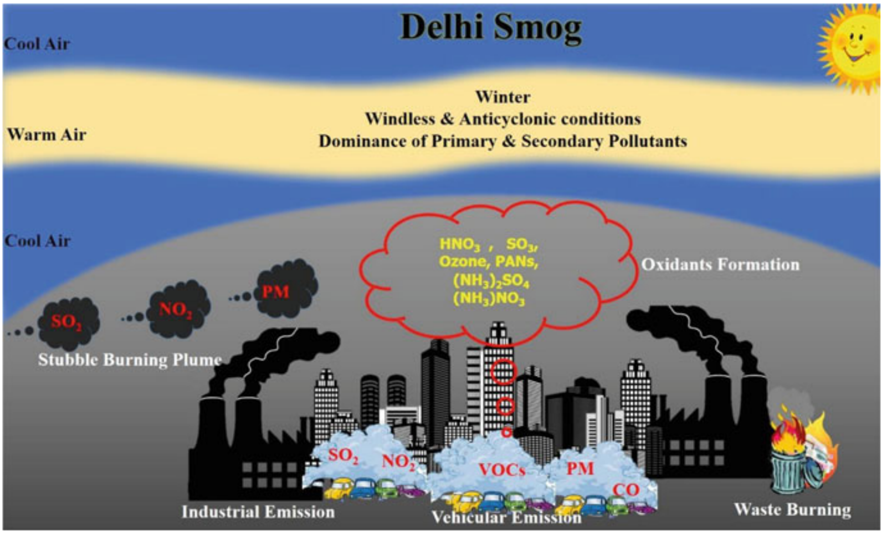


Fig. 9.3 A schematic diagram explaining factors responsible for Delhi's Great Indian smog and formation of major chemical components

Table 9.4 Reported smog events over different parts of northern India. (NAAQS-National Ambient Air Quality Standards, 2009)

S. no.	Place of study	Findings	Duration	Study
1	Mohali, Punjab	High amounts of benzenoids and other gases, linked strongly to ozone-forming potential observed in Punjab. It can be linked to high ozone concentrations in the downwind sites	2012	Sarkar et al. (2013)
2	Delhi	Severe smog episode with extremely low visibility. High pollution (PM_{10} and NO_2 almost 10 times and 7 times more than NAAQS, respectively). Under adverse meteorological conditions, regional pollution could be a stronger factor in air quality deterioration, as compared to local pollution	2012	Sati and Mohan (2014)
3	Delhi	Concentration of aerosols breaching the NAAQS, especially during winter months	2014–2015	Sawlani et al. (2020)
4	Chandigarh, Punjab	Daily average $PM_{2.5}$ concentration nearly 3 times the NAAQS, and an approximate 2.2 times reduction in visibility. Satellite data and backward air mass trajectory analysis showed rice stubble burning on a large scale. Enhanced concentrations of organic carbon and K^+ ions in $PM_{2.5}$ and acetonitrile, which are biomass burning tracers, were observed	2015	Ravindra et al. (2020)
4	North India	The plumes generated from biomass burning during post-monsoon season were transported over the Indo-Gangetic plain region due to favorable meteorology. Higher aerosol optical depth values were also observed during this time. This depletes air quality over regions of North India, especially Delhi–NCR, and is linked to intense atmospheric pollution, resulting in haze and smog over long durations	2016	Chauhan and Singh (2017)
5	Delhi	Severe smog episode—≤ 5 km visibility, average $PM_{2.5}$ concentration exceeding NAAQS by nearly 13 times, just after Diwali. Secondary particulates were actively being formed during the smog period due to stagnant meteorology	2016	Sawlani et al. (2019)
6	Delhi	$PM_{2.5}$ levels 10 times more than the NAAQS; AQI on November 8, 2017, was 999	2017	Basu (2019)
7	Delhi	Conducive meteorological conditions such as regional airflow, reduced	2017	Terry et al. (2018)

(continued)

Table 9.4 (continued)

S. no.	Place of study	Findings	Duration	Study
		temperature, inversions, and low-speed winds led to smog build-up		
8	Delhi	Very high concentrations of air pollutants were observed indicating severe air quality—a serious matter of concern necessitating awareness among farmers to curb crop residue burning	2017–2018	Garg and Gupta (2020)

pointed on to the massive quantities of fireworks and crackers burning during the festival. During the night hours, the coarse PM_{10} concentrations rose to 2000 μgm^{-3}, almost 20 times the NAAQS. Burning of agricultural waste residues also continued for several days, adding to the pollution load. In December 2015, many schools restricted outdoor activities owing to high levels of air pollution, and soon, Delhi became the world's most polluted city, surpassing Beijing for air pollution limits.

Yet again, the smog returned next year in November 2016. High concentrations of $PM_{2.5}$ and PM_{10} were reported making this event, as one of the worst in terms of air quality, in Delhi since 1999. Numerous investigative analyses hinted toward cold weather and calm winds, with reduced speeds, trapping the emitted pollutants. This was understood to have been caused due to an anti-cyclonic circulation, which also caused pollutants to stick to water vapor, and severely aggravate the persisting conditions (Sawlani et al. 2019). It was an unusual event characterized by active secondary particulate formation. Primary sources of smoke were the same as before road dust, burning of crop stubble and waste, etc. (Fig. 9.4). This period also coincided with Diwali, and hence, firecracker burning was among a key cause. $PM_{2.5}$ and PM_{10} levels shot up almost 17 times the recommended standards. Visibility had reduced to about 200 m with an average temperature of around 20 °C.

In 2017, the smog, now regarded as an annual event, repeated itself once again and came to be known as "the great smog of Delhi." It was very clear visually how bad the air quality had become in the national capital territory (Fig. 9.5). A toxic haze blanketed the city, and it was so severe that schools were closed, flights were delayed and in the own words of Delhi's chief minister, the city had become a gas chamber. Research studies and medical professionals stressed on the severity of the situation that could result in irreversible severe lung damage, even among healthy nonsmoking young people, particularly children (Slutsky 2017; Chetambath and Jesin Kumar 2019). The level of PM_{10} and $PM_{2.5}$ was more than 20 times the prescribed standards. It continued even until the end of December, as the weather got chillier and fog engulfed the city. Delhi continued to face the most polluted days of the year, with the air quality index at an "emergency" level.

Smog was back in 2018 as the air pollution rose to hazardous levels, particularly after the Diwali festival that once again led to firecracker burning, despite court bans.

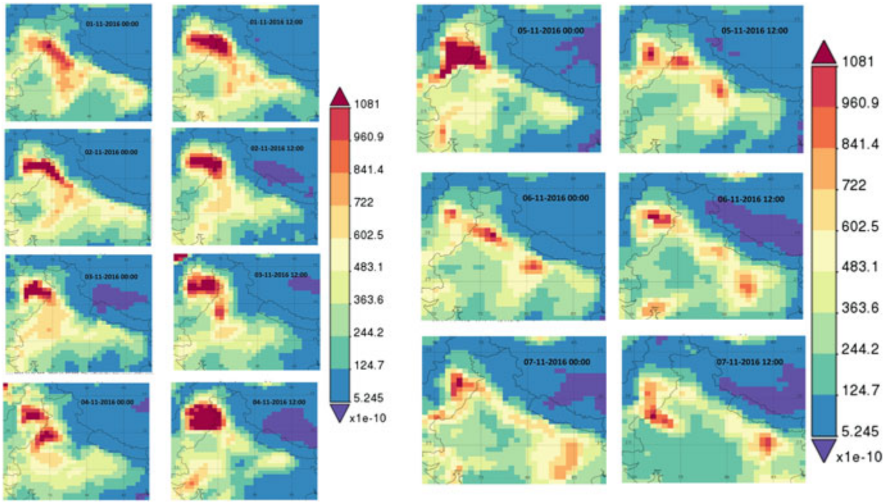


Fig. 9.4 Dust surface mass concentration of $PM_{2.5}$ during the smog event of 2016, time average hourly 0.5 × 0.625 deg. (MERRA-2 Model M2T 1NXAER v5.12.4) kgm^{-3}

Fig. 9.5 The great smog of Delhi (08.11.2017, 09:00 AM) (location: Patel Nagar Metro Station, New Delhi)

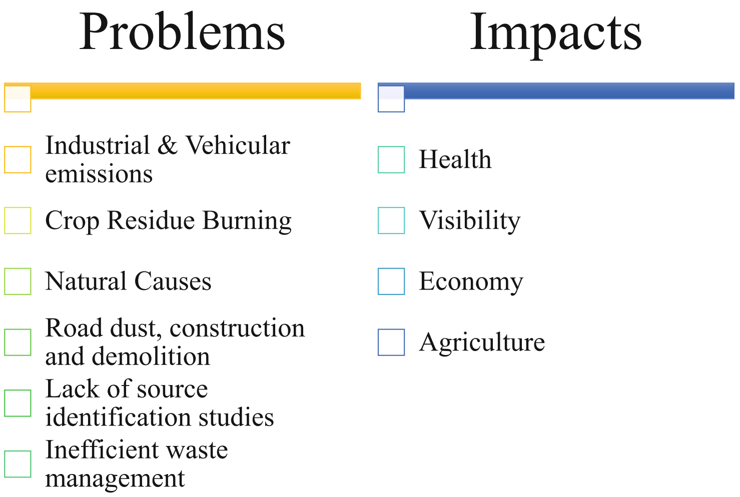
Residents woke up the next day after Diwali to a thick blanket of highly toxic smog. This, besides crop residue burning emissions and emissions of a mixture of primary air pollutants ensured that the smog lasted for more than 2 months, throughout the winter season.

In 2019 also, the air quality of the city dipped and for almost 2 weeks at a stretch, the air quality was in the hazardous category, suggesting air pollutants were at levels where the entire population is getting affected. Owing to low visibility, flights were diverted and Supreme Court—the highest court of India, stated that living in Delhi is even worse than living in hell. The air quality crisis was owing to a noxious mixture of pollutants emanating from crop residue burning, celebratory firecrackers, vehicular emissions, industrial fumes, etc.

Being a rapidly developing region, North India is facing the problem of ambient and household air pollution. This tendency of repeated and a sharp increase in the smog events not only over Delhi, but entire Northern India, is a cause of concern.

9.4 Challenges: Problems and Allied Impacts

The Great North Indian Smog is in every way an emergency—even NCR's Environment Pollution (Prevention and Control) Authority declared it as a public health emergency. Every year, several cities of North India turn dystopian, and this continues for months, till the winter ends. It is a burgeoning event, a product of numerous problems that continue to strengthen more and more with time. The ensuing smog manifests at an exponential scale, as a direct function of an indifferent attitude and lack of any stringent action. The chief concerns have been listed in the chart below, and associated key challenges are discussed in detail later:



9.4.1 Industrial and Vehicular Emissions

Industrial clusters are a key cause of air pollution. Lack of emissions data that are accurate and easily available is a major hindrance to warrant compliance to the air quality standards. Comprehensive Environmental Pollution Index (CEPI) was developed by CPCB in 2010, to assess environmental pollution at the industrial clusters in India, and 43 clusters were identified as critically polluted—most being in North India such as Faridabad, Ghaziabad, Ludhiana, Kanpur, and Agra.

Guo et al. (2017) quantified how much the different source types contributed to fine particulate matter ($PM_{2.5}$) and its components, in Delhi, Chandigarh, Lucknow, and Jaipur, and reported that industrial and residential activities govern primary particulate matter (PPM) mass by more than 60%. High secondary inorganic aerosol (SIA) concentrations (~25 mg/m^3) were mainly ascribed to energy, industry, and residential sectors. Industrial sector was second, after residential sector for its contribution to total $PM_{2.5}$ (~70 mg/m^3) in North India. In Delhi, Jain et al. (2017) estimated 13.4% and 6.2% contribution of industrial emission in the mass concentration of $PM_{2.5}$ using UNMIX and positive matrix factorization (PMF) models, respectively, while about 7.2% of the PM_{10} mass were contributed by industrial emissions (Sharma et al. 2014). Sharma et al. (2016a, b) quantified industrial emissions and fossil fuel burning as major source of PM_{10} in Delhi, contributing almost 7.3% and 15.5%, respectively, to the PM mass.

Vehicles are another key cause of air pollution. Several studies have reported the percentage contributions of vehicular emissions to the ambient air pollution. Guttikunda and Goel (2013) conducted a study at six residential and industrial zones of Delhi, and modeled contribution to $PM_{2.5}$ by different emission sources. It was reported that vehicular exhaust contributed nearly 16–34%, while industries contributed approximately 14–21%. The remaining 20–27% contribution was from diffused sources, 3–16% from diesel generator sets, and 4–17% for brick kilns. Similarly, Goyal et al. (2013) used the international vehicle emission model to estimate vehicle-generated emissions of criteria pollutants over Delhi. The estimated emissions of CO, NOx, and PM in 2008–2009 were found to be 509, 194, and 15 tons/day, respectively, while calculated emissions of CO and NOx from personal cars were about 34% and 50%, respectively, and CO emission due to two wheelers was 61%. Jain et al. (2017) estimated 19.7% contribution of vehicular emission in $PM_{2.5}$, while others (Sharma et al. 2014, 2016b) reported 16–17% contribution from vehicular emissions to the PM mass. Rajput et al. (2018) studied PM_1—their abundance, temporal variability, and source apportionment. Vehicular emission and industrial activities were among the seven dominant sources of PM_1 in Kanpur.

Kandlikar and Ramachandran (2000) discussed the use of emission factors to estimate pollutant emissions from the total number of vehicles. It requires relating the quantity of ambient air pollutants to how much is the activity of different vehicles. Indian cities have larger emission factors because of absence/insufficient pollution control equipment, poor maintenance of vehicles, insufficient monitoring, and implementation of emission standards, and average traffic speeds are usually low owing to bad condition of roads, heavy vehicle density, and the quality of fuel used. In Delhi, the total available space on roads did increase, but so did the number of vehicles per kilometer. Between 2003 and 2009, the city also witnessed a sharp increase in the annual rate for both private and commercial vehicles—7.40% and 9.15%, respectively. Delhi is also fifth worst in the world with respect to traffic jam (Goyal et al. 2013). This is a significant reason for severe transportation and environmental problems (Goyal et al. 2013).

Even though the medium and heavy commercial vehicles do not contribute much to the total number of vehicles, they have substantial contributions to the pollution. Regular inspection and monitoring are required, but are a challenging task. Another challenge is that these measures majorly are followed stringently over the big cities, while many smaller cities or rural areas over northern India do not have any support system to access these facilities; therefore, not much implementation is done. Adoption of Bharat Stage emission norms, nationwide, is therefore recommended.

Another important concern is public transport. With cities seeing an incessant growth, there is a growing need to have a basic facility for a safe and clean public transport system. Even though there is an established public transport facility in big cities, there is a constant need to augment the current fleets, but with cleaner options. For instance, the Delhi government converted public transport such as auto rickshaws and buses to CNG between 1998 and 2002. However, the situation still has not improved—neither in terms of traffic density nor in terms of air pollution. For smaller cities, the situation is even worse. Most lack an organized public transport system, relying on paratransit systems, which ply only on main corridors of the city. With the majority of cities still lacking these kinds of transport facilities, and with the growing population and economy, the burden over these cities' road is escalated, which is visible as the rising level of air pollution.

9.4.2 Crop Residue Burning

With the advent of the green revolution and process of liberalization and economic reforms in the past two decades, the manufacturing sector geared up in northern Indian states. This led to agricultural reforms and modifications in farming practices as well, which correspondingly increased the levels of air pollution over time. Biomass burning is one of the foremost sources of trace pollutant emissions. These tend to severely influence the climate and health. RSPM (respirable suspended particulate matter) and atmospheric trace gas levels have been reported to be above the maximum permissible limits by CPCB as a direct consequence of it. It has been indicated by the several studies conducted that emitted particles are transported across IGP from the burning agricultural lands (Fig. 9.6). Millions of hectares of land of the IGP are under agriculture—mostly rice–wheat rotation, and farmers preferably use combine harvesters for harvesting them. However, this technique leaves large quantities of straw stubble, standing tall (25–30 cm) in the field, which is then burnt down. This is mainly because of its inability to be consumed as fodder due to high silica content. Furthermore, there is only a short duration of just 2–3 weeks available in between which the farmer has to harvest the rice crop and sow the wheat

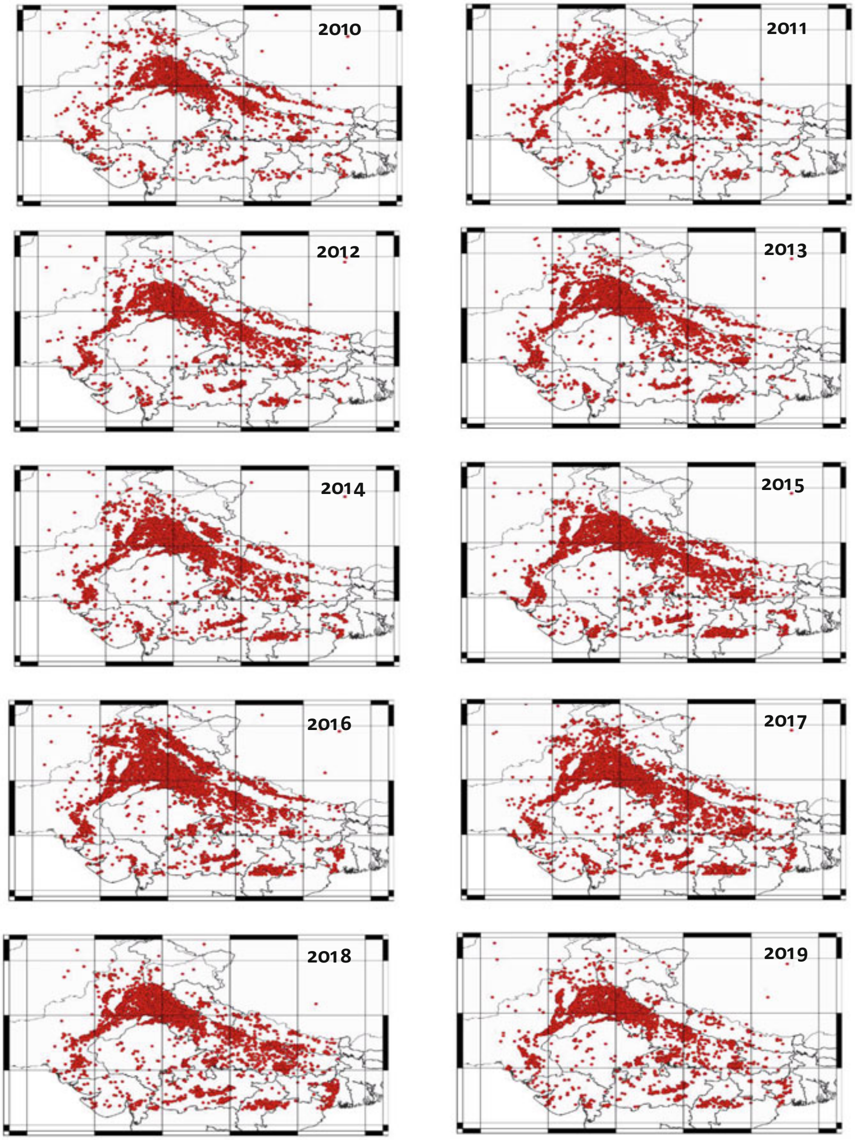


Fig. 9.6 MODIS aqua fire radiative product (FRP) data were used to see the number of fire events in northern India during October, November, and December. The increase in the fire events is visible by the increase in the density of the red dots signifying the number of fires (downloaded from https://firms.modaps.eosdis.nasa.gov/map/#d:2020-09-23..2020-09-24;@40.1,7.6,3z)

crop. High labor wages and resultant anxiety among farmers to harvest, collect, and market their crops are some of the multiple reasons, due to which they find it easier to burn the stubble off.

Crop residue burning, during the harvesting season, releases huge emission load, in the form of trace gases and aerosols, which disturbs the regional atmospheric chemistry and is a health hazard as well. Jain et al. (2014) reported that nearly 80% of the crop straw was being burnt in situ in Himachal Pradesh, Punjab, and Haryana. This led to emissions of air pollutants such as CO_2, N_2O, CH_4, CO, NH_3, NOx, SO_2, NMHCs, VOCs, semi-VOCs, and particulate matter, which were not only harmful to human health but also contributed toward global warming (Mittal et al. 2009). It was observed that burning of 98.4 Mt of crop residue resulted in tonnes of emissions of CO, CO_2, SOx, NOx, NH_3, NMVOC, NMHC, and PM during 2008–2009 (Jain et al. 2014). Similarly, Nagar et al. (2019) also confirmed that the crop residue burning emissions in Punjab, Haryana, Uttar Pradesh, get transported toward the eastern side of the Ganga basin, causing air quality degradation over Delhi and Kanpur. Sembhi et al. (2020) reported that burning of crop residues in Punjab and Haryana led to the smog event of 2016 across the IGP. It was not only hazardous to the health, but also caused biodiversity loss over the IGP and soil fertility deterioration via loss of organic carbon, nitrogen, and other nutrients (Jain et al. 2014; Lohan et al. 2018).

Hence, mostly a hard trade-off arises between environmental improvement and profitable economic opportunities (Shyamsundar et al. 2019), and despite regulations, burning continues to take place because of lack of implementation, uncertainty regarding alternative technologies, etc. However, a more coordinated effort involving public and private partnership both could be a way ahead for a transition toward a more sustainable agriculture.

9.4.3 Natural Processes

The formation of fog over northern India is a natural phenomenon, which dominates particularly during the winter season, under suitable meteorological conditions like atmospheric stability, calm winds, low temperatures, and high humidity. Low-level temperature inversions are formed, which eventually facilitate formation and persistence of fog over northern India (Fig. 9.7).

A combination of atmospheric and anthropogenic factors can be held accountable for magnified pollution levels across Northern India. In summers, vertical mixing is enhanced as the surface temperatures are high. This ensures effective dispersion of the released pollutants away from the ground, as the warm air rises upward easily. The same process is diminished during winters, when the surface air in the planetary boundary layer remains cool and hence dense. It gets trapped under the warm air above, and this is called winter inversion. This hugely reduces the dispersion of pollutants from the surface layers to the upper layers of the atmosphere.

Moreover, as the winter onset happens, the wind direction over the IGP changes from west to east, which brings in pollution load from the burning agricultural fields

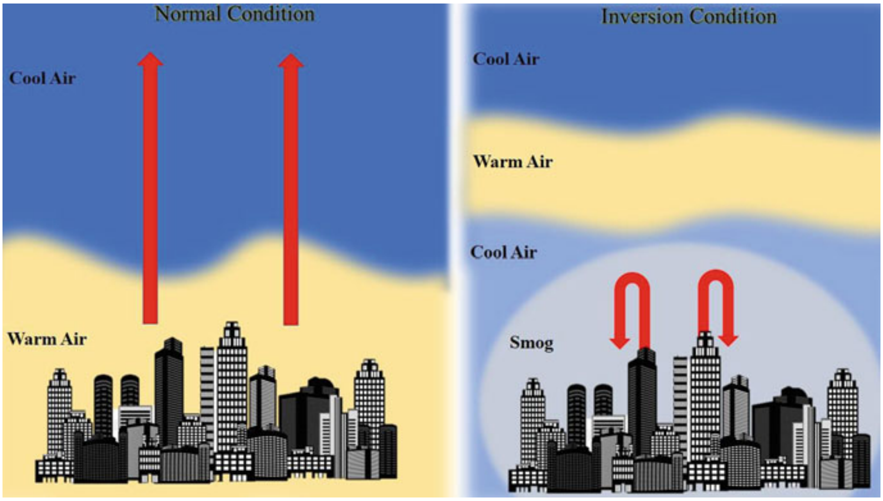


Fig. 9.7 Normal atmospheric unstable conditions, with air in contact with a warm surface, and layer of cool air above while inversion conditions are when stable conditions persist. The layer of air in contact with the surface is cool with a warm layer of air sandwiched between two layers of cool air. Under such conditions, the pollutants released and formed at the ground level get trapped at the surface level. This provides ideal conditions for smog formation and persistence at the surface level. It continues to persist until the inversion layer breaks

of Punjab and Haryana. Wind speeds also slows down. The geography of IGP is truly cursed—it is like a hugely populated and polluted low-lying valley, surrounded by Himalayas in the north and Vindhyas in the south. Without any possible outlet and low wind speeds, the pollutant emissions thus collect and accumulate in this landlocked, low-lying valley, which is also known as the valley effect. Moreover, heavy emissions from industries, vehicles, biomass burning activities, etc., cause an even intense pollution, specifically, over major cities like Delhi, Kanpur, and Varanasi, especially when temperature inversions are prevalent.

Ground-level emissions of pollutants under these circumstances lead to fog transformation into smog. The aerosol formation is one of the key mechanisms of smog manifestation. The abundance of nitrogen dioxide (NO_2) in the ambient atmosphere of northern India results in its reaction with hydroxyl radical (OH) and forms nitric acid ($HONO_2$), which can further undergo reaction with ammonia (NH_3) to generate ammonium nitrate (NH_4NO_3), which is an important contributor to the secondary aerosol formation in urban and regional settings.

$$\mathrm{OH} + \mathrm{NO_2} \rightarrow \mathrm{HONO_2}$$

$$\mathrm{HONO_2} + \mathrm{NH_3} \rightarrow \mathrm{NH_4NO_3}$$

Hydrogen peroxide is very soluble in water and can also react very rapidly with sulfur dioxide (SO_2) in cloud droplets or on wet aerosol surfaces to form sulfuric acid

(H_2SO_4). The ambient SO_2 can be transformed into sulfate, which further transforms into sulfate particles. Moreover, sulfuric acid can also undergo reaction with ammonia and create ammonium bisulfate (NH_4HSO_4) and ammonium sulfate [$(NH_4)_2SO_4$]. Under low humidity levels, these persist as solid particles, while under high levels of humidity, these continue to persist as solution droplets, henceforth causing visibility reduction.

$$H_2O_2 + SO_2 \text{ (aqueous)} \rightarrow H_2SO_4$$

9.4.4 Road Dust, Construction, and Demolition

Road dust consists of solid particles that are generated by mechanical processes like crushing, grinding, impaction, detonation, and decrepitation of materials like rock or ore (Khan and Strand 2018). When vehicles ply on roads, any resulting friction of tyres moving on the roads causes the dust to become airborne which is then known as the road dust. This road dust, along with the construction and demolition (C&D) dust, are key contributors to pollution in the Indian cities (Guttikunda and Gurjar 2012; Guttikunda 2012). A contribution of nearly 131 Gg year^{-1} has been reported from windblown road dust for PM_{10} (Sahu et al. 2011). High concentrations of heavy metals like lead, nickel, and chromium have been reported from the road dust samples of industrial areas (Suryawanshi et al. 2016). Similarly, vehicular sources contribute high levels of zinc, copper, and barium, while industrial sources contribute high concentrations of cobalt, chromium, copper, and manganese (Rajaram et al. 2014).

Jain et al. (2020) studied source apportionment of $PM_{2.5}$ and PM_{10} using three different models and observed that road dust has significant contribution in both $PM_{2.5}$ and PM_{10} levels of Delhi, though the percentage contribution of road dust varies with season and model. Road dust emits more particles in the coarser particles range and these coarse particles then become major components of smog, reducing visibility after being suspended in the air. About 22.4% of the PM_{10} mass were contributed by soil dust, the largest contributor among all the major sources of PM_{10} mass concentration (Sharma et al. 2014).

This source largely contributes to the coarse PM_{10} pollution, and several factors like vehicle movement on roads, type of roads, silt loading on the roads, and prevailing meteorological conditions determine the quantitative contribution of road dust. It can be managed by strategic planning and measures like wet sweeping, vegetation, landscaping, road pavement, and maintenance that prevent dust resuspension (Sonwani et al. 2021; Sonwani and Saxena 2021).

For dust management, the Ministry of Environment, Forest and Climate Change issued a dust mitigation notification in January 2018. Under this, efforts were taken to reduce air pollution via compulsorily including dust mitigation measures in infrastructural projects and demolition activities nationwide. However, the compliance of these rules is still an issue, especially in smaller cities.

9.4.5 Lack of Source Identification Studies

With an incessant and continuous rise in air pollution over the Indian cities, research in this area is gradually snowballing and there has been an increase in published work in this area. However, the problem is that it is still widely scattered, with a severe lack of studies discussing the aspects of air pollution pertaining to their sources and eventual impacts.

For pollution abatement, source apportionment is a valuable tool to derive information about the sources of air pollution, and how much they contribute to the pollution levels. Receptor models apportion the measured mass of an air pollutant at the receptor site to its sources of emission. However, the results of receptor modeling approach are representative only of the area within and around the sampling location. Hence, multiple site analysis is required to be conducted to obtain a detailed data set that can give the needed information (Peshin et al. 2017). Moreover, a detailed chemical characterization of emission sources is also needed, for the completion of receptor modeling study. This makes it a comparatively expensive method with inadequate spatial coverage.

Similarly, source modeling is another useful tool to derive information about air pollution over a region and relies on the availability of data including that of vehicles, fuel consumption in the different domains, population, and meteorology. With the help of computational facilities, source dispersion modeling can be achieved.

There have been some source apportionment studies that have been conducted over North India—such as Kanpur (Rajput et al. 2018), Mirzapur (Murari et al. 2020), Varanasi (Murari et al. 2020), Delhi (Srivastava et al. 2008; Sharma et al. 2014, 2016a, b; Jain et al. 2017, 2020), and Patiala (Singh et al. 2016). However, it is vital to develop these data and use preexisting knowledge as a tool to design effective pollution strategies in India.

9.4.6 Inefficient Waste Management

Several million metric tonnes of municipal solid waste are generated annually in India, which is a cause behind the numerous environmental and health problems, and still, unsustainable practices of solid waste management continue to plague the North Indian cities. These include open burning, landfill fires, and incineration that are a common sight all over Northern India. Open disposal and burning of MSW are becoming a serious issue. The burning of waste products like plastic and rubber releases noxious fumes containing dioxins and furans in the ambient atmosphere, while burning of e-waste releases harmful toxins like cadmium, dioxin, and furans.

Landfills are the most commonly implemented practice for waste disposal in India. However, a key problem is the lack of an effective design and planning for a scientifically engineered landfill. This results in several environmental problems, expanding into severe health problems. For instance, methane emissions, groundwater contamination from the toxic leachate, and soil pollution are all commonly observed scenarios over the North Indian landfills, or more commonly mere dumpsites. There are several landfills scattered across North India dented with occurrences of hazardous methane emissions leading to frequent fire outbreaks, mudslides, smell nuisance, and diseases for the people residing there. Methane not only is a much potent greenhouse gas but also is a key precursor to ozone formation, which is a major ingredient of smog (Sharma et al. 2017).

Incinerators are another way to tackle the solid waste problem and are slowly gaining ground in India. However, since majority of the waste has high moisture content, therefore, waste burning in incinerators becomes an inefficient process, which worsens air pollution further through emissions of toxic gases and particulates, while offering little to no benefits for solid waste management. These are also precursors to ground-level ozone formation and hence contribute to smog.

9.4.7 Impacts

9.4.7.1 Health Impacts

The smog events over northern India are a health emergency. In fact, during the intense smog days, the government declared it as a public health emergency and all schools, offices, and government centers were shut down. The primary impact of such recurring smog events is on health. Poor air quality is like an invisible danger, and smog can be thought of as a "slightly visible, but highly perilous danger" significantly affecting body function. We breathe every second of our lives, taking about 20,000 breaths per day and undoubtedly, our health is strongly influenced by the air we breathe. So, many people die prematurely due to diseases of the respiratory system, such as asthma, bronchitis, and lung cancers, affecting every individual beyond the barriers of status, age, or place of habitat.

Air pollution comes consistently at the top risk factors for death and disability. Some of these effects are short term; for example, WHO reports that high pollution events can trigger asthma or lead to a spike in hospitalization related to cardiovascular and respiratory disease, while long-term exposure could lead to an increase in the potential of developing chronic heart and lung diseases and also cancers. On an average, it has been studied that air pollution can reduce life expectancy. On an average, citizens living in the IGP region did lose nearly 7 years of their lives, because of bad air quality, especially with respect to fine particulate pollution (Greenstone and Fan 2018). A special report on global exposure to air pollution and its disease burden, the State of Global Air, outlined that in the year 2017, air pollution was identified as the fifth major risk factor that causes the highest mortality in that year, with nearly 4.9 billion deaths. Due to air pollution, premature mortality and rise in disease burden could be evident, particularly higher in low- and middle-income countries.

Millions of people living in the northern region account for 40% of the Indian population residing in the country, and all of them are at varying levels of risks and impacts. Rise in pollution over this region has caused a drastic change in its health burden, patterns of diseases, their composition, the type of dominant disease, morbidity and mortality determinants, etc. The report of the Global Burden of Disease stated that air pollution was a large risk factor for disease burden, second only to malnutrition, in 2016.

Even though air pollution continues to plague India nationwide, high concentrations of particulate matter in the north, including cities of Delhi, Gurgaon, Ghaziabad, Chandigarh, and Kanpur, are prominent. Studies have also indicated proof of irreversible health damage of children residing in polluted cities such as Delhi, especially vulnerable are those who walk to school alongside polluted, busy roads (Slutsky 2017). Restricted outdoor activities because of smog are another disadvantage for these children, being deprived of physical activity, in their growing years. Poor air quality during smog could reduce the lung capacity, trigger headaches, and lead to sore throat, coughs, fatigue, and cancers (Sonwani et al. 2022).

The annual exposure of the Indian population to ambient $PM_{2.5}$ was highest compared to the world, in the year 2017 (89·9 $\mu g/m^3$) (Balakrishnan et al. 2019). The disability-adjusted life year (DALY) is another parameter used to measure the burden of disease and is an expression for the number of lost life years as a result of disability, bad health, or premature death. Balakrishnan et al. (2019) reported that DALY rate for the ambient air particulate matter was highest in the North Indian states—Uttar Pradesh, Haryana, Delhi, Punjab, and Rajasthan. Rizwan et al. (2013) identified significant associations of air pollution with adverse health outcomes and its severe effects on respiratory functions and morbidity.

All Indian states had annual population-weighted mean ambient $PM_{2.5}$ higher than the recommended levels by the WHO. In fact, states especially Uttar Pradesh, Rajasthan, etc., had some of the highest levels of both ambient and household air pollution levels, while citizen of states like Delhi, Haryana, and Punjab was exposed to some of the highest particulate matter pollution in the country.

India has been witnessing a continuous upsurge in the cases of chronic obstructive pulmonary disorder (COPD) mortality, and this is projected to be among the highest in the world (Bhome 2012). The National Family Health Survey (NCMH) estimates showed that there were around 17 million COPD patients in India, most likely to reach 22 million by the next 10 years. The Indian Council of Medical Research (ICMR) conducted a questionnaire-based study with several thousand respondents from urban and rural areas. It was revealed that nearly 4.1% of surveyed individuals (5% males to 3.2% females) were affected by COPD.

However, a much bigger challenge is resource constraints for conducting effective large-scale surveys based on spirometry. Mostly, the studies and estimations are done using questionnaire-based methodologies. The understanding of air pollution sources and events over the northern plains and its critical relationship with trends in air pollution levels, population structure, underlying disease, and economic factors will help estimate the air pollution effects. These trends will help to develop an understanding of the air pollution trend over the northern plain, which will be helpful to take requisite actions to reduce pollution in ways that have the greatest potential to benefit health.

9.4.8 Visibility Reduction

Visibility is the measure of how well an observer can view a scene. It serves as a good measure to specify a location's air quality given the fact that even laypersons can recognize when it undergoes impairment. Horizontal surface visibility range is critical not only for ease of movement of the surface transportation, but also for the aviation sector (Jaswal et al. 2013). The reduction in visibility occurs when tiny particles and gases in the atmosphere cause scattering or absorption of light. Internationally, fog is defined as a phenomenon when visibility is less than 1 km (Kumar and Goyal 2014). Smog is a dispersion of smoke within fog, and hence, visibility reduction is a part of it.

The impact of air pollutants on visibility reduction in the North Indian cities has been studied and reported (Choudhury et al. 2007; Guttikunda and Gurjar 2012; Sati and Mohan 2014; Ravindra et al. 2020). Most studies conclude that during winters, dense fog or smog is mostly widespread all through the north and northeast plains including the Indo-Gangetic Plain region, which results in visibility reduction, sometimes down to just a few meters. Jaswal et al. (2013) reported that winters coupled with fog, water vapor, and aerosol pollution led to a nationwide decrease in visibility, especially over the IGP.

Meteorological factors such as temperature, wind speed, wind direction, relative humidity, rainfall, and air pressure are key determinants for air pollution over a region. In the ambient atmosphere, the rate at which one pollutant is transformed into another depends upon these meteorological factors like availability of moisture, sunlight, and clouds, whereas the atmospheric vertical temperature determines pollutant's lifetime in the ambient atmosphere—whether they will get mixed or diluted or get trapped and accumulated. During the cleanest, clear, and windiest days, the emitted pollutants are well mixed in the ambient atmosphere. However, under stable conditions, either the pollutants will form a plume or stagnate over the site to form haze.

Low-visibility conditions are challenging for transportation and general movement and consequently lead to economic losses. Yadav and Rawal (2016) reported extremely poor visibility conditions during November 2016, down to around 200 m. Poor visibility was caused by dense smog over the IGP even before the fog season started and had thrown flights and rail schedule out of gear. In 2017, the smog event led to the delay of 69 trains and rescheduling of many others, while a lot of others were canceled. In 2019 smog event, nearly 150 flights got impacted, some diverted, and hundreds were delayed and canceled. Low visibility during this time also led to a high number of road accidents and affected the day-to-day life of people living in northern India.

The aviation sector in India is huge, and domestic and international air traffic is continuously increasing. For instance, Delhi's Indira Gandhi International (IGI) airport is ranked one of the busiest in the country and worldwide, meanwhile significantly contributing to Delhi's and national gross development product, as per a survey by the National Council for Applied Economic Research.

The dense winter fog affects flight operations of IGI airport, causing interruptions, alterations in flight departures, or cancelations, trigger significant economic losses. A growing intensity and frequency of fog events over north India have resulted in significant increase in the low or poor visibility days during the last five decades. Kulkarni et al. (2019) reported that the number of fog/smog-ridden days with visibility less than 1000 m and dense fog/smog days with visibility less than 200 m over Delhi have doubled up in the last three decades. This severely affected flight operations, leading to increased diversion, delays, and cancelation of flights, ultimately causing economic losses to aviation industries, worth millions of rupees.

9.4.9 Economic Losses

The World Bank and the Institute for Health Metrics and Evaluation (IHME) at the University of Washington, Seattle, collaborated for a study and reported that governments across the world are prioritizing pollution control at the top of their agendas. However, any expenditure done for this will ultimately be competing with other budgetary priorities and policy objectives, further increasing an economic burden, particularly on developing nations. On a global scale, premature deaths due to air pollution are responsible for several trillion worths of losses annually (World Bank and IHME 2016).

Countries that have a greater proportion of younger population tend to suffer from higher pollution-related income losses because children have more years remaining in their lifetimes in which they are likely to work. If we start accounting for the mortality effect of the pollutants, the monetary burden is likely to increase substantially. However, most of this monetary burden of air pollution gets unnoticed and the impacted individuals continue to bear it.

Maji et al. (2017) reported that the particulate air pollution is a grave concern in urban cities in India. The study reported losses increasing from 0.34 million to 0.75 million due to PM_{10} triggered total DALYs from year 1995 to 2015. Due to PM_{10}, the estimated total costs for 2005 increased from 2714.10 million to 6394.74 million, almost by 135%, over Delhi, while a nearly 59% increase, from 2680.87 million to 4269.60 million, was observed for Mumbai, from 1995 to 2015 (Maji et al. 2017). For the non-OECD (Organisation for Economic Co-operation and Development) economies, including India, the welfare costs from premature deaths are projected to increase, from USD 1.7 trillion in 2015 to reach USD 15–22 trillion by 2060 (OECD 2016).

Ghatak et al. (2016) described the challenges of economic losses due to air pollution. They discussed that urbanization has not been carried out in a structured manner, which triggered different problems like air pollution, and the resulting diseases have caused more income loss than any other disease. Loss of wages and loss of labor productivity caused the consequential loss of household income, especially in an economy where labor is majorly manual and informal. It is this informality that adds to the vulnerability of those affected, as casual employment signifies that all income losses will be borne by them.

9.4.10 Agricultural Loss

Cities are expanding, as a result of which the agricultural areas within the cities are interspersed with built-up areas and industry. They are therefore more exposed to air pollution also. The smog levels and air pollution are severe problems that eventually lead to crop yields being damaged. Burney and Ramanathan (2014) reported that significant impact on the crop yields is being observed due to the short-lived climate pollutants (SLCPs). States like Uttar Pradesh and Punjab in the IGP region are hit especially hard. In 2010, a 18.9% yield loss for wheat was particularly due to the SLCPs, translating roughly to 24 million tons of wheat loss worth almost 5 billion dollars. Burney and Ramanathan (2014) also asserted that increasing temperatures due to global warming also has significant negative impacts on crop yields. SLCPs like black carbon and ozone trigger climate change, influencing temperature, precipitation, radiation, etc., which then directly affects the plant yield and agricultural productivity (Sharma et al. 2016a).

Similarly, negative impacts of air pollution on the crop yield in Varanasi were corroborated when air pollutants like SO_2, NO_2, and O_3 were monitored alongside measurements of respective plant responses—their physiological characteristics, pigment, biomass and yield, and parameter reductions like biomass accumulation, yield, etc. (Agrawal et al. 2003; Agrawal et al. 2006).

Debaje (2014) reported that the highest winter wheat relative yield loss (RYL) was estimated in the North Indian states, where normally high O_3 concentrations prevail due to high NOx emissions and favorable atmospheric conditions for photochemical O_3 formation. O_3 damages the plants as it gets absorbed via stomatal pores on the surface of the leaf. It leads to formation of free radicals, which then attack the cell membranes, causing yellowing, cell injuries, bronzing, reddening, etc., grossly affecting the flowering, crop growth, and crop yield. The exposure of ozone concentration above 40 ppb can cause yield loss and many other agricultural losses. Nearly 90% of the vegetation is affected due to the ozone. Gupta et al. (2017) also reported reduced wheat yields in India by about 5.2%.

9.5 Conclusion

Smog has existed since the thirteenth century. Only the advancement in science during the mid-twentieth century revealed the pollutant species and their hidden chemistry behind it. The awareness coupled with stringent legislations helped many countries combat it. Presently, India is facing the same situation from last decade and the concern of scientists, government, and the public shifted toward the rising extreme events of smog over the Northern India.

The reasons for the rising trend of smog events across the North India are numerous. The unique, almost ill-fated, geography of Northern India creating a valley effect, the rise in the emission of pollutants due to the boom in population, industries and energy sector (thermal power plants), etc., turned it into the smog center of our country. The stubble burning during the post-monsoon season is a well-recognized contributor of air pollution, is one of the reasons for formation of smog over northern India. The change in meteorological conditions after the monsoon season and during winters reverses the wind flow. The northwesterly winds transport pollutants emanating from the burning croplands to other IGP states.

The rising and intensifying smog events create a great number of problems not only for the people living in the northern region but also for the whole country. Even though the pollution events are being incessantly and largely observed, only some information is available on the social, economic, and health impacts of smog.

A vast number of studies have been conducted to identify the causes of these smog events, and presently, we do understand the key sources, which roots the foundation of smog over Northern India, but still every year, the region continues to get trapped under these perilous conditions. Immense challenges such as rising population and urbanization, increase in power and goods demand, rising waste production in urban areas, non-compliance of air pollution norms by industries and the general public, and the lack of adequate public transport facility are reasons that make a smog-free winter in North India a distant dream.

There is no doubt to the fact that the frequency of what used to be unusual events has risen in the past few years. There is a strong need to reassess the current situation and adopt measures that are sustainable, innovative, and in sync with the present technologically progressive setup. Policies about air pollution mitigation should be more pragmatic, involving sustainability not merely as an adjunct addition. One of the best ways to spur action in this regard is through education and awareness campaigns. Small initiatives by individuals who care to bring change can go a long way to tackle this problem at the very base.

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10

Volcanic Emissions: Causes, Impacts, and Its Extremities

Rahul Kant Yadav, Debasish Mahapatra, and Chinmay Mallik

Abstract

Volcanoes are an extreme expression of the mostly invisible movements of the fragments of the earth's crust connecting the interior of the earth to its exterior. Since eons, they have had a major impact on the exterior surface of the earth and its gaseous envelope modulating the earth's surface and its atmosphere. Depending on the type, intensity, and location of an eruption, the impacts can be both short term and long term, mild to extreme. The intensity of a volcanic eruption represents its explosivity in terms of volume of material ejected, ejection height, and distance the volcanic cloud travels away from its origin, which can span a wide range of scales. The requirement of a logarithmic scale to classify an eruption itself indicates how extreme one volcano can be compared to another. Volcanic emissions encompass all the three states of matter with tephra in solid form, lava in liquid form, and several acidic gases. The volume of ejected material for a very large eruption can amount to several cubic miles as in case of Krakatau (1883). Strong eruption can be related to silica-rich magma leading to large viscosity enabling trapping of gases until pressure builds up high enough to cause explosive eruption. The atmospheric impacts of volcanic eruptions range from small particles and ash playing havoc with aviation to ozone-depleting gases to global cooling as a result of emitted sulfur gases. The most explosive volcanoes can easily reach over 20 km and can lead to several feet of ash even 150 km away from the eruption site. Relationships between volcanic events and ENSO are an active field of research. Severe volcanic eruptions like Mt. Pinatubo have had an impact in all the five major spheres of the earth including the lithosphere,

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hydrosphere, atmosphere, biosphere, and the anthroposphere. The potential severe consequences of volcanic eruptions demand greater awareness and investigation of these extreme events with extreme consequences.

Keywords

Volcano · Eruption causes · Extreme events · Atmospheric impacts · Tephra · Volcanic gases

10.1 Introduction

The earth as a planet is dynamic. There are forces on and inside the planet that bring about drastic changes to the planet's interior, surface, and its gaseous envelope, the atmosphere. While the surface forces change the surface of the planet gradually in hundred thousand and millions of years through various exogenic processes like weathering and erosion, there are other changes that may be brought about by endogenic processes. Endogenic processes include diastrophic processes (orogenic or mountain-building processes and epeirogenic processes or continent-building processes) and sudden movements like earthquakes and volcanism.

A volcano is a rupture on the earth's crust through which hot lava, volcanic ash, and gases are spewed out during the course of the eruption from a magma chamber underneath the surface. Most of them are found near the tectonic plate boundaries, where they converge and subduct or diverge. Volcanism can be caused by diapirs 3000 km deep within the earth forcing their way from the core–mantle boundary, with impacts far away from plate boundaries. As a result of this hotspot, volcanism occurs, for example, the Hawaiian hotspot and the Reunion hotspot. As the planet's 71% of total surface area is covered by water, it is only logical that most of these volcanoes are found underwater. Depending upon the type and region of eruption, a volcanic eruption may have a very profound effect on the atmosphere and the environment. They have the potential to change the global climate. As a matter of fact, this has occurred in the past geological age. The evidence of these ancient catastrophic eruptions can be found in the stratigraphic column in many places in the world. Other proxies include evidence of tephra deposits from ice cores and from tree rings, which make valuable paleoclimatic proxies to effectively describe the impacts of volcanic gases and tephra on the atmosphere. While the impacts of volcanic eruptions can be alarming and devastating, their scale and magnanimity provide fascinating and awesome insights. The Vesuvius eruption in 79 AD, despite the damage caused, preserved for us Pompeii and insight into that civilization (Capellas 2007). The Toba eruption in Indonesia was suspected to spew almost 230 cubic miles of erupted material on the planet's surface 75,000 years ago. Indonesia is a region of large eruptions with Mt. Tambora being one of the most explosive ones, killing thousands of people and eclipsing the sun in 1815. The Mt. Pelee eruption notoriously subdued a whole city in its lava killing thirty thousand people in the Caribic in 1932. The Pinatubo eruption of 1991 is known all across the globe for its explosivity and atmospheric impacts including plummeting temperatures and large-scale ozone depletion. The most famous observatory for climate research is located in the cradles of one of largest volcanoes of the world, the Mauna Loa. While eruptions like Krakatoa (1927) have left us with fear due to the devastating effects, eruptions like that of the Etna are impacting the earth and its atmosphere for millions of years now. Though India is a region to many extinct volcanoes, there are also active ones as in Barren and Baratang Islands. However, volcanic eruptions do not recognize any borders and plumes can span transoceanic and transcontinental domains. The Dalaffila eruption in Ethiopia caused SO_2 enhancement as far as Delhi in India (Mallik et al. 2013).

As volcanoes can connect the whole world in terms of their impacts, it is necessary to understand the science of volcanoes in reach of common people. The rationale of this book chapter is to provide a holistic walk pertaining to volcanoes and their atmospheric impacts. It aims to simplify and summarize the information available regarding volcanic eruptions from an atmospheric science perspective. First, we introduce the different types of volcanoes and then discuss the causes of volcanic emissions. This discussion is followed by the impacts of volcanic emissions mainly from an atmospheric and climate perspective and ends with the case study of the most famous volcano the Mt. Pinatubo of 1991.

10.1.1 Types of Volcanoes

To understand the magnanimity of volcanic eruptions, it is essential to understand the type of volcanoes and how they erupt. Depending upon the basis of classification of structure or activity, volcanoes can be grouped into several types as mentioned below.

10.1.1.1 On the Basis of Activity

(a) **Active volcanoes:** According to the Smithsonian global volcanism program, a volcano is considered active if it has erupted in the Holocene within the last ten thousand years. Most active volcanoes can be traced to the Pacific ring of fire. According to the Smithsonian global volcanism program, a volcano is considered active if it has erupted in the Holocene, i.e., in the last 10,000 years, while the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) considers historical times to define active volcanoes. So, there is actually no consensus among volcanologists on the definition of an active volcano. Most active volcanoes are situated on the Pacific Ring of Fire. A map of active volcanoes is shown in Fig. 10.1. The Smithsonian Global Volcanism Program (SGVP) has documented till date about 560 volcanoes whose historical eruptions have been confirmed (Global Volcanism Program 2013). Despite the fact that the SGVP has documented over 10,000 Holocene eruptions, only six eruptions account for more than half of the total quantified fatalities (Cottrell 2015).

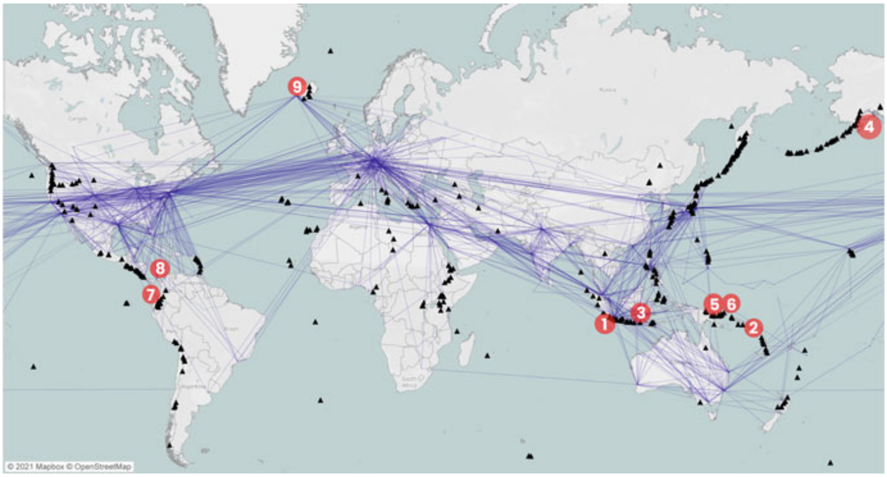

Fig. 10.1 Active volcanoes around the world and the top nine most explosive volcanoes of the past 2000 years superimposed on global aviation route map. (1) Samalas, in 1257. (2) Kuwae of 1452. (3) Tambora in 1815. (4) Mount Churchill in 700 CE. (5) Rabaul Caldera between 531 to 566 CE. (6) The Rabaul caldera in Papua New Guinea is the fifth and sixth from 531 to 566 CE. (7) Quilotoa in 1280. (8) Ilopango in 450 CE. (9) Grimsvotn and Laki eruptions around 1785. The active volcano locations are based on https://volcano.si.edu/list_volcano_holocene.cfm#. The route data are taken from https://openflights.org/data.html and filtered on Codeshare and Airline. The Codeshare filter keeps null. The Airline filter keeps 13 members. The view is filtered on exclusions (Destination airport, Path ID, Source airport), which keeps 75,174 members (*illustration*: Debasish Mahapatra & Madhumay Mallik)

(b) **Dormant volcanoes:** Dormant volcanoes are the ones that have not been associated with any eruption in the last ten thousand years but may erupt in the near future. Such volcanoes can erupt suddenly after remaining dormant for a fairly long time and then. The Geological Survey of India has classified the Narcondam Island in the Andaman and Nicobar archipelago as a dormant volcano. Other examples are Mount Kilimanjaro in Tanzania and Mount Fuji in Japan.

(c) **Extinct volcanoes:** They are the ones that are thought unlikely to erupt again most likely because it does not have a magma supply. Some examples of extinct volcanoes are Hohentwiel of Germany and Zuidwal in the Netherlands. It is difficult to determine whether the volcano is fully extinct. There are also many active volcanoes in India dating about 750 million years before present.

10.1.1.2 On the Basis of Structure

On the basis of structure, volcanoes may be identified as fissure volcano, shield volcano, composite volcano, supervolcano, submarine volcano, and subglacial volcano. The internal structure of a volcano is shown in Fig. 10.2 along with the eruption cloud.

(a) **Fissure volcano:** Fissure volcanoes are fractures on the earth's crust through which lava flows. Large fissure eruptions are considered as one of the hazardous

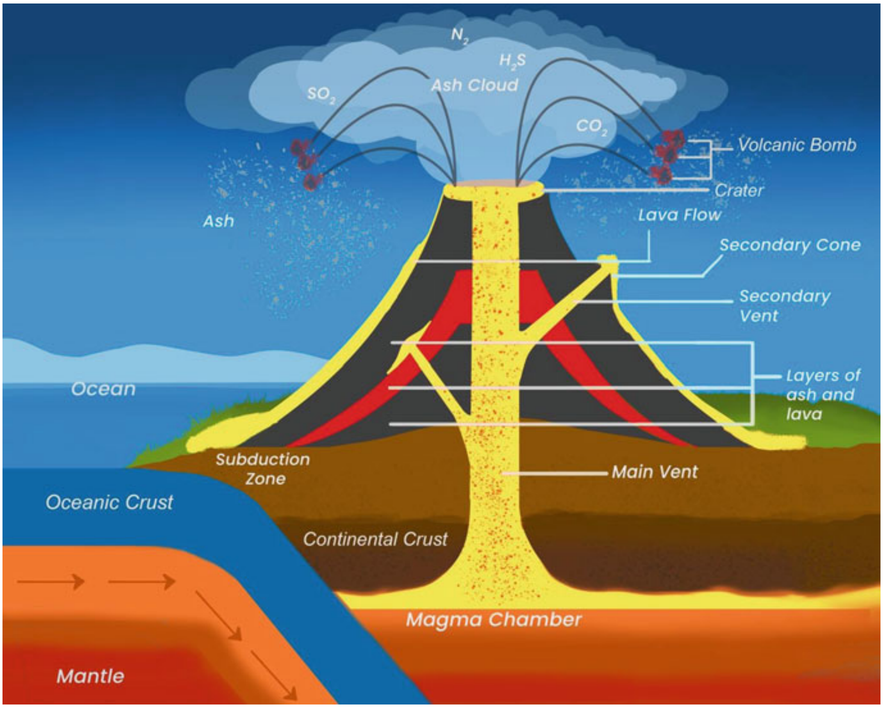

Fig. 10.2 Structure of a volcano (adapted from abc.net.au and modified)

volcanic situations because of their huge arrival of gases and aerosols into the troposphere and lower stratosphere (Ilyinskaya et al. 2017). The Holuhraun eruption in Iceland in 2014–2015 is one of the biggest such occasions.

(b) **Shield volcano:** It is a large volcano with a very large diameter and very gentle slopes. The name suggests the similarity of its structure to that of a warrior's shield. It is a low-angle volcano formed by the piling up of low-viscosity lava flow, mainly basaltic lava (Paris 2013) Most of these volcanoes are in the mantle plume region and a result of hotspot volcanism. The magma is almost always mafic, basaltic, and basic, and the eruption is generally effusive. They include the largest volcano on earth like Mauna Loa in Hawaii. Giant shield volcanoes are also discovered in Mars and Venus. The largest volcano in the solar system is found on Mars, known as Olympus Mons, and is interestingly a shield volcano. Sapas Mons of Venus is another example of giant shield volcanoes in the inner planets of the solar system.

(c) **Composite Volcano:** They are the most common types of volcanoes. Almost all of these volcanoes are found near subduction zones, i.e., destructive plate boundaries. The lava is acidic, felsic, and ranges from rhyolitic and dacitic to andesitic. Because the lava is highly viscous and has relatively lower temperature than basic lava, it solidifies rapidly. The rapid solidification of lava in the vents sometimes clogs it and thereby increasing the pressure in the vent. This results in a loud explosion, and the volcano throws a large amount of volcanic bombs and other pyroclastic material. These volcanoes can also be commonly known as stratovolcanoes as they are built by many layers of solidified felsic lava and tephra. These volcanoes have steeper sides and a summit crater that erupts periodically. Some of them have collapsed summit craters called Calderas. Owing to its high viscosity, the lava does not flow extensively. Examples of stratovolcanoes include the Krakatoa in Indonesia, which had a catastrophic eruption in 1883 and the recent Mount Pinatubo eruption. Simkin and Siebert (1994) said that at least 700 stratovolcanoes are active. Pyroclastic density currents, also called pyroclastic flows, which are sort of an avalanche of volcanic tephra, are possibly the most catastrophic among all impacts of volcanic hazards. The density of the current, the gradient of the slope, and the volcanic output rate are deciding factors of its speed. Its kinetic energy is enough to vanquish building, trees, crops, and almost everything in its path. They can incinerate any living organism and that is what makes it particularly so lethal. Example of such an event was the devastation of Pompeii when it was, along with some of its inhabitants, buried by the pyroclastic flows from the eruption of **Mount Vesuvius in 79 CE**. Stratovolcanoes are on the eighth out of top ten killer volcanoes over twentieth century (Witham 2005), and it has killed more than 0.2 million people since 1783 AD (Tanguy et al. 1998). Mount St. Helens, a stratovolcano in Washington state that erupted on May 18, 1980, caused devastation of 200 sq. miles of forest winds that carried the volcanic ash eastward over the USA during the day, causing total darkness in Spokane, Washington, 236 miles from the volcano (Nania and Bruya 1982). Stratovolcanoes have the most considerable effect on local weather and can also considerably affect the climate of one or both hemispheres and significantly modulate the atmospheric chemistry and the earth's energy balance.

(d) **Supervolcano:** According to the USGS, these eruptions can exhibit of Volcanic Explosivity Index (VEI) of 8 and have ejected more than 1000 km^3 of materials. VEI is used to measure the explosiveness of an eruption. Supervolcanic eruptions are extremely rare and the most dangerous types. Supervolcanoes can also be associated with formation of widespread lava flows and basaltic traps, and Deccan traps in India and Siberian traps in Russia are such examples of such large igneous provinces (LIPs). These are very large eruptions and can usually be related to hotspot (Yellowstone) and destructive plate boundaries (Toba) (Wotzlaw et al. 2015; Budd et al. 2016). These can cause lasting changes to the climate and can cause extinction events. The Siberian Traps coinciding with the Permian–Triassic extinction event are the largest flood basalt event and were formed around two hundred fifty million years ago and. The Deccan Traps are produced by the Réunion hotspot, currently lying in the Indian Ocean under the Réunion Island, some 66 Mya, and are coincident with the Cretaceous–Paleogene extinction event (Keller 2014).

(e) **Submarine volcano:** More than 70% of all volcanic eruptions occur underwater. Submarine volcanoes are the volcanoes that are formed underwater. Most submarine volcanoes are found near divergent plate boundaries in the mid-oceanic ridge. The total number of submarine volcanoes is indeed very high and easily reaches a million, although most of these types of volcanoes are now extinct (Speight and Henderson 2013). Most submarine volcanoes are found in deep waters, but some are present in shallow waters and reveal their presence when they erupt with steam and eject rock high above the surface of the sea. Hydrothermal vents found near submarine volcanoes are rich sites of biological activity. The unlimited supply of water changes the characteristics of these eruptions. The weight of the copious amount of water prevents explosive eruption of the volcano, and when magma comes in contact with the water, it cools rapidly and turns into Obsidian, which is a volcanic glass and advancing lava flows from pillow lava. **Seamounts** are submarine volcanoes that are extinct and rise abruptly from the seafloor. Despite the fact that no big explosive undersea eruption is yet documented, prevalence of such eruptions is evident from ancient seafloor deposits. Large-scale, caldera-forming explosive submarine eruptions of silicic magmas have occurred on the modern seafloor south of Japan in the geological past, and in 2012, the sea surface expression of such a large-scale explosive eruption was identified for the first time ever (White et al. 2015).

(f) **Subglacial Volcano:** These types of volcanoes are also known by the name of Glaciovolcano, which represents a volcano that is formed beneath the surface of a glacier or ice sheet. Most of these volcanoes are found in Iceland and Antarctica. During the eruption of the Subglacial Volcano, the ice over it melts forming a lake, and the water cools the lava rapidly and thus forming pillow lava shapes similar to underwater eruptions. On a later stage, however the pillow will break off and fall down and form hyaloclastite, tuff breccia, and pillow breccia. If a large amount of meltwater is formed, these volcanoes can produce dangerous floods called a **Jökulhlaup**. A Jökulhlaup is an Icelandic term and refers to a flood that is produced due to a subglacial volcano melting the surrounding glacier. These volcanoes are generally flat in the early stages due to the weight and pressure of the overlying layer of ice and water. But in later stages, they can erupt subaerially and form the more conventional conical shape. In late evening of September 30, 1996, a Jökulhlaup occurred following the subglacial eruption on the Vatnajökull ice sheet, Iceland. On November 7, the Jökulhlaup came to an end. A new subglacial ridge 6–7 km long was produced by volcanic materials with a volume of 0.7–0.75 km^3 and floods affected an area of 750 km^2, stretching the shoreline by 800 m. The eruption and flood were Iceland's fourth largest natural disasters in the twentieth century (Smellie 1999).

10.2 Causes of Volcanic Emissions

Most of the volcanoes are not continuously in a vigorous state of activity. They spend a lot of their life span at rest, typically for thousands of years before eruption. The landforms and eruptive nature of volcanoes are diversified, reflecting numerous complex interactions, which determine how magma is generated, stored, rises up along dykes, and conduits and finally erupts. Eruptions are **inveigled** by the tectonic setting. Additionally, the different properties of earth's crust can impact the final eruption, and hence, the history of the volcano can also play a major role as past eruptions can also modify these governing properties. However, despite the great uncertainty about how and where different volcanoes can erupt, the causes can be mostly grouped into a set of common chemical and physical processes. Understanding the formation and eruption of volcanoes and the consequences of these eruptions can be obtained from an understanding of geographic and geologic processes, which can cause melting of rocks to melt and alter its composition, leading to the storage of molten magma in the earth's crust and eventually causing into rising to the surface, and interact as well as impact the surroundings.

10.2.1 Plate Tectonics

We have already discussed how dynamic our planet is. Events like earthquake and volcanic eruptions have occurred throughout the history and are constantly changing and reshaping our planet. Yet, it is only a few decades ago that we got a glimpse into why these events occurred that could explain almost every important question in the field of geology. It is like the grand unified theory of earth science. This fascinating new theory is called plate tectonics. According to plate tectonics, the crust is broken into many rigid plates and they move horizontally with respect to each other, which means the crust is not stationary, it is mobile, and the continents move around on earth's surface. As these plates move, they interact with each other and these interactions build the most amazing features like mountain belts and volcanoes and deep ocean trenches. The theory was built on the concept of continental drift and seafloor spreading. In the year 1912, a meteorologist by the name of Alfred Wegener described the idea of continental drift and gave the theory in his book "The Origin of Continents and Oceans." This theory was endorsed by the scientific community after the idea of seafloor spreading was validated by the works of W.J. Morgan and J.T. Wilson in the 1960s and 1970s (Bangar 2008).

10.2.1.1 Crustal Plates

The earth's crust is composed of several rigid but relatively thin plates. The earth's outer layers are categorized into lithosphere and asthenosphere. The lithosphere is not only cooler but also more rigid compared to the asthenosphere, which is much more hotter and plastic. On an average, these plates are 125 km thick. Continental plates (200 km) are thicker than oceanic plates (50–100 km). The plates slide over the partially molten and plastic asthenosphere. The asthenosphere occurs below the lithosphere in the upper mantle at depths of 100–200 km. This zone is highly viscous, ductile, and mechanically weak. In this zone, the velocity of seismic waves decreases, and thus, it has been called the low-velocity zone (Forsyth 1975). The LVZ's lower boundary is located at a depth of 180–220 km (Condie 1997). Due to the high temperature and pressure conditions in the asthenosphere, the rocks become ductile and plastic, deforming and moving slowly at speeds of cm/y, and eventually moving thousands of kilometers in millions of years. The rigid lithosphere is thought to float on the slowly flowing asthenosphere (Garrison and Ellis 2016). The plates can move with respect to one another format an annual rate of 0–100 mm (Read and Watson 1975). The earth's lithosphere is divided into 20 crustal plates, of which 7 are large and are called major plates, while the rest are called minor plates. The large plates are as follows: (1) the North American plate, (2) the South American plate, (3) the Eurasian plate, (4) the African plate, (5) the Indo-Australian plate, (6) the Pacific Plate, and (7) the Antarctic plate. Some plates are so large that they are constituted from both continental and oceanic crustal portions like the African plate and the South America plate and North American Plate, while the Pacific plate is almost entirely ocean.

10.2.1.2 Plate Boundaries

Plate margins are regions of meeting of two plates. Almost all seismicity volcanicity and tectonic activity happen around plate margins. The majority of the world's active volcanoes occur along these plate boundaries (Fig. 10.1). Depending open the relative motions of the adjoining plates, the ***plate boundaries can be classified into three types***.

(a) **Divergent plate boundaries**

Divergent plate boundaries additionally known as constructive plate boundaries are places where plates move away from each other. This process happens along spreading center where the plates are moving apart and the magma that rises up from the asthenosphere to fill the newly created gap forming the new lithosphere. This phenomenon is called seafloor spreading. Perhaps the best known example of a divergent boundary is the mid-Atlantic ridge. Such boundaries are characterized by high volcanic activity and shallow focus earthquakes. Most of earth's volcanism occurs on the seafloor along spreading zones. These volcanoes are mostly submarine. Iceland being the most famous exception is on the mid-oceanic ridge and has high volcanic activity. The diverging and thinning lithosphere plates allow hot mantle rock to rise and thus causing decompression melting. Ultramafic mantle rock mostly consisting of peridotite partially melts to produce basaltic magma. This is why almost all volcanoes on the ocean floor are basaltic in nature. This basaltic lava erupts underwater and forms pillow-shaped pillow basalt. Deep-sea hydrothermal vents or black smokers are vents that are tall and emit black hot mineral-rich water near mid-oceanic ridges enable entire ecosystems to thrive underwater. Thus, the oceanic ridges are the newest part of earth's lithosphere. The rates of seafloor spreading at ridges vary from 1 cm to 6 cm per year. Some volcanoes also erupt at continental rifts where crustal thinning is caused by diverging continental plates. One such example is the East African Rift Valley.

(b) **Convergent Plate Boundaries**

A convergent plate boundary, additionally referred to as destructive plate boundary, is the type of plate margin where two or more plates move toward each other. Eventually depending upon the densities, one plate slides beneath the other by a process called subduction. Convergent boundaries occur between oceanic–oceanic plate, oceanic–continental plate, and continental–continental plate. These collisions between the plates have occurred over millions of years and can lead to volcanic activity and sometimes even earthquakes and orogenesis.

Oceanic–continental plate Continental lithosphere is of lower density and thus more buoyant than oceanic lithosphere. By the process of subduction, the denser oceanic plate is pushed beneath the less-dense continental plate when continental and oceanic plates converge. As the subducting plate is forced deeper into the mantle, the temperature reaches the melting point and the plate starts to melt. This partial melting produces magma chambers under the overriding continental plates. And these magma chambers are more buoyant and thus begin its slow ascent often melting and fracturing the overlying layers of rock. If and when a magma chamber rises to the surface, the magma will cause a fissure on the ground and will break through the crust in the form of a volcanic eruption. When multiple eruptions occur in a chain on the overriding plate, it is called a volcanic arc. Some of the well-known examples of continental volcanic are the Cascade Mountains in the western North America and the Andes Mountains in South America. Here, the dense Juan de Fuca oceanic plate dives beneath the North American Plate and the Nazca Plate is subducting under the South American plate, respectively.

Oceanic–oceanic plate The characteristics of a subduction zone in which an oceanic plate is forced to sink under another oceanic plate are the same as a continent–ocean subduction zone. The older, denser plate as mentioned before subducts underneath the less-dense plate. The region where the plate is pushed down into the mantle is marked as an ocean trench. In such a region, there can exist a line of volcanoes that thrives on the upper oceanic plate and is popularly known as an island arc.

Continent–continent plate When two continental plates collide, they can form another type of convergent plate boundary known as continent–continent plate. The continental lithosphere although very think cannot subduct as it is low in density. Thus, during the collision of two continental plates, as subduction of one of the plates is not a possibility, the plates just smash together, which forces the material to up as it cannot go down. The result of the tremendous forces of the collision is the genesis of earthquakes and metamorphic rocks. These continent–continent collision zones are not conducive for volcanoes as the crust is too thick for magma to get through.

(c) **Transform Fault Boundaries**

These are boundaries along which plates slide past one another. Hence, at transform fault boundaries, there is no production or destruction of lithosphere. The transform faults are characterized by shallow focus earthquakes with horizontal slips.

Hotspot Volcanism Hotspot volcanism is different as it does not occur at the zones of convergence and divergence, rather this type of volcanism occurs at the interior parts of the lithospheric plates. The cause of hotspot volcanism can be traced to abnormally hot centers in the mantle, which are commonly also known as mantle plumes.

10.3 Emissions from Volcanoes

The volcanic eruption can be violently explosive to gently effusive and can persist for few hours to several decades (Siebert et al. 2015). The volcanic eruption may get triggered due to internal magmatic system of the volcano or due to external processes like precipitation, landslides, or earthquakes. The magnitude and intensity of the volcanic eruption are usually described by its total erupted mass and the mass eruption rate and were quantified by Pyle (2015):

$$\text{Magnitude} = \log_{10}(\text{mass, in kg}) - 7, \text{and}$$

$$\text{Intensity} = \log_{10}(\text{mass eruption rate, in kg/s}) + 3$$

Newhall and Self (1982) introduced “The Volcano Explosivity Index” (VEI). VEI scale is logarithmic with indices ranging from 0 to 8. The 0 value is given to nonexplosive eruptions, and the largest volcanic eruptions in history are given the value of 8. Events with smaller VEI are usually common, whereas larger VEI events are dramatically less continuous (Siebert et al. 2015).

The style of volcanic eruption includes factors like emission span and relentlessness, extent, gas transition, column height, and association of magma or potentially external source of water. Grouping of eruption style is often qualitative and dependent on historical records of trademark emissions from type volcanoes. Notwithstanding, many sort volcanoes show a scope of emission styles over the long haul, which has led to terms, for example, subplinian or violent Strombolian.

On the basis of the nature of volcanic eruptions, volcanoes can be classified as Plinian, Vulcanian, and Strombolian.

(a) **Plinian eruptions** are highly explosive continuously sending out a variety of ejecta with a wide range of sizes. Pyroclastic flows result from gravitational collapse of Plinian eruption columns or lateral explosions and from gravitational collapse of lava domes (Nakada 2000). The explosive eruption generates an enormous amount of tephra, and belches ash, which can exceed 11 km in height into the atmosphere (Auger et al. 2001). These are accompanied by excessive degassing.

(b) **Strombolian eruptions** are also violent in nature sending out ejecta tens of meters into the atmosphere. Low-viscosity, silica-poor magmas characterize Strombolian eruptions and include the complex bursting of gas pockets around the volcanic vent (Taddeucci et al. 2015).

(c) **Vulcanian eruptions** are short-lived, ash-rich, and generate bombs and blocks. In an early earth, gas from volcanic eruptions resulted in the formation of our atmosphere and produced our oceans, without which life would never have existed on this planet. The volcanic emissions majorly contain water vapor (H_2O), carbon dioxide (CO_2), sulfur gases (SO_2, COS, H_2S, CS_2), and hydrogen halides (HCl, HBr, and HF) (Textor et al. 2004). More than 95% by volume of volcanic gases is comprised of H_2O, CO_2, and SO_2 (Symonds et al. 1994). The abundance of these gases differs considerably from volcanoes to volcanoes. The volcanic emissions reveal the composition of their source magma. The characteristics of volcanic emissions depend on the geological setting of the region where it is located; e.g., eruptions near subduction zones are associated with more water vapor and chlorine (Sigurdsson 2000).

Volcanic emissions include violent eruptions and noneruptive degassing. The degassing process occurs continuously during eruptions and through vents and fumaroles. The degassing determines the type of eruption that will take place. Volcanoes are responsible for about 14% to the global sulfur emissions (Graf et al. 1997). It is a no-brainer that gases emitted from subduction zone volcanoes should be commonly very rich in water vapor (95%). However, in hotspot regions the compositions are different and here volcanic gases are much more CO_2-rich and H_2O-poor (Giggenbach 1996; Wallace 2005). These gas emissions occur not only from the craters, but also from faults, vents, or even through soils or even dissolve in groundwater and springwater.

Although the composition of magmas can be widely variable, in general they are constituted mainly from only eight elements: oxygen, aluminum, silicon, calcium, iron, magnesium, sodium, and potassium. Among these eight elements, oxygen is the most abundant followed by silicon. The magma is formed by melting of rocks, and the magmatic composition depends on the rock it was formed from and the conditions of that melting. Melting induces generation of magma as temperatures rise, pressure is released, and influx of volatiles occurs (Peterfreund 1981).

Most of the magma erupted from volcanoes is of basaltic nature mostly occurring in deep ocean water at the mid-oceanic ridges and forms pillow lava basalt and in hotspot volcanism. When the eruption rate is large, the eruption reaches the atmosphere. The basaltic magma is poor in silicate and rich in magnesium and iron, hence characterized by low viscosity and low gas content. Basaltic magma contributes very less portion of sulfur emissions into the atmosphere and it reaches the stratosphere rarely.

Another kind of magma is called Felsic magma, which is rich in silicate and has high viscosity and is associated with explosive eruptions. Normally, felsic magmas tend to have higher levels of volatile compounds, which are emitted as gases during eruptions. The most abundant volatile in magma is H_2O, followed typically by CO_2, and then by SO_2. Compared to basaltic volcanoes, felsic magma erupts less frequently. Sometimes, they release large amounts of ashes and gases directly into the atmosphere.

10.3.1 Volcanic Material

A volcanic eruption can spew material in form of gases, lava, and tephra as mentioned below:

(a) **Volcanic gases:** In an early earth, gases from volcanic eruption gave us not only our atmosphere but also our oceans without which there would be no life on planet earth. The most common gases from volcanoes are water vapor, carbon dioxide, and sulfur dioxide. Other gases that are also emitted during volcanic eruptions are carbon monoxide, H_2S, HCl, CH_4, HF, etc. The abundance of these gases differs considerably from volcanoes to volcanoes. Due to the addition of seawater in the magmas at convergent plate boundaries, volcanoes near subduction zones erupt with more water vapor and chlorine. Similarly, volcanoes at divergent plate boundaries and at hotspots produce significantly less water vapor and chlorine (Sigurdsson 2000).

(b) **Lava:** Lava is nothing, but magma erupted to the surface due to volcanic eruption. The temperature of lava usually ranges from 800 to 1200 °C. As we know, the eruption can be either effusive or explosive. Effusive eruption causes lava flow by outpouring of lava. Explosive eruptions on the other hand produce volcanic ashes and tephra. There are two basic types of lava flow ***'A'ā and pahoehoe***. While *'A'ā* flow is rough and rubble-like and composed of broken cinder blokes, the *pahoehoe* type is smooth and ropy. The surface is formed due to very fluid lava under a solidified crust.

(c) **Tephra:** Explosive volcanism sometimes ejects materials like rock fragments into the atmosphere. These rock fragments are called tephra regardless of composition or size (Amaral and Rodrigues 2019). Tephra represents airborne pyroclastic material that is ejected during the course of an eruption (Durand and Thorarinsson 1981). Tephra is classified into three size groups: (1) ash, when particles are minuscule to the tune of less than 2 mm in diameter; (2) moderate size particles are called lapilli or volcanic cinders, with diameter between 2 and 64 mm; and (3) large size ejected materials with diameter greater than 64 mm constitute volcanic bombs or blocks. Bombs and blocks are shot from the volcano ballistically. Because these fragments are large, they generally fall near the source. Most particles greater than 1 mm will fall out within hours of eruption. Being smaller in diameter, ash can travel thousands of kilometers from its originating volcano. The wind speed and direction, the air temperature, and the height of the eruption column are the variables that decide the distance that tephra will be transported away from the volcano. Larger particles, lapilli, and volcanic bombs fallout within an hour they are ejected from the volcano. The smallest particles can remain even for a couple of years after the eruption in the atmosphere. Sometimes, they produce amazing sunsets like seen after the 1991 Pinatubo eruption.

10.4 Impacts of Volcanic Emissions

10.4.1 Radiative Forcing

Radiative forcing is a concept to understand change in energy fluxes in the earth atmosphere system. The particles and the gases present in the atmosphere change the balance between incoming solar radiation and outgoing IR radiation (Pulselli and Marchi 2015). The term forcing explains the earth's radiative balance being pushed away from the normal state. The particles present in the atmosphere absorb or scatter solar and terrestrial radiation. Positive forcing is exerted when particles absorb the radiation and it contributes to warming of the earth's surface, whereas negative forcing is exerted when the particles present in the atmosphere scatter the incoming solar radiation and it causes the cooling of the earth's surface (Fig. 10.3).

Volcanism induces short-term climatic variations. The secondary sulfate aerosols (SO_4^{2-}) emitted from volcanoes can change the energy balance of that area (Franklin 1784; Charlson et al. 1991, 1992; Stenchikov et al. 1998). Sulfate aerosols scatter the incoming solar radiation due to their high single scattering albedo. In troposphere, SO_2 gets converted to H_2SO_4 and it increases the aerosol optical depth and the albedo. It causes cooling at the surface (Robock 2000). In the biologically important UV-B region, the average cross section for SO_2 is double of ozone (O_3); thus, for regions of high SO_2, if the changes in UV-B need to be predicted, we must consider the changes in both SO_2 and O_3 columns. Shindell et al. (2003) simulated the volcanic forcing and found that the mean annual cooling for the periodic Pinatubo eruption, Tambora 2P eruption, and Tambora 3P eruption and for the observed 1959–1999 volcanoes were −0.35 °C, −0.77 °C, −1.99 °C, and −0.44 °C, respectively, and the average instantaneous forcing was −0.47, −0.91, −1.39, and −0.44 W/m^2, respectively.

Crop failure and famine have been found to be associated with large eruptions as an aftermath as a result of the cooling produced, the ashes, and gases emitted. Large historic eruptions are aptly documented in archives such as that of 1815 Tambora eruption, which was associated with large-scale global cooling, which had eventually led not only to famine, but also social unrest, and as if this was not enough, this was followed by epidemic typhus, leading to as described beautifully in Oppenheimer (2003) was what came to be known as the "Year Without a Summer". The Laki eruption of 1783 caused several years of crop failure and cold winters leading to death of ~20% of the Iceland population (Grattan et al. 2003; Thordarson and Self 2003).

Without mention of the little ice age, the discussion would remain incomplete. Regional cooling was very intense during this period roughly between 1300 and 1850 AD with temperature in Europe and North America plummeting by as much as 2 °C. This intense drop in average temperatures can be attributed to several large sulfur-rich explosive eruptions, and may be possibly triggered or enhanced by the massive Samalas volcanic eruption in 1257 (Amos 2013). Geological records suggest that throughout the little ice age there was heightened volcanic activity (Robock 1979). Historical evidence suggests that many rivers and lake in Europe

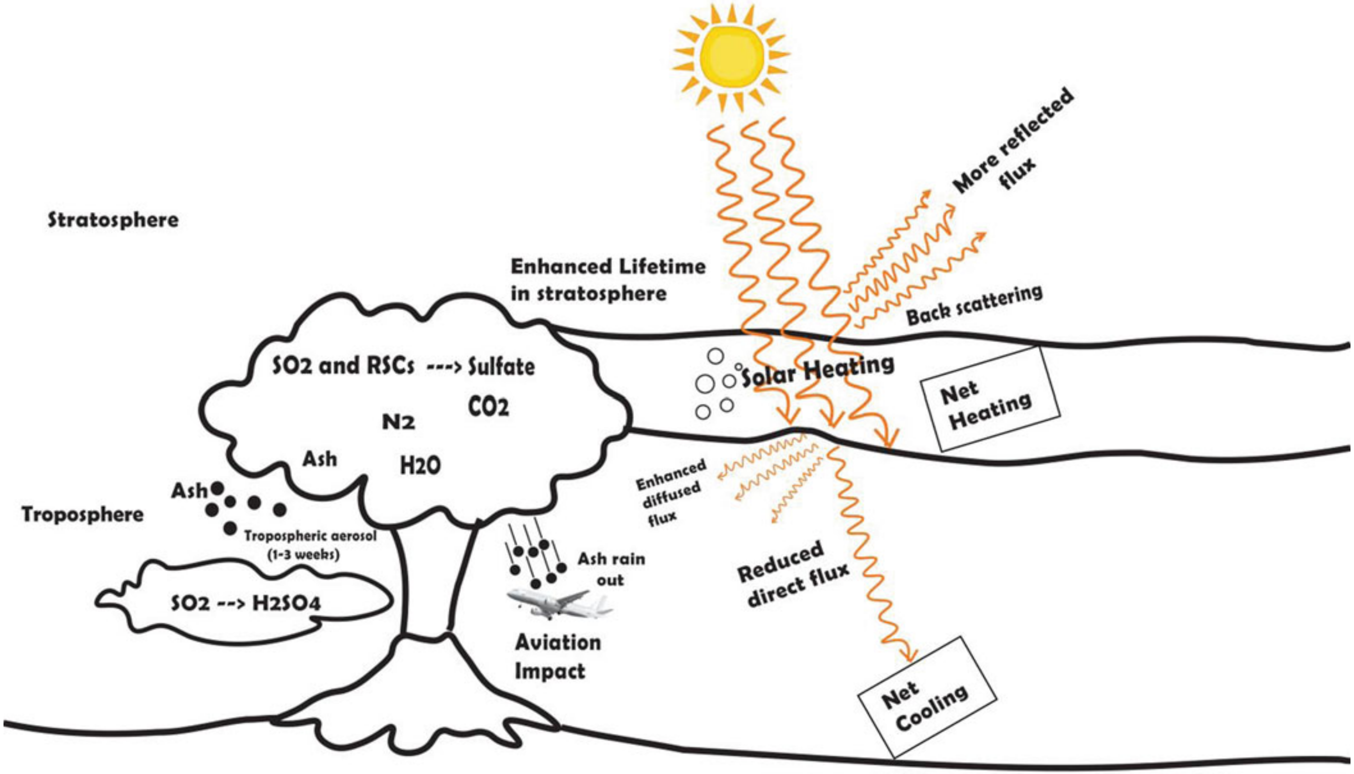

Fig. 10.3 Impacts of volcanic emissions. The impacts range from radiative effects of ash and sulfate leading to regional cooling, O_3 depletion by acidic gases, damages to aircraft engines, acid rain, and direct demolition of buildings and burying of crops by ejected material (*illustration*: Debasish Mahapatra & Souveek Roy)

froze over. Some records even suggest the Baltic Sea freezing (Meacham 2020). The period was marked with advancing glaciers in Scandinavia, with tree line and snowline dropping. Crops failed, and there were widespread droughts across Europe due to the prolonged cold and dry climate. Unemployment and malnutrition and poor living standards resulted in many vector diseases and epidemics (Post 1984). As a result, there was increase in crime rate and caused massive social unrests. The whole period was marked with unpleasant weather, crop failure, large-scale unemployment, increase in intergroup violence, economic hardship, and high mortality rate due to malnutrition and several epidemics. It did not only cause socioeconomic problems but also cause political unrest throughout Europe. Historians also suggest this period of high social unrest may have led to the 30 years of war (1617–1648) (Zhang et al. 2011).

10.4.2 Impact on Ozone

The ozone layer protects the living beings on the planet surface by absorbing 93–99% of the sun's high-frequency ultraviolet light. Oxidation of molecular oxygen leads to O_3 formation, but the mechanisms exist in the troposphere and stratosphere. Stratospheric O_3 is considered beneficial because it prevents the harmful UV from reaching the earth's surface, while tropospheric O_3 has several ramifications to air quality, atmospheric chemistry, crop yield, environment, and human health (Saxena et al. 2019; Saxena and Sonwani 2020). Though most of these ramifications are a problem for the humanity, O_3 being an oxidant may also help to remove pollutants from the atmosphere (Mallik et al. 2018).

Up in the troposphere, radiation is intense enough to destroy O_3 either by itself or through a chain of free radical reactions involving the nitric oxide radical (NO), atomic chlorine (Cl), and atomic bromine (Br). Bromine released during volcanic eruption has the potential to damage the ozone even more compared to chlorine, Br being 40 times more effective than Cl w.r.t. O_3 depletion (Daniel et al. 1999). All of the mentioned radicals can have both natural and anthropogenic origins. Of particular concern is the dramatic increase in the levels of chlorine and bromine attributed to anthropogenic activities, mostly traced to halocarbons, e.g., chlorofluorocarbons (CFCs) (Mohanakumar 2008). The CFCs are stable organic compounds and find their way to the upper atmosphere due to their substantial lifetime. As CFCs reach the stratosphere, UV radiation splits them releasing the Cl and Br atoms from the parent, which were acting as effective reservoirs for these radicals. The below equation shows this mechanism. Here, "h" is Planck's constant and "ν" is frequency of electromagnetic radiation.

$$\mathrm{CFCl_3} + h\nu \rightarrow \mathrm{CFCl_2} + \mathrm{Cl}^{\circ} \tag{10.1}$$

The free halide easily decomposes O_3 into its the more stable form of O_2. The halogen oxide can react with another ozone molecule and will give another halogen radical and two oxygen molecules.

$$Cl^{\circ} + O_3 \rightarrow ClO + O_2 \tag{10.2}$$

$$ClO + O_3 \rightarrow Cl^{\circ} + 2O_2 \tag{10.3}$$

Similar reactions can occur for most halides. As the concern of depletion of O_3 in the stratosphere grew, the scientists started examining the role of volcanoes in ozone depletion. It was observed that the gases emitted by the volcanoes during eruption can quickly reach the upper troposphere and lower stratosphere (UTLS); hence, their lifetime increases as they are saved from the high concentration of oxidants in the lower troposphere/boundary layer. The hydrogen halides particularly HCl emitted during eruption, when it reaches the stratosphere, they lead to destruction of ozone (Solomon et al. 1996; Hofmann and Solomon 1989). In addition, aerosols produced by volcanoes can increase the effectiveness of halides in depletion of O_3 in the stratosphere. While most sulfur eruptions reach the stratosphere, halogens are susceptible to being washed away by water and ice in the rapidly ascending column. The increased lifetime of particles and gases from volcanic emissions in the UTLS region makes them more impactful in their radiative and chemical effects.

Zuev et al. (2015) studied the O_3 depletion caused by Erebus volcanic eruption during which the emitted HCl and SO_2 reached the UTLS (upper troposphere and lower stratosphere) with the aid of high latitude cyclones and polar vortex. The polar stratospheric clouds also significantly assist O_3 depletion by converting chlorine compounds into more destructive forms.

Ozonesonde experiments traced a significant decrease in the total ozone column in lower stratosphere after the eruption of Mt. Pinatubo (Grant et al. 1994; Schoeberl et al. 1993; Tang et al. 2013). The decrease in tropospheric and stratospheric ozone was also noted by Fusco and Logan (2003) and Oltmans et al. (1998). Tang et al. (2013) found that the maximum decrease was 2 ppb on interannual time scale, whereas 5 ppb decrease was observed in monthly averages. Robock (2000) estimated the column depletion, and it ranged from 2% in the tropics to about 7% in the midlatitudes.

10.4.3 Acid Rain

The term acid rain entered the scientific domain in 1872 when Robert Angus Smith used it for the first time to describe the acidic nature of rain around the industrial town of Manchester, UK. Bouwman et al. (2002) identified atmospheric acid deposition in the form of rain, fog, or snow to be a major problem for the environment.

SO_2 and oxides of nitrogen are the primary cause of acid rain (Singh and Agrawal 2008). Acid rain can occur in the form of H_2SO_4 and HNO_3, so the emission sources for SO_2 and NO_2 including motor vehicles, power plants, refineries, and industries are precursors for acid rain. These precursor gases are converted into sulfuric acid and nitric acid in wet atmospheric conditions.

Acid rain adversely affects biogeochemical cycles and soil quality, and it also harms flora and fauna. It also causes degradation of buildings and yellowing and weakening of fabrics. Human health is affected by acid rain as it can cause itching, skin burn, respiratory problems, headache, etc.

The sulfur dioxide gas emitted from volcanoes when reacts with oxygen and moisture present in the atmosphere produces acid rain and can also lead to volcanic smog (vog). VOG can not only corrode metals and impact plants but also lead to respiratory and cardiovascular problems in humans. The main vent of Kilauea Volcano on the Hawaii islands emits 63,000–95,000 metric tons of SO_2 every year due to ordinary fuming leading to acid rain, but discrepancies exist if SO_2 is the sole cause of reduced pH (Siegel and Siegel 1984; Gerlach and Graeber 1985; Casadevall et al. 1987; Siegel et al. 1987; Nachbar-Hapai et al. 1989).

10.4.4 Impact on Aviation

Since the beginning of the aviation age in 1960s, with the advancement in technology there have been rapid advances in the sector of air travel. Correspondingly, there has been an increase in probability of an aircraft encountering the volcanic clouds. The ash particles ejected by volcano in the atmosphere impact the fuselage, windscreens, and compressor fan blades and can essentially chafe these forward-facing surfaces. The navigational and operational instruments might fail critically when contaminated with the ash. Ash particles consist of the glassy silicate material, which can melt at combustion temperatures inside modern jet engines (Chen and Zhao 2015). The melted ash particles rack up as re-solidified deposits in cooler parts of the aircraft leading to deterioration of engine performance even to the point of in-flight compressor stall and loss of thrust power.

Volcanic ash poses a major threat to the aviation sector with immediate and long-term consequences (Casadevall 1993). Over 129 incidents have been reported of aircrafts encountering volcanic ash from 1953 to 2009 (Guffanti et al. 2010). Of all these reported incidents, 79 are related to inflicting some physical damage to the aircraft, and 26 led to severe ramifications among which nine led to in-flight power loss in one or more engines. Miller and Casadevall (2000) documented incident of “all engines out” encountered by a Boeing B747 in 1982 with volcanic ash from Galunggung volcano over Indonesia and Boeing B747 in 1989 from Redoubt volcano over Alaska.

10.4.5 Environment and Health

Of an approximately 500 active volcanoes, 10–40 eruptions occur on an annual basis (Zuskin et al. 2007). Volcanic eruptions not only affect climate, but also affect terrestrial ecosystem and human and animal health (Mather et al. 2003). Volcanic eruptions can pose a threat on the environment even from a distance of thousand kilometers from the eruptive center (Galas 2016). Due to rapid accumulation of the ashes and the high density of individual volcanic ash particles during ash fallout, the buildings may collapse (Spence et al. 2005). The volcanic ash fall can also contaminate the water supplies (Stewart et al. 2006).

SO_2 emitted during volcanic eruption can change the precipitation rate (Twomey 1974; Nober et al. 2002). SO_2 acts as cloud condensation nuclei, and it increases the number of cloud droplets resulting in decrease in rain. It increases the albedo of the cloud, which causes cooling at the surface. As discussed above, the sulfate aerosols emitted during a volcanic eruption can react with the oxygen in the troposphere and cause acid rain.

The sulfate aerosols are generally injected in the upper troposphere above the boundary layer. At this height, mixing is weaker and the removal process is slower and the sulfate aerosols remain there for considerable time compared to the anthropogenic sulfur (Graf et al. 1998). Compared to the heating effect of each CO_2 molecule in the atmosphere, a molecule of SO_2 can overcompensate in cooling by at least a factor of 50 (Kaufman et al. 1991). The volcanic aerosols in the stratosphere can lead to a rise in stratospheric temperatures. It also increases the pole to equator temperature gradient (Quiroz 1984; Parker and Brownscombe 1983).

The impact on health can be traced to the type and style of volcanic eruptions, e.g., the effusive emissions, which mainly emit gases, and aerosols may cause disorders of the respiratory system (Horwell et al. 2015; Saxena and Srivastava 2020). We know volcanoes emit hazardous gases. The SO_2 emitted by the volcanoes can be transported globally and potentially trigger acute respiratory diseases like asthma in the exposed people (Hansell and Oppenheimer 2004; Horwell and Baxter 2006).

10.4.6 Volcano and ENSO Relation

El Nino and the Southern Oscillation, also known as ENSO, are a large-scale oceanic warming and the variation in the air pressure of the overlying atmosphere in the tropical Pacific Ocean that occurs every few years. Though ENSO originates and develops in equatorial Pacific region, it affects the climate, ecosystem, and economies around the world (Fang and Xie 2020; Ropelewski and Halpert 1987). ENSO is receptive to external forcing on different time scales, and solar forcing is the cause for millennial ENSO variability due to orbitally induced changes in insolation (Predybaylo et al. 2020; Moy et al. 2002). According to Timmreck (2012), strong volcanic eruptions can rattle ENSO on a short time scale (2–5 years).

As discussed in the previous section, the presence of sulfate aerosols in the atmosphere causes cooling at the surface that can persist for years in the stratosphere with potential to impact the ocean temperature and circulation (Church et al. 2005; Gleckler et al. 2006). Handler and Andsager (1993) proposed that the reduction in incoming shortwave radiation due to the emissions from volcanoes has increased the number of ENSO in the last 150 years. Also, the strong tropical volcanic eruptions may change the atmospheric and oceanic circulation (Mann et al. 2005; McGregor et al. 2010; Shiogama et al. 2010; Zanchettin et al. 2012). At the end of the twentieth century, the relation between ENSO and strong tropical volcanic eruptions is an active field of research. The three largest eruptions in last 50 years (Agung in 1963, El Chichon in 1982 and Pinatubo in 1991) took place in conjunction with the warm phase of ENSO; therefore, there are possibilities that the strong tropical volcanic eruptions do have a role to play in ENSO system (Ohba et al. 2013). Adams et al. (2003) also found that the ENSO system may become more active due to volcanic eruptions. In contrast, Self et al. (1997) found that the volcano–ENSO relationship does not exhibit a statistically significant value over the last 150 years. Further millennium-long climate and volcanic records analysis points to the fact that even most explosive eruptions are too small to affect ENSO (Emile-Geay et al. 2008).

10.5 Impacts and Extremities

Depending on the type and region of eruption, volcanic events can range from mild to severe resulting in mild to extreme impacts on the different spheres of the Earth. The impacts of volcanoes are already discussed in the above paragraphs. However, depending on the circumstances, the net result is different. The tropospheric aerosols resulting from a quiescent volcano will have a lifetime of weeks, but an explosive eruption injecting the aerosols in the stratosphere can scale up the lifetime from weeks to years. The resulting impact on radiative forcing will hence be much more significant. The extremity of an eruption impact is not only visible in the amount of material that is ejected but also by the distance the impact propagates. Even smaller eruptions can have a long-range impact under favorable meteorological conditions. The Dalaffila eruption of November 2008 in the Afar region of Ethiopia, despite generating only about 0.1–0.2 Tg SO_2 in the eruption cloud, was one of the few recent volcanoes whose effect was observed as far as India (Mallik et al. 2013). SO_2 plume from this small eruption in Ethiopia traversed over 5000 km under favorable winds causing 10–20 times enhancement in background SO_2 columnar levels over the Indo-Gangetic plains of India and injected 1.4 Tg SO_2 over the Delhi region, equivalent to 25% of annual anthropogenic emissions over Delhi (Mallik et al. 2013). Recently in 2018, Manaro Voui Volcano on Ambae Island of South Pacific injected a record amount of 400,000 tons of SO_2 in the UTLS region, which was thrice the amount of SO_2 released from all volcanoes in the previous year (NASA report 2018). The impacts ranged from destruction of homes, burying of crops, blackening of the sky by volcanic ash, acidifying the drinking water, and forcing the entire population of the island to evacuate. No discussion of severity of volcanic impacts is complete without describing the Mount Pinatubo eruption.

10.5.1 Mount Pinatubo: A Case Study

The Mount Pinatubo eruption on June 15, 1991, was a landmark event not only for the Philippines but also for the entire planet as this was the world's largest volcanic eruption to happen in the past 100 years. Mount Pinatubo is an active volcano amid a chain of volcanoes located on the western fringe of the island of Luzon. They are subduction volcanoes, formed by the Eurasian Plate drifting below the Philippine Plate along the Manila Trench to the west. Smith (1909) provided the first geologic narration about Mount Pinatubo, describing it as destitute of "volcanic ash (and) any of the usual indications of volcanic activity." He surmised that "Mount Pinatubo is not a volcano and we saw no signs of it ever having been one, although the rock constituting it is porphyritic.... The region is quite unique and I have seen nothing in the Philippines quite like it."

Ash production was documented for Mount Pinatubo eruption for the first time at 0851 local time on June 12, 1991, where a series of explosive eruptions with an eruption cloud crossing 19 altitudes (Koyaguchi and Tokuno 1993). Satellite image analysis indicated that the high-level winds (~15–20 m/s) carried the ash clouds from the eruption of June 12 into the airspace west of Manila along the heading of 215° from the volcano (Potts 1993). Pinatubo Volcano Observatory Team also reported the intermittent lapilli fall and fine ash fall mainly in the region of the southwest of Pinatubo. Pinatubo exploded most violently releasing the largest ash cloud on June 15. (Koyaguchi and Tokuno 1993). Because of the passage of Typhoon Yunya, the pattern of dispersion of these ash clouds was complicated (Oswalt et al. 1991). The ash would have moved to west–southwest under normal weather conditions, but the Typhoon Yunya forced the ash clouds to the south (Paladio-Melosantos et al. 1991). The eruption of Mount Pinatubo caused the evacuation of more than 0.2 million people with more than 300 deaths mainly due to heavy ashfall and rain leading to collapsing of buildings. The amount of 6000–10,000 Mt of dacite magma in a Plinian eruption was ejected during the 9-h eruption of Mount Pinatubo volcano on June 15, 1991 (Pallister et al. 1996).

Aerosols from the eruption of Mount Pinatubo caused solar dimming in turn led to a lower troposphere cooling across the globe. This cooling was so strong that it led to a decrease in water vapor concentrations globally. The eruption cloud spanned 1100 km wide and 35 km high ejecting volcanic gases and ash leading to 17 megatons of SO_2 injected into the stratosphere, as documented in "Fire and Mud" by Self et al. (1997). The cooling continued over 2 years up to 1993, leading to 0.4 °C temperature drop over several regions. Bluth et al. (1992) and Hansen et al. (1992, 1996) also reported that around 20 MT of SO_2 was ejected in that eruption. SO_2 from Pinatubo was detected in the stratosphere as late as June 1994, 3 years after the eruption. Parker et al. (1996) observed a global cooling of about 0.5 °C at the surface and 0.6 °C in the troposphere between the eruption of Mount Pinatubo and the northern summer of 1992, interrupted, however, by relative warmth between January and March 1992.

Research on tree rings shows that after the eruptions of large volcanoes including Pinatubo and Tambora, Mongolia, and most parts of southern China continued to receive less rainfall, while an increase in rainfall was observed over mainland Southeast Asia in the reduced precipitation due to Pinatubo led to a record decrease in runoff and river discharge into the ocean from October 1991–September 1992. In April 1993, that is around 2 years after eruption, the ozone column showed a deficit of around 6% compared to the annual mean from 1979 to 1990 (Gleason et al. 1993;

Herman and Larko 1994). The cloud spread covered most of the area of the equatorial band from about 10° S to 20° N on June 15.

The eruption had great effect on the aviation sector contaminating some of the world's busiest air traffic corridors. Eruptions between June 12 and 15, 1991, led to as many as 16 damaging encounters between drifting ash clouds from the eruption and jet aircrafts. Out of these 16, three encounters occurred within a 200 km of eruption site with fresh ash clouds less than 3 h old. Further away between 720 and 1740 km west from the volcano, 12 encounters occurred over Southeast Asian region with 0.5- to 1-day-old ash clouds. A total of ten engines were damaged by the ash cloud, with additional two instances of in-flight loss of power. Long-term damage to aircrafts and engines attributed to Pinatubo SO_2 led to resulted in crazing of acrylic airplane windows, premature fading of polyurethane paint on jetliners, and accumulation of sulfate deposits in engines (Pallister et al. 1996).

10.6 Summary

Volcanism is an endogenic process that has the potential to change the earth's surface fairly quickly in contrast to exogenic processes through surface forces whose effects become perceptible in millions of years. A volcano is a rupture on the earth's crust through which hot lava, volcanic ash, and gases are spewed out during the course of the eruption from a magma chamber underneath the surface. Most of the volcanoes on earth are found near the tectonic plate boundaries, where they converge and subduct or diverge. Active volcanoes are those that have erupted in the Holocene, i.e., within the last 10,000 years and mostly concentrated along the Pacific Ring of Fire. Also of concern are dormant volcanoes, which are likely to erupt in near future. Identifying volcanoes on the basis of their structure gives a better insight into the type and intensity of eruption. Plate Tectonics, which is like the grand unified theory of Earth Science, is generally invoked to explain the causes behind volcanic eruptions. Depending on the volume of products and height of eruption, the explosiveness of a volcano is estimated on the basis of VEI scale of 1–8 representing the smallest, nonexplosive to mega-colossal explosions. On the basis of the nature of volcanic eruptions, volcanoes can be classified as Plinian, Vulcanian, and Strombolian. Volcanic emissions include violent eruptions and noneruptive degassing, which occurs continuously during eruptions and through vents and fumaroles. The degassing determines the type of eruption that will take place. The characteristics of volcanic emissions depend on the geological setting of the region where it is located; e.g., eruptions near subduction zones are associated with more water vapor and chlorine.

Eruptions spew out gases, lava, and tephra. Most of the magma erupted from volcanoes is of basaltic nature. The solid tephra includes ash, lapilli, and bombs/ blocks. Most particles greater than 1 mm will fall out within hours of eruption. Ash can travel thousands of kilometers from its originating volcano due to its tiny size of less than 2 mm. The most common gases from volcanoes are water vapor, carbon dioxide, and sulfur dioxide but additionally include carbon monoxide, hydrogen sulfide, chlorides, and fluorides of hydrogen and methane. Most often, volcanism induces short-term climatic variations. The secondary sulfate aerosols emitted from volcanoes can change the regional energy balance and lead to cooling at the surface. Volcanic cooling can cause crop failure and famine for many years after large eruptions as was observed for Tambora eruption of 1815. The halogen-containing gases from a volcano impact the stratospheric ozone layer. Significant decrease in the total ozone column in lower stratosphere was observed by ozonesondes after the eruption of Mt. Pinatubo. Volcanic material can lead to increased pH of rainwater and can even contaminate drinking water sources of a region as was observed during the recent Manaro Voui eruption of 2018. The severest impacts of volcanoes are borne by the aviation sector leading to engine damage and aviation hazards. Apart from modulating climate due to perturbed radiative balance, volcanic eruptions have also been associated with ENSO, changed rainfall patterns, and modified circulation patterns. The Mt. Pinatubo eruption has acquired a special place in volcanology due to its gigantic scale and extreme impacts. However, on VEI scale, Tambora eruption of 1815 is higher than Pinatubo, while the highest is Yellowstone Caldera, which erupted 0.5 million years ago. But the Pinatubo has given us a lot more information due to the presence of modern technology and satellites.

The effects of volcanic eruptions are already incorporated in global climate models and earth system science models. While on one hand, specialist scientific agencies and vulcanologists are always on lookout for possible new eruptions, a synergistic approach additionally involving other branches of science where eruption effects are anticipated can be an important step to face the challenges posed by volcanic emissions. Scientists working with emission inventories can incorporate the effects of transcontinental and transoceanic plumes in regional inventories for relevant eruptions; e.g., SO_2 enhancement observed over Delhi was traced to an eruption in Afar region of Ethiopia (Mallik et al. 2013). Policymakers will also be benefitted from such inclusions, specifically in regions and localities prone to impacts of volcanic emissions. Such holistic approach will also lead to greater awareness and understanding among nonexpert stakeholders who knowing/unknowingly suffer from these extreme expressions of nature.

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Assessment of Extreme Firework Episode in a Coastal City of Southern India: Kannur as a Case Study

11

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Abstract

Bursting of firecrackers turns out to be a vital part of festivals and celebrations. The amount of air and noise pollutions caused by such celebrations has been increasing significantly for the past few years till the COVID episode. Particulate matter and toxic gases emitted as part of fire bursting pose a serious threat to human health. A variety of festivals and celebrations taking place in different parts of India pollute the rural and urban areas. Vishu is a regional New Year festival being celebrated with coordinated fireworks all over the south Indian state of Kerala. Intense fireworks usually start on the eve of Vishu from 18:00 to 22:00 h (IST) and on the day of Vishu from 04:00 to 07:00 h in two spells, which create smoke and dust in the atmosphere that leads to deterioration of air quality. Here, we describe the variations of surface ozone (O_3) and other trace pollutants for pre-, post- and Vishu days for two successive years (2020 and 2021) at Kannur town. No significant variations in air pollutants were observed on the Vishu days in 2020 due to countrywide lockdown to curb the transmission of COVID in India. But higher levels of trace pollutants were found during the intense fireworks during the two spells in the night of Vishu eve and early morning of Vishu day in 2021. Surface O_3 was found to be increased by 51%

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during the evening spell of fireworks on the eve of Vishu day and 61% on early morning spell on the Vishu day. A sharp increase in NO, NO_2, CO, SO_2, BTEX and NH_3, PM_{10} and $PM_{2.5}$ concentration was observed during the evening spell of fireworks on the eve of Vishu day and early morning spell on the Vishu day when compared to the respective time in the pre-Vishu days. Metal concentrations associated with particulate matter were found to be higher during Vishu days than pre- and post-Vishu days. The average concentrations of metals are shown in the order S > Al > Cl > Ca > K > Zn > Na > Mg > Pb > Cu > Ba > Cr > Fe > Ni > Sr > Mn. This shows that air pollution due to trace gases and particulate matter increases exponentially on fireworks days, unlike normal days. Such short duration activities carried out for visual and auditory pleasure have far-reaching effects. Therefore, it is evident that fireworks associated with celebrations and festivals are an event that can influence air quality to a large extent. In a densely populated area like Kerala, it is necessary to assess the consequences of such celebrations using fireworks and come up with a protocol for its use. Further, this work throws light on the absence of air pollution during the festival ban in 2020 in connection with a severe lockdown to curb COVID-19 transmission.

Keywords

Fireworks · COVID-19 · Air pollution · Air quality · Southern India

11.1 Introduction

Celebrations associated with festivals, traditions and cultural events are considered to be an integral part of Indian social life, which is always enriched with spectacular display of fireworks. Thus, fireworks play a vital part of religious celebrations, sporting events, political victories and New Year celebrations in the world. Many cultural and national celebrations such as Bastille Day in France, Guy Fawkes Night in the UK, Lantern festival in China and Taiwan, Diwali festival in India, Anzac Day celebration in Australia, Canada Day in Canada and Independence Day in the USA are celebrated with extensive and colourful fireworks displays. Widespread emissions of air pollutants released by fireworks can reduce visibility and significantly deteriorate air quality (Pope et al. 2016; Kong et al. 2015; Nasir and Brahmaiah 2015) in the fire bursting site and the neighbouring regions, which induces a direct impact on human health (Hamad et al. 2016; Seidel and Birnbaum 2015). The lightening of fireworks starts with an exothermic process engendering intense sound and smoke as a by-product holding gases like CO_2, CO, SO_2, NO, NO_2, VOCs, PM_{10} and $PM_{2.5}$ along with several metal salts such as aluminium, manganese, magnesium, strontium, barium copper, potassium and cadmium (Garg et al. 2018; Kumar et al. 2016; Singh et al. 2010). Nishanth et al. (2012) have classified a variety of hazardous organic compounds in the atmosphere during the fireworks associated with a south Indian festival of Vishu. Inhalation of trace metals

(Cd, Ni, Cr, Mn, Cu, etc.) released from fireworks results in severe health effects such as neurological, carcinogenic, lung diseases and haematological effects (Greven et al. 2019; Gouder and Montefort 2014; Barman et al. 2008).

Diwali (Deepavali) is a festival of light celebrated across India every year in the end of October or the first week of November with great enthusiasm by all sections of people. Detailed studies by various researchers on the widespread air quality changes caused by Diwali fireworks in north India have already been published (Saxena et al. 2020a; Singh et al. 2019; Peshin et al. 2017; Parkhi et al. 2016; Mandal et al. 2012; Pal et al. 2013; Chatterjee et al. 2013; Tiwari et al. 2012; Kulshrestha et al. 2004; Ravindra et al. 2003).

Firework display is an essential part of all festivals and celebrations, which usually attracts large crowds due to the spectacular display of colours in the sky. Even though it occurs in small duration, it is a potential source of air and sound pollution. Hence, short-term exposure to air pollution results in severe health issues. Since infants are more active in pyrotechnics, they are more prone to mortality from short-term exposure to elevated levels of air pollution (Greven et al. 2019). The oxidative potential of particulate matter, toxic gases and trace metals present in the emission plume of smoke makes fireworks an extreme event that changes the atmosphere in a short duration of time (Sonwani et al. 2021).

Vishu is celebrated as a regional New Year Day in Kerala State, which marks the commencement of agricultural activities. This festival is celebrated not only in Kerala but also in the border areas of the neighbouring states. Being the beginning of a New Year Day, it is often celebrated with extensive fireworks on 13 or 14 April throughout the state. Fireworks usually set off at home on the eve of Vishu from late evening to midnight and on the early morning of Vishu day. Thus, the intense fireworks in a short span create a terrifying smoke and dust in the atmosphere accompanied by extreme sound pollution. This smoke that spread during night time often produces a thick morning fog, which reduces the visibility. Moreover, black carbon dust and toxic gases present in this morning fog severely affect human health to a large extent (Saxena et al. 2020b). The interior of houses is generally contaminated with dust and pollutant gases emitted from the fireworks during night and early morning spells of the fireworks. As a result, inhaling dust and toxic gases in the whole night of Vishu can cause severe health issues, especially to infants and elderly people.

Research activities have been initiated in Kannur University to explore the chemistry of trace gases in a rural environment since 2009 with the support of ISRO and these activities and extended to Kannur town in 2019. This case study is an outcome of our long-term observation in the variations of trace pollutants such as surface O_3, NO, NO_2, CO, SO_2, BTEX and NH_3, PM_{10} and $PM_{2.5}$ at a residential site of Kannur town during the Vishu festival in 2020 and 2021. This work is a result of the air samples collected from 10 to 17 April in 2020 and 2021. We could not perform the qualitative and quantitative classifications of the organic compounds during fireworks, which is highly relevant.

11.2 Description of Monitoring Site

Kannur is the northern district of Kerala lying along the coastal belt of the Arabian Sea, which makes it one of the most popular tourist destinations in South India. The geographical coordinates are 11.87 N and 75.37 E, 3 m msl, which spans an area of 2961 km^2 with a population density of 852 per km^2. The map of Kannur is shown in Fig. 11.1a, and the outlook of Kannur town with the monitoring location is shown in Fig. 11.1b. Kannur town is an urbanized city having few industries including plywood, rub wood, mattress factories and handlooms in its neighbourhood areas. Agriculture and fisheries are the key sectors in the villages of this district. The monitoring station is installed close to the National Highway (NH 17), which has reasonably heavy traffic during the day and minimum at night. Further, it is surrounded by administrative buildings and residential areas and is about 2 km away from the Arabian Sea. Since the industries are quite far, transport-related activities, such as emissions from vehicular traffic, are major sources of various gaseous and particulate pollutants at this site.

Kannur is conferred with a pleasant climate throughout the year, due to the proximity of Arabian Sea in the west and the Western Ghats in the east. Relatively higher temperatures, low rainfall and a faintly humid climate are the main features of the summer season in Kerala. Measurements of trace pollutants were carried out using the respective ground-based gas analyzers from Environment S.A France. Detailed description of the instruments used for the study is reported in our previous publication (Resmi et al. 2020).

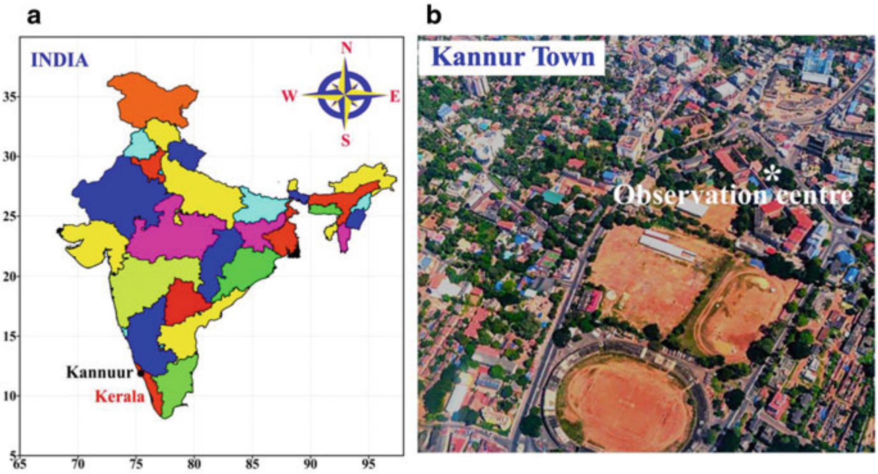

Fig. 11.1 (**a**) Kannur in South India (**b**) airborne vision of Kannur town and the monitoring station

11.3 Results and Discussion

11.3.1 Variation of Surface O_3

In order to investigate the effect of fireworks on the concentrations of trace pollutants over Kannur town, the study retro is divided into three four, viz. pre-Vishu days (10, 11, 12 April), day before Vishu (13 April), Vishu day (14 April) and post-Vishu days (15, 16 17 April). Figure 11.2 shows the 24-h variation of O_3 over the monitoring station for the study period days during 2020 and 2021. It is found that the diurnal variation of O_3 during these 2 years exhibited a similar profile with different amplitudes. On a diurnal basis, O_3 concentration usually starts to increase in-tune with solar radiation from the morning hours and reaches its maximum level at noontime hours. Then, it exhibits a declining phase in afternoon hours and reaches its low level during the late evening and night hours. The high concentration of O_3 observed in the daytime is primarily due to the enhanced VOC-NOx chemistry in the presence of intense solar radiation. During night-time hours, photochemical production becomes weak and O_3 titration with NO is more pronounced, which leads to a decrease in O_3 concentration. However, no significant change in ozone has been noticed in 2020 as the fire bursting has been banned in the wake of country wide lockdown.

In 2021, O_3 concentrations show a momentous increase on the eve (18:00–22:00 h) of Vishu day and the early morning (04:00–10:00 h) of Vishu day due to intense fire bursting over the observational site. Thus, just after the fire bursting, O_3 concentration enhanced from ~19.2 ppbv to ~29.0 ppbv (an upsurge of 51%) in the evening spell on the eve of Vishu day and from ~11.4 ppbv to ~18.4 ppbv (an increase of 61%) on the early morning spell on Vishu day. Surface O_3 is usually formed only in daytime by the photodissociation of NO_2 in the presence of sunlight ($\lambda < 420$ nm). Thus, in a closed state, the following set of reactions shows a production and dissociation of O_3 (Seinfeld and Pandis 2006).

$$NO_2 \rightarrow NO + O \tag{R11.1}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{R11.2}$$

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{R11.3}$$

The exciting feature of our measurement is the upsurge in O_3 level during the evening and early morning spells of Vishu even in the lack of solar radiation. This growth is connected with fire bursting that occurred in two spells of 2021. Accordingly, the O_3 produced during this episode was mainly at the expense of firecrackers. The additional NO_2 essential for the upsurge of O_3 was produced from the fire bursting event.

$$NO + HO_2 \rightarrow NO_2 + OH \tag{R11.4}$$

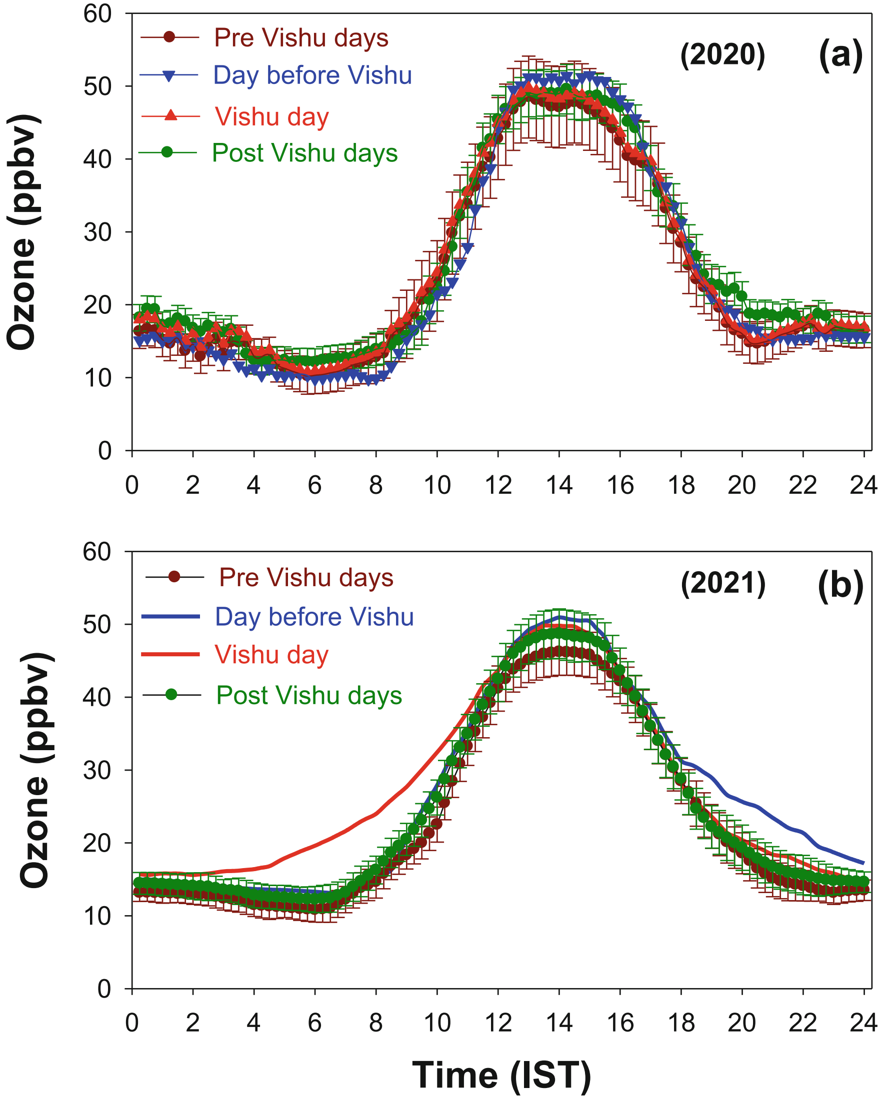

Fig. 11.2 Variation of surface O_3 during the study period in (**a**) 2020 and (**b**) 2021

$$NO + RO_2 \rightarrow NO_2 + RO \tag{R11.5}$$

Thus, night-time O_3 enhancement is by the photolysis of NO_2 present in the smoke activated by intense flash of the fireworks.

11.3.2 Variation of Oxides of Nitrogen

Variation of NO and NO_2 in the days of observation in 2020 and 2021 is shown in Fig. 11.3a–d. The diurnal profiles of NO and NO_2 show higher concentrations in the morning and late evening hours and low concentrations during daytime hours. The enhancement in the concentrations of NO and NO_2 during the morning and late evening hours is due to vehicular exhaust and shallow boundary layer height. Soon after sunrise, peroxyacetyl nitrate (PAN) breaks into NO and NO in the presence of sunlight interacts quickly with O_3 or O_2 to form NO_2 due to its short lifetime (Wang et al. 2019). Subsequently, NO_2 undergoes photolysis in the presence of sunlight to form NO and atomic oxygen, which combines with molecular oxygen produces surface O_3 indicated by reactions R1 and R2. After the maximum concentration observed in the morning, NO_2 starts declining until it extends its lowest concentration between 14:00 and 16:00 h, and then reaches a steady upturn until late-night hours. The main reason behind the decline of NO_2 during day time is due to the increased photolysis by intense solar radiation. Thus, this decrease in NO_2 concentration is at the expense of photochemical production of surface O_3 in the presence of intense solar flux. The night-time concentration of NO and NO_2 shows a gradual increase from 19:00 h to midnight on 13 April 2021.

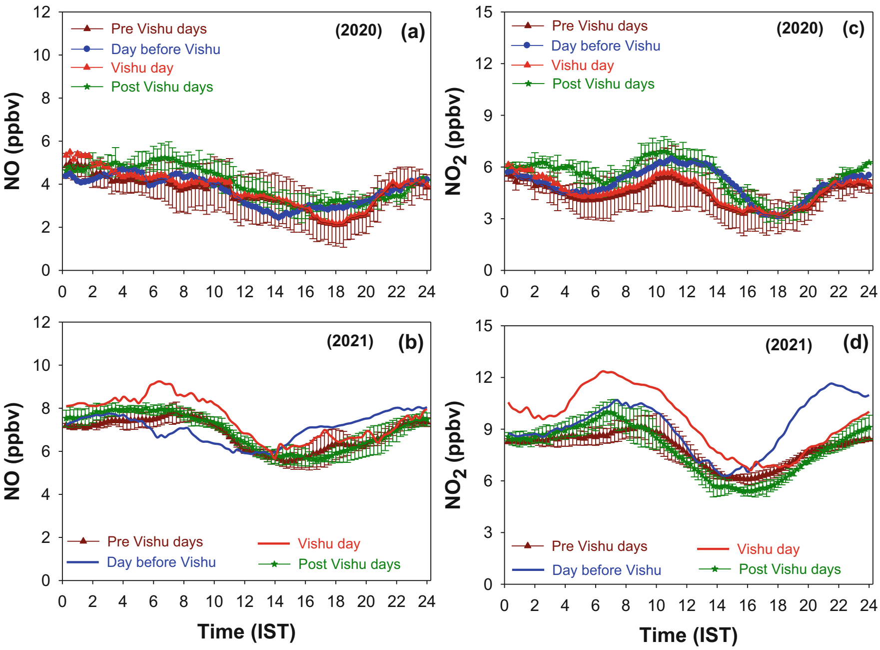

Fig. 11.3 Diurnal variation of NO during the study period in (**a**) 2020 and (**b**) 2021 and NO_2 during the study period in (**c**) 2020 and (**d**) 2021

In this festival episode, NO concentration also exhibits a small increase from ~6.2 ppbv to ~7.8 ppbv (an upsurge of 26%) observed in the evening spell on the eve of Vishu and from ~7.1 ppbv to ~9.4 ppbv (an upsurge of 32%) on the early morning spell on Vishu day. Surprisingly, the concentration of NO_2 enhances from ~7.5 ppbv to ~11.6 ppbv (an increase of 56%) in the evening spell on the eve of Vishu and from ~8.1 ppbv to ~12.4 ppbv (an upsurge of 53%) on the early morning spell on Vishu day. This shows an increase in NO and NO_2 concentrations in the evening and the early morning spell only in 2021 due to the lockdown imposed in 2020.

11.3.3 Variation of CO and SO_2

Figure 11.4a, b shows the diurnal variations of CO during pre-, post- and Vishu days in 2020 and 2021 at Kannur town. Diurnal variation of CO displayed two peaks in morning and evening due to traffic hours in the town. Usually, the morning and evening peaks are observed at 08:00–10:00 h and 17:00–20:00 h in this location. Various groups in India have reported a similar variation of CO in many urban areas (Beig et al. 2007; Mahapatra et al. 2014; Verma et al. 2017; Resmi et al. 2020). Generally, during pre- and post-Vishu days, the observed concentration of CO varies from 340 to 680 ppbv and an increase (62%) in CO concentration is noticed from the beginning (540 ppbv) of fire bursting on the evening spell on the eve of Vishu day

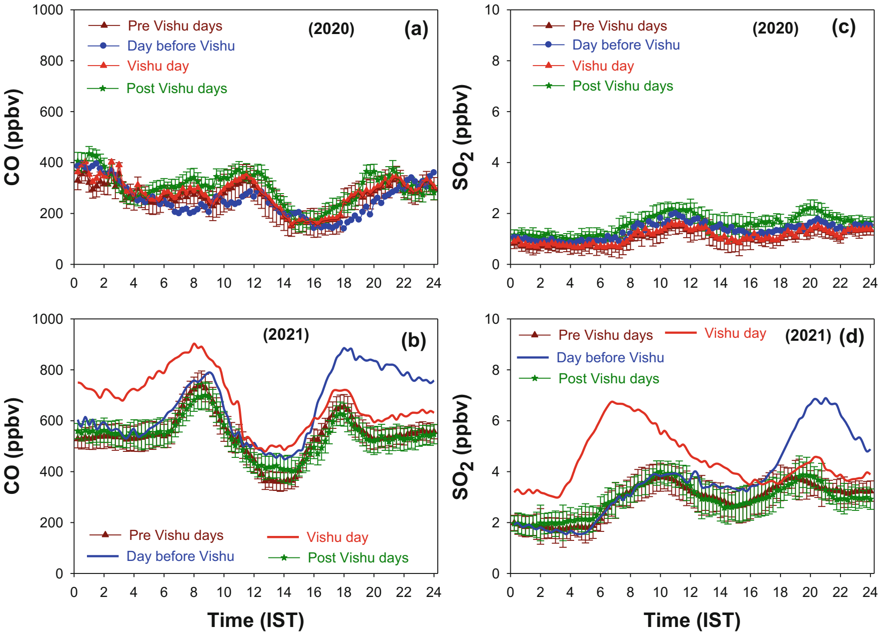

Fig. 11.4 Diurnal variation of CO during the study period in (**a**) 2020 and (**b**) 2021 and SO_2 during the study period in (**c**) 2020 and (**d**) 2021

and it reaches a maximum value (850–882 ppbv) during 19:00–20:00 h. Likewise, during the early morning on the Vishu day, the concentration of CO shows an upsurge of 72% and attains a maximum value (840–890 ppbv) between 06:00 and 08:00 h with respect to the pre-Vishu concentration of 520–540 ppbv. Further, its concentration is observed to be high during the evening on Vishu day with respect to pre-Vishu days, which account for the bursting of fireworks in the surroundings of the observational site.

The diurnal variations of SO_2 during pre-, post- and Vishu days in 2020 and 2021 at Kannur town are shown in Fig. 11.4c, d. The primary source of SO_2 at the observational site is from vehicles after the combustion of sulphur present in diesel. During daytime, the anthropogenic activities (such as vehicular and industrial actions, and biomass burning) contribute fairly large release of SO_2 in the lower atmosphere and it remains gas-phase SO_2 in night-time hours. The diurnal variation of SO_2 exhibited two distinct peaks during morning (9:00–11:00 h) and evening (19:00–22:00 h) of the pre- and post-Vishu days, and it varies from 1.7 ± 0.41 to 3.8 ± 0.52 ppbv. Just after the fire bursting, SO_2 concentration enhances from ~3.52 ppbv to ~6.88 ppbv (an increase of 96%) in the evening spell on the eve of Vishu day and from ~2.4 ppbv to ~5.8 ppbv (an increase of 142%) on the early morning spell on Vishu day.

11.3.4 Diurnal Variation of BTEX and NH_3

Benzene, toluene, ethylbenzene and xylene (BTEX) are the main hydrocarbons found in the lower atmosphere in the group of volatile organic compounds (VOCs). Figure 11.5a, b shows the diurnal variation of BTEX and during pre-, post- and Vishu days in 2020 and 2021 at Kannur town. BTEX shows a pronounced enhancement in the morning, and evening hours and low in noontime hours. Daytime and nocturnal concentrations of BTEX exhibit a considerable increase during fire bursting episode in 2021 over Kannur town. BTEX concentration enhances from ~6.3 ppbv to ~12.1 ppbv (an increase of 92%) in the evening spell on the eve of Vishu day and from ~5.5 ppbv to ~11.3 ppbv (an increase of 105%) on the early morning spell on Vishu day.

Figure 11.5c, d describes the 24-h variation of NH_3 during pre-, post- and Vishu days in 2020 and 2021 at Kannur town. NH_3 shows a progressive deviation with higher concentrations during daytime hours due to the anthropogenic activities and a build-up of pollutants by low wind speeds (Kuttippurath et al. 2020; Behera et al. 2013). During pre- and post-Vishu days, the mixing ratios of NH_3 vary from 4.65 ± 0.42 to 5.88 ± 0.48 ppbv on a diurnal basis. The concentration of NH_3 starts increasing from 5.25 ppbv at the beginning of the fire bursting and reaches its maximum level of 5.88 ppbv with an upsurge of 12% in pre-Vishu days. Quite similar to this, on the Vishu day, the concentration of NH_3 increases from 5.02 ppbv to 5.75 ppbv with an increase of 15%. Despite the fire bursting activity is reduced considerably after the morning of 14 April on Vishu day, the concentrations of trace gases except BTEX and NH_3 remain higher level compared to post-Vishu days.

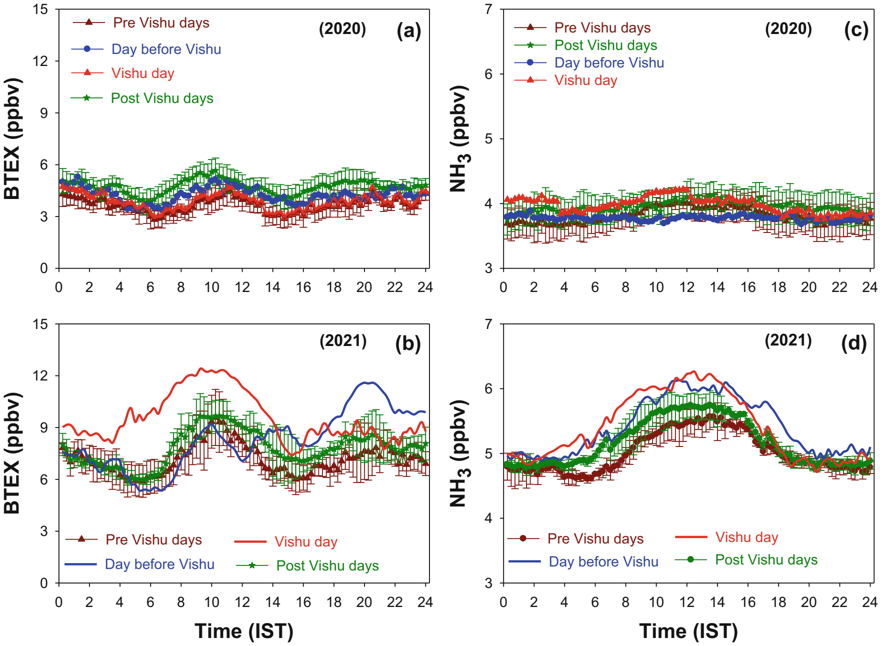

Fig. 11.5 Diurnal variation of BTEX during the study period in (**a**) 2020 and (**b**) 2021 and NH_3 during the study period in (**c**) 2020 and (**d**) 2021

11.3.5 Variation of PM_{10} and $PM_{2.5}$

Particulate matter is formed by a cluster of small and large particles of different chemical configurations, and it consists of both fine ($PM_{2.5}$) and coarse (PM_{10}) modes of airborne particles (Pakbin et al. 2010). The fine mode particles are formed by burning or gas-to-particle conversions and are rich in carbon, sulphates, ammonium and nitrate ions, as well as trace elements (Liu et al. 2015). The anthropogenic emissions of trace gases and particulate matter thus exert a significant influence on the chemistry and radiative balance of the local urban environment. Further, it influences the regional production of surface O_3 and OH radicals affecting the urban air quality. Diurnal variations of PM_{10} and $PM_{2.5}$ observed in 2020 and 2021 are shown in Fig. 11.6a–d. In 2021, PM_{10} and $PM_{2.5}$ show higher concentrations during morning (09:00 to 12:00 IST) and evening (16:00 to 20:00) hours due to the crowning traffic and late-night hours due to the accumulation of pollutants by shallow boundary layer. After morning enhancement between 07:00 and 10:00 h, the concentrations of particulate matter gradually decrease until 15:00 h due to the diffusion of pollutants by broadened boundary layer height in the presence of intense solar radiation (Qu et al. 2017).

An increase in concentration of PM_{10} and $PM_{2.5}$ is noticed from the beginning of fire bursting on the eve of Vishu day and the early morning on the Vishu day. Just

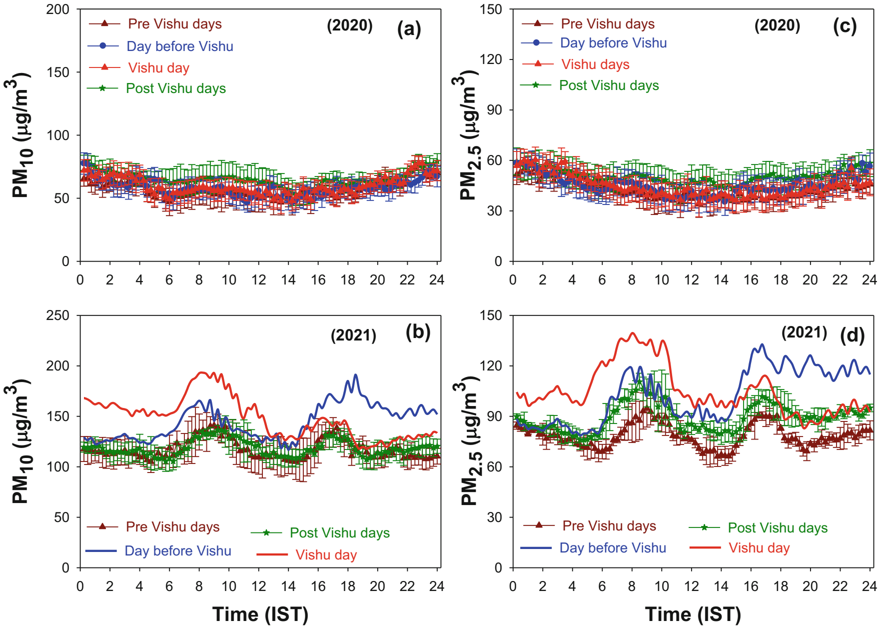

Fig. 11.6 Diurnal variation of PM_{10} during the study period in (**a**) 2020 and (**b**) 2021 and $PM_{2.5}$ during the study period in (**c**) 2020 and (**d**) 2021

after the fire bursting, PM_{10} concentration enhances from ~110 µg/m^3 to ~191 µg/m^3 (an upsurge of 74%) in the evening spell on the eve of Vishu day and from ~108 µg/m ^{3} to ~195 µg/m^3 (an increase of 81%) on the early morning spell on Vishu day. Likewise, an increase in concentration of $PM_{2.5}$ is observed from the beginning of fire bursting on the evening spell on 13 April and morning spell on 14 April 2021. Likewise, mounting levels of $PM_{2.5}$ are observed from ~84 µg/m^3 to ~135 µg/m^3 (an increase of 61%) in the evening spell on the eve of Vishu day and from ~75 µg/m^3 to ~140 µg/m^3 (an increase of 87%) on the early morning spell on Vishu day.

11.3.6 Variation of Metal Concentrations Associated with Particulate Matters

The present study extended to monitor the concentration of various inorganic elements present in the ambient air of Kannur town during the observation days in 2021. Beni and Esmaeili (2020); Jan et al. (2015) have reported the adverse effect of metals contained in particulate matter on the respiratory tract of human beings due to their bio-accumulative and poisonous nature in the environment. World Health Organization (WHO 2016) that included PM_{10} containing Pb, Ni, Co, Cd and As is a prominent air pollutant. Exposure to high levels of Pb and Mn can lead to severe neurotoxic and haematological effects in children, and Ni, Cd and Cr cause

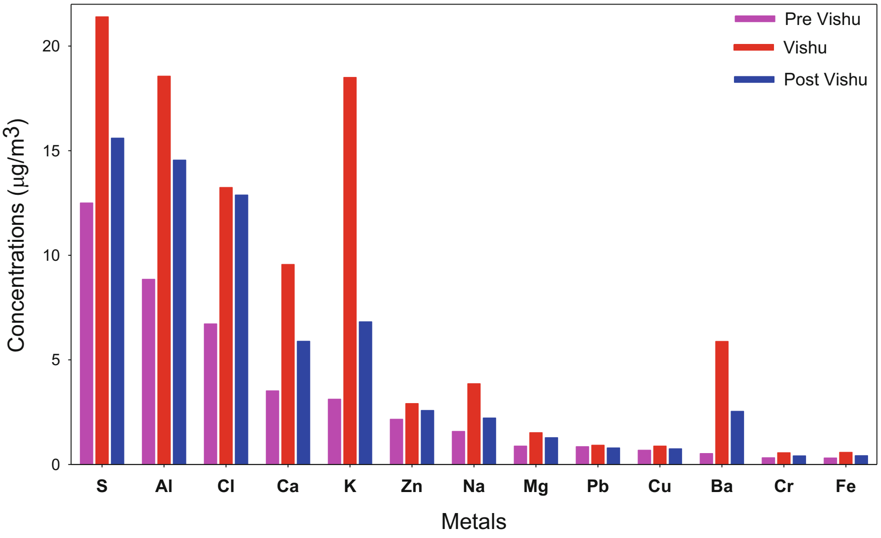

Fig. 11.7 Concentration of metals present in ambient air during pre-, post- and Vishu days

oncogenic effects in humans (Shen et al. 2018; Singh et al. 2011). In order to study the metal concentrations bounded with the particulate matter, PM_{10} in the ambient air on the observational days is collected using a high-volume air sampler located on the roof in the monitoring station. The concentration of metals associated with PM_{10} during pre-Vishu, Vishu and post-Vishu days is shown graphically in Fig. 11.7.

It is observed that metal concentrations are found to be higher in Vishu days than pre- and post-Vishu days. The average concentration of metals shows in the order S > Al > Cl > Ca > K > Zn > Na > Mg > Pb > Cu > Ba > Cr > Fe > Ni > Sr > Mn. Based on the concentrations, major upsurge is observed for seven metal species in PM_{10} samples (S, Al, Cl, Ca, K, Zn and Na) on Vishu day compared to samples from pre- and post-Vishu days. A similar enhancement in metal species has been observed by different groups across the globe (Shivani et al. 2020; Pervez et al. 2016; Tsai et al. 2012; Perrino et al. 2011). Generally, all the firecrackers contain potassium nitrate, potassium chlorates and potassium perchlorates in the form of a black powder, which acts as a combustible material (Moreno et al. 2007). Sulphur (S) is used as a propellant, whereas aluminium (Al) and copper (Cu) are used for colour displays and sparklers, while sodium (Na) was commonly used as metal oxidizer (Pervez et al. 2016; Tandon et al. 2008).

11.4 Conclusion

Colourful fireworks display is one of the main attractions of festival seasons. The south Indian state of Kerala celebrates Vishu, which earmarks the regional New Year, which falls in the middle of April month every year. This festival usually starts in the evening of Vishu eve with coordinated fireworks set up to late night and resume in the early morning of Vishu day with two distinct spells of fire bursting episodes. Our observations were conducted on trace gases in 2020 and 2021, and it is further observed that the concentrations of all trace gases remain unchanged due to the ban of fireworks in the wake of strict lockdown. The observations in 2021 reveal the increase in O_3 concentration from 19.2 ppbv to 29.0 ppbv on the evening spell on the eve of Vishu day and from 11.4 ppbv to 18.4 ppbv on the morning spell of Vishu day. The concentration of NO increases from its value of ~6.2 ppbv to ~7.8 ppbv on the evening spell on the eve of Vishu day and from ~7.1 ppbv to ~9.4 ppbv on the morning spell of Vishu day. The abundance of NO_2 shows a clear upsurge of 4.1 ppbv on the evening spell on the eve of Vishu day and 4.3 ppbv in the morning spell for the year 2021. A sharp increase in CO concentration was observed during the evening spell (62%) and morning spell (72%) of firework event. The observed SO_2 concentration enhanced to 96% on evening spell and 142% to early morning spell for the year 2021. The concentration of BTEX increased from its value of ~6.3 ppbv just after the fire bursting to ~12.1 ppbv on evening spell and from ~5.5 ppbv to ~11.3 ppbv on early morning spell of Vishu day. NH_3 shows an enhancement of 12% in the evening spell and 15% in the morning spell of Vishu day. Mixing ratios of PM_{10} increase in the evening spell in Vishu eve from 110 $\mu g/m^3$ to 191 $\mu g/m^3$, and in the morning spell of Vishu day, it is from 108 $\mu g/m^3$ to195 $\mu g/m^3$. Similarly, the concentration of $PM_{2.5}$ is found to increase from 84 $\mu g/m^3$ to 135 $\mu g/m^3$ in the evening spell in Vishu eve and vary from 75 $\mu g/m^3$ to140 $\mu g/m^3$ in the morning spell of Vishu day. All metal concentrations associated with particulate matters are found to be much higher during Vishu days than pre- and post-Vishu days.

The Indian festivals are the reflections of the vast cultural diversity in the country, and all festivals are becoming colourful, which are being celebrated with much enthusiasm. The common feature of all festivals is an extensive firework display at the end of the festivals. The use of firecrackers in festivals and celebrations in Kerala has been alarmingly increasing in every year. On the day of Vishu, it is a joyful experience to witness the spectacular wonders of the firecrackers in the sky over each house. Such type of celebrations enhances the concentrations of trace gases and particulate matter in the atmosphere, leading to serious health problems. Celebrations employing fireworks in India have not yet been legally restricted except in the lockdown periods. Instead of legally banning such activities, the use of fireworks in celebrations and festivals can be curtailed to some extent once the public is made aware of the harmful effects of fireworks. Thus, a public awareness of the air and sound pollutions of fireworks may be created to discuss on the severity of this man-made environmental threat through the media in order to save our environment.

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Air Pollution Episodes: Brief History, Mechanisms and Outlook

12

Narendra Ojha, Meghna Soni, Manish Kumar, Imran Girach,
Som Kumar Sharma, and Sachin S. Gunthe

Abstract

The occurrences of pollution episodes have brought out the strong linkages of pollution with health subsequently catalysing numerous regulations worldwide. Pollution episodes have been driven by a variety of mechanisms such as accidental large emission, trapping of pollution by stagnant meteorology and intense photochemistry involving strong anthropogenic emissions. Few regions of the world, e.g. the Indo-Gangetic Plain (IGP) and Northern China Plain (NCP), experience recurring pollution episodes with enhanced levels of fine particulate matter ($PM_{2.5}$), ozone (O_3) and other pollutants. Reductions in industrial and vehicular emissions should be planned by taking unfavourable meteorology also into account, besides control measures on burning of the crop residues and forest biomass to reduce the severity of pollution episodes. The development of greenbelts in residential and commercial areas and green roofing over buildings could reduce dust and other pollutants. Air quality monitoring over dense networks and high-resolution modelling with assimilation of observations

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would be of paramount importance for more accurate forecasts and better preparedness to minimize potential impacts.

Keywords

Air quality · Trace gases · Aerosols · $PM_{2.5}$ · Ozone · Smog · Health effects

12.1 Introduction

The periods of very high pollution levels lasting for a few hours to several days have commonly been referred to as the air pollution episodes. The impacts of air pollution episodes on the health of living beings depend on the type (toxicity) of pollutants, concentrations and the duration of the episodes (Saxena and Srivastava 2020; Sonwani and Saxena 2022). Some common examples of episodic air pollution events include the accidental releases of toxic pollutants from point sources, large-scale forest fires, dust outbreaks in dry regions and season-specific smog in stable atmospheric conditions. Historically, the occurrence of air pollution episodes has established the links between pollution and health of living beings. In addition, numerous studies following up each major episode unravelled the diverse physical, chemical and dynamical processes, which govern pollution over a given region and the factors that could lead to severe pollution episodes. Pollutant concentrations over a particular region depend on the strength of various emission sources, effects of transport from upwind regions, photochemistry and the local atmospheric (meteorological) conditions such as boundary layer height, wind speed and humidity (Saxena and Ghosh 2011). With the dominance of one or more factors, the concentration of pollutants can be strongly enhanced resulting in extreme pollution episodes/events. Pollution episodes have pronounced impacts on the health of living beings and are often linked with premature mortalities.

Air pollution episodes have been caused by a wide variety of different mechanisms. Classic episodes, such as smog of Meuse Valley (1930) and Donora (1948), were linked with the accumulation of industrial emissions by terrain and local meteorological conditions. Strong coal burning and limited atmospheric ventilation caused the Great London smog (1952) leading to death of thousands of people. Summertime smog of Los Angles (1940s) was due to photochemical ozone production involving local emissions of ozone precursors. In contrast, the Bhopal gas tragedy (1984) leading to a large number of deaths within a short span of time was an industrial accident. Natural processes such as volcanoes and forest fires have also been found to dramatically impact the air quality and visibility conditions (Jain et al. 2021). Several regions of the world, such as the Northern China Plain (NCP) and the Indo-Gangetic Plain (IGP), experience recurring air pollution episodes. Higher $PM_{2.5}$ in winters and strong ozone pollution in the summers impose a significant threat to the health of large population living in these regions (Sonwani et al. 2022).

Besides providing scientific understanding, the unprecedented impacts of pollution episodes have led to numerous legislations and regulations worldwide. Donora smog episode is suggested to have catalysed initiatives towards the first clean air legislation in the USA. Air Pollution Control Act of 1955 in the USA was aimed to facilitate research and technical assistance to different states to reduce air pollution. This was followed by the Clean Air Act of 1963 defining emission standards for industries and power plants in the USA. Several additional acts and amendments were also made subsequently (Jacobson 2002), for instance defining the National Ambient Air Quality Standards (NAAQS). In the UK also, Clean Air Act 1956 was passed in response to the London smog episodes leading to shifting of power plants to the rural areas. Industries were required to build chimneys to avoid near-surface accumulation of pollution under the act of 1968. Since then, numerous efforts have been ongoing towards new environmental legislations and implementations in different countries of the world. A detailed history of all major air pollution episodes and their impacts have been covered extensively in the literature (e.g. Jacobson 2002; Brimblecombe 2017; Fowler et al. 2020 and references therein). Here, in this chapter, we present an overview of the history of air pollution episodes and their impacts, key driving mechanisms, followed by an outlook including some perspectives on the control measures.

12.2 Global Distribution of Air Pollution

Air pollution episodes cause adverse health impacts including premature mortalities, and therefore, monitoring and forecasting of air quality are being carried out globally on a regular basis. While pollution has been naturally present since the onset of the atmosphere on the earth, nevertheless, since industrialization (the 1750s) it has increased dramatically over several developed and developing regions across the globe (IPCC 2007; IPCC 2013; Fowler et al. 2020). The twenty-first century has been experiencing a global spread of air pollution with nearly all remote locations, such as the mountain peaks, oceanic regions and free troposphere being affected by increasing amount of several pollutants (e.g. Lelieveld et al. 2001; Seinfeld and Pandis 2006; Sarangi et al. 2014; Monks et al. 2015; Girach et al. 2017, 2020; Ojha et al. 2019). In this scenario, air pollution issues have no longer been confined to highly urbanized and industrialized regions and profound impacts are being experienced in the rural and remote environments (e.g. Ravishankara et al. 2020).

The greatest health risks are predominantly linked with the fine particulate matter ($PM_{2.5}$; particulate matter with aerodynamic diameter ≤ 2.5 μm) affecting the health of millions of people across the globe (Chuang et al. 2007; Zanobetti and Schwartz 2009; Kim et al. 2015). Additionally, ozone (O_3), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), volatile organic compounds (VOCs), etc., deteriorate the air quality (Forster et al. 2007; Monks et al. 2009; Jacobson 2002; Sahu and Saxena 2015). United Nations' World Health Organization (WHO) and the World Meteorological Organization (WMO), in particular, provide valuable data sets on global air quality, health impacts and meteorological variations. Regional agencies, such as the United States Environmental Protection Agency (US EPA), European Union (EU) and India's Central Pollution Control Board (CPCB) also

Table 12.1 List of key air pollutants, major sources and standard levels

Pollutant	Major sources	Standard level
$PM_{2.5}$	Industrial, vehicular and urban emissions; combustion of fossil and biomass fuels; soil/mineral dust; sea salt from oceans; living organisms	10 $\mu g{\cdot}m^{-3}$ (annual mean); 25 $\mu g{\cdot}m^{-3}$ (24 h mean)
O_3	Photochemistry involving NO_x, CO and non-methane hydrocarbons (NMHCs)	100 $\mu g{\cdot}m^{-3}$ (8 h mean)
CO	Incomplete combustion of fossil fuels; biomass burning; oxidation of hydrocarbons	10 $mg{\cdot}m^{-3}$ (8 h mean); 7 $mg{\cdot}m^{-3}$ (24 h mean)
NO_x	Fossil fuel combustion; biomass burning; lightning; denitrification in soils and plants	40 $\mu g{\cdot}m^{-3}$ (annual mean); 200 $\mu g{\cdot}m^{-3}$ (1 h mean)
SO_2	Fossil fuel combustion; volcanic emissions; mineral ore processing; oxidation of DMS; power generation, motor vehicles	20 $\mu g{\cdot}m^{-3}$ (24 h mean); 500 $\mu g{\cdot}m^{-3}$ (10 min mean)
VOCs	Biogenic; gasoline combustion; solvents; building materials; biomass burning; fossil fuel combustion	Benzene: 1 $\mu g{\cdot}m^{-3}$; formaldehyde: 0.1 $mg{\cdot}m^{-3}$ (30 min mean)

support and carry out observations from network of monitoring stations, which are eventually disseminated to the general public in terms of Air Quality Index (AQI). Additionally, various research institutions and universities also perform measurements and modelling of the local, regional and global air quality. The objectives of air quality monitoring are mainly to observe and report whether the concentrations of pollutants are below (or above) the standards recommended by the WHO, EPA and local governmental bodies. A list of major air pollutants, emission sources and standard levels, generally based on WHO guidelines - global update 2005, is summarized in Table 12.1.

The concentrations of air pollutants are highly variable in space and time due to the effects of varying emissions and the meteorological conditions (see Sect. 12.4 on details of various mechanisms). Air pollutants are emitted from diverse natural and anthropogenic sources. Major natural sources include forest fires, volcanic eruptions, dust storms and biogenic emissions (Luterbacher et al. 2004; Jacobson 2002; Mather et al. 2012), whereas the major anthropogenic sources include the emissions from the industries, power plants, vehicular exhausts, open burning of crop residues, etc. (Seinfeld 1986; Rhind 2009; Lippmann et al. 2015; Ivanova 2020).

Figure 12.1 shows the global distribution of $PM_{2.5}$ (μgm^{-3}) during May and January months representative of contrasting seasons of the year 2015, based on the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis (Inness et al. 2019). $PM_{2.5}$ levels show hotspots over South Asia, East Asia, the Middle-East, Southeast Asia and South Africa regions. $PM_{2.5}$ levels are seen to be significantly higher than the prescribed WHO standards suggesting severe health implications over these hotspot regions. As discussed in Sect. 12.3 also, the IGP and NCP regions are global hotspots of $PM_{2.5}$ in particular during the winter conditions (Fig. 12.1).

Global distributions of ground-level NO_2 and O_3 derived from the CAMS reanalysis are shown in Fig. 12.2 for 2 months, May and January, representing

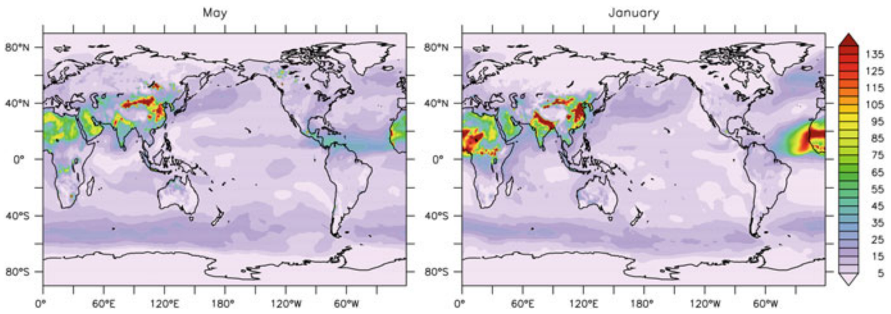

Fig. 12.1 Global distribution of $PM_{2.5}$ (μgm^{-3}) during May and January months of the year 2015, based on the CAMS reanalysis

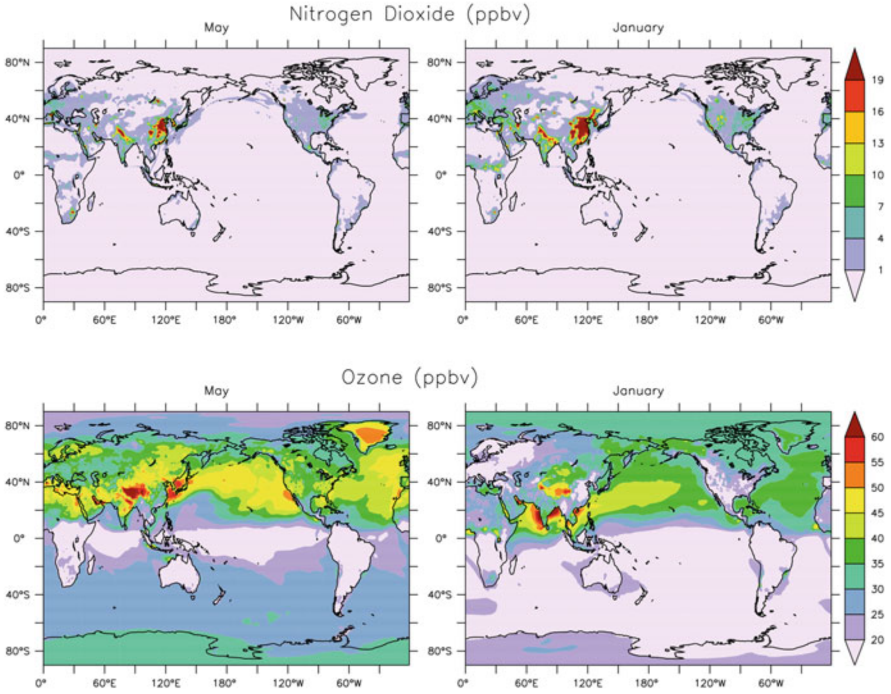

Fig. 12.2 Global distribution of ground-level nitrogen dioxide (NO_2) and ozone (O_3) during May and January months of 2015, based on the CAMS reanalysis

contrasting seasons of the year 2015. NO_2 shows higher levels (16 ppbv and higher) generally near the source locations most prominently over the IGP region, eastern China and North America. Due to shorter lifetime of NO_2, elevated levels seem to be more near emission source regions. Additionally, the NO_2 build-up is particularly strong during winter conditions due to lesser ventilation. In contrast with NO_2, elevated levels of O_3 are not confined only to the source regions of precursor gases. Interestingly, widespread O_3 enhancements are also seen over the remote mountains and oceanic regions due to its transport and chemical production in the urban outflows (e.g. Lawrence and Lelieveld 2010; Girach et al. 2017, 2020). O_3 pollution over continental regions is seen to be most severe during dry spring–summer conditions (Fig. 12.2), whereas $PM_{2.5}$ and primary pollutants are strongly enhanced by stagnant conditions during winter (Fig. 12.1).

12.3 Major Historical Episodes and Impacts

Table 12.2 lists some of the most severe air pollution episodes experienced in different parts of the world through diverse mechanisms. In the late nineteenth and early twentieth century, major air pollution episodes were associated with the combustion in coal and chemical factories. The mixture of smoke and fog has been termed as the smog (smoke + fog). The severity of air pollution episodes depended very strongly on the prevailing meteorological conditions. Here, we describe several major air pollution episodes from history and their impacts.

A severe air pollution episode occurred in the Meuse Valley, Belgium, during December 1930. The episode, which caused more than 60 deaths within 2 days, was a result of strong industrial emissions being trapped in the valley through stagnant winter conditions. Thousands of illnesses related to respiratory problems were reported among people, besides impact on cattle. The episode provided scientific evidences strongly linking the air pollution with severe illness and premature deaths (Nemery et al. 2001). Donora, a mill town in Pennsylvania, experienced a severe pollution episode during October 1948. The episode resulted in the deaths of 20 people immediately and about 50 people in the following days, besides causing

Table 12.2 A list of few major air pollution episodes developed through diverse mechanisms

Episode	Period	Remarks
Meuse valley episode	December 1930	Caused by stagnant conditions and industrial emissions; more than 60 people died within 2 days
Donora episode	October 1948	Caused by industrial emissions and temperature inversion; 20 people died and thousands suffered respiratory problems
London smog or the Great smog of 1952	1950s	Caused by industrial emissions in prevalence of cold and low wind conditions; linked with deaths of up to 120,000 people
Los Angeles smog	1940s	Summer smog associated with photochemical ozone formation involving vehicular and industrial emissions
Bhopal gas tragedy	1984	Leakage of industrial methyl isocyanate; considered among worst industrial disasters; thousands of lives lost and about half a million suffered health problems
World Trade Center	2001	Large amount of dust emissions due to collapse of the twin towers
Icelandic Volcano Eyjafjallajökull	April–May 2010	Caused by volcanic eruption; severely impacted the civil aviation

respiratory problems to about 7000 residents. The episode was driven by strong emissions of sulphur dioxide and hydrogen fluoride in Donora, which were trapped by meteorological inversion into a shallow volume near the surface.

The smog episodes prevalent in London were described as the London-type smog. The episode was most severe on 5–9 December 1952 termed as the Great Smog of London with peak levels of SO_2 and particulate matter recorded as 1.4 ppmv and 4460 μgm^{-3}, respectively. This episode was a result of strong coal burning emissions and prevalence of very low atmospheric ventilation. Visibility was drastically reduced to a few metres, and about 4000 people died within first 4 days due to health issues caused by this episode. Several additional premature mortalities have also been reported subsequently and the great London smog strongly pushed for detailed studies and control measures (Bell and Davis 2001; Brimblecombe 2017).

In the early twentieth century, there was a tremendous growth in the vehicular emissions and industries, which led to the development of severe photochemical smog (O_3 pollution) over Los Angeles, California, USA. In 1943, a thick fog severely impacted the health of people with their eyes sting and running nose. This episode made the "smog" word more common with Los Angeles being referred to as the "smogtown" (Jacobs and Kelly 2008). To differentiate, the photochemical smog is also called as the summer smog as these are most severe in the atmospheric conditions of higher temperature and intense solar radiation. The detailed mechanism producing ozone was first unravelled by Haagen-Smit (1952). Ozone pollution has been shown to have considerable health effects such as eye irritation, nose/throat irritation and respiratory problems, and headache.

The Bhopal gas tragedy in India (2–3 December 1984) is widely considered to be the worst chemical disaster in history (Sriramachari 2004). The disaster was an accidental leakage of industrial methyl isocyanate (CH_3NCO) during winter 1984 causing deaths of more than 2000 within the first few days. In addition, about half a million people suffered severe health issues ranging from eye and throat irritation, cough, conjunctivitis, drowsiness and cardiorespiratory problems. Destruction of the World Trade Center (2001) towers added an unprecedented amount of highly alkaline coarse dust in the air over Manhattan causing severe acute and chronic health effects (Lippmann et al. 2015). Ash from the Icelandic Volcano Eyjafjallajökull severely disrupted civil aviation during April–May 2010 stranding millions of passengers (Alexander 2013; Langmann 2012). During Amazonian deforestation of 2019, 4966 premature deaths were attributable to fire emissions making up 10% of all $PM_{2.5}$-related premature deaths in Brazil (Nawaz and Henze 2020).

Besides the aforementioned events of severe air pollution, there have been recurring haze episodes in some parts of the East and South Asian regions. The persistent and widespread haze has been observed over the densely populated IGP and over the Himalayan foothills, typically every post-monsoon and winter (e.g. Ramanathan and Ramana 2005; Ojha et al. 2020). Severe haze episodes have also been experienced in China, in particular over the NCP during stagnant meteorological conditions and high relative humidity (An et al. 2019; Fowler et al. 2020).

The combined effect of elevated emissions (biomass burning over north-west India and local emissions) and stagnant weather conditions led to a severe air pollution episode (1–7 November 2016) over New Delhi, India (Kanawade et al. 2020). $PM_{2.5}$, CO and Air Quality Index (AQI) were higher than 500 μg m^{-3}, up to 10 mg m^{-3} (~8700 ppbv), and 999, respectively, during 11–14 November 2017 over IGP, including the cities of Delhi, Agra, Kanpur, Lucknow, Patna and Kolkata (Dekker et al. 2019). Unfavourable meteorology such as low wind speeds and shallow atmospheric boundary layers have been found to be a key driver of the extreme pollution episodes by allowing the accumulation of pollutants. Local sources (residential and commercial combustion) were suggested to be more important during this episode than the biomass burning over north-west India (Dekker et al. 2019). As per the estimation by David et al. (2019), about 60% of premature mortalities due to $PM_{2.5}$ pollution in India are linked with emissions from the same region, whereas transport from other regions within India and from other countries accounts for 19% and 16%, respectively.

Thick smog blanketed Beijing and northern China affecting more than 600 million people (Sheehan et al. 2014) during January 2013. The widespread extreme haze pollution in northern China caused ~3 km thick haze layers, high UV Aerosol Index >2.5, aerosol optical depth (AOD) > 2.0 and peak value of PM_{10} around 1000 mg·m^{-3} (Tao et al. 2014). Unusual heavy pollution due to intense regional transport became extremely severe under anomalous weather conditions (Tao et al. 2014). Average $PM_{2.5}$ levels for 2013 were more than five times the WHO annual maximum level in 58 Chinese cities (Sheehan et al. 2014).

Besides the high background $PM_{2.5}$ and other air pollutants over annual cycle, sudden spikes during haze events can cause irreversible damage to organ systems, in particular to the cardiovascular system (Awasthi et al. 2010; Gupta 2019). In addition to the winter haze in India and China, the exposures to mineral dust during episodic dust outbreaks have been reported to cause acute silicosis and other respiratory ailments (Derbyshire 2007). The annual premature mortality in India attributed to exposure to $PM_{2.5}$ exceeds one million (Cohen et al. 2017). The projected $PM_{2.5}$-induced premature mortality burden over India using various RCP (representative concentration pathway) scenarios suggests that the health impacts would remain substantial in the future and that these can be aggravated by the climate change (Chowdhury et al. 2018). While the exact mechanisms of the health burden of dust outbreaks are not very clear, nevertheless, the co-emission of other pollutants, coating and transport of other pollutants with dust particles and the associated biological load are suggested to be important factors.

12.4 Important Mechanisms and Challenges

As discussed in the previous sections, diverse mechanisms have been involved in causing severe air pollution episodes around the world, making it very challenging to deal with at the time of occurrence and to design and implement control measures for future. Many episodes were results of sporadic large emissions of one or more

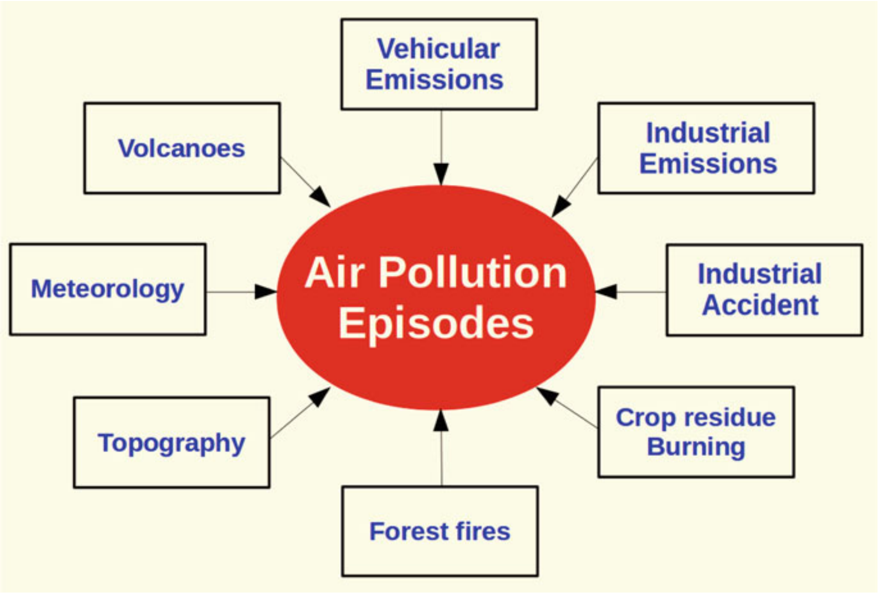

Fig. 12.3 A summary of various factors that could be important in the development and evolution of air pollution episodes

pollutants enhancing their concentrations to levels much higher than the standards prescribed in Table 12.1. Besides strong emissions, prevailing atmospheric conditions also played very crucial roles in favouring photochemistry to form secondary pollutants (O_3, secondary aerosols) and/or in controlling the dispersion and ventilation of the pollution. A summary of various factors that could be important in the development and evolution of air pollution episodes is compiled in Fig. 12.3. Key driver of individual major episodes are described briefly in Sect. 12.3 and in the literature (Brimblecombe 2017 and references therein).

It has been discussed in cases of individual major air pollution episodes in Sect. 12.3 that extremely high pollution concentrations have often evolved through unusual combination of strong emissions and stagnant meteorological conditions. Several of these episodes took place over different regions of the world over different periods of time in the early twentieth century. In contrast, recurring seasonal pollution episodes are experienced over polluted regions such as in the East Asia and over the IGP region in South Asia. Stronger anthropogenic emissions can get trapped into shallower boundary layers during winters leading to enhanced pollution, which can further lead to widespread haze over these regions (Kumar et al. 2015, 2017; Ojha et al. 2020). The transport of pollution from upwind regions can further exacerbate these episodes. The post-monsoon time high $PM_{2.5}$ is attributed to the transport of crop residue burning over upwind agricultural regions (Sen et al. 2017).

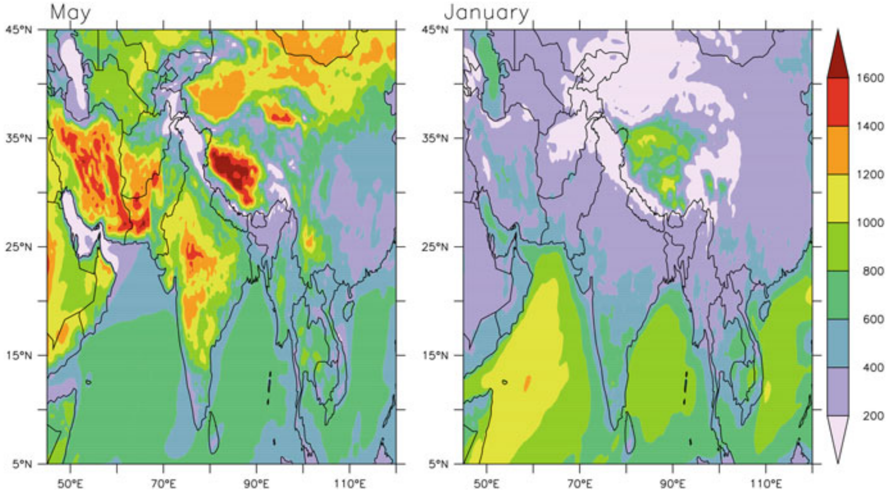

Fig. 12.4 Boundary layer height (m) over South and East Asian regions during summer (May) and winter (January) conditions for the year 2015, derived from the ERA5 reanalysis

The stagnant atmospheric conditions play a key role in confining anthropogenic emissions near the surface during winter over the IGP (Ojha et al. 2020). Variations in the meteorological conditions played pivotal role in more atmospheric ventilation reducing near-surface pollution during the Asia-Pacific Economic Cooperation (APEC) (Ansari et al. 2019). Figure 12.4 shows the variations in the boundary layer height over South and East Asian regions during summer (May) and winter (January) conditions as derived from the ERA5 meteorological reanalysis for the year 2015. Boundary layer height over northern and central Indian regions decreases drastically from summer (800–1600 m) to winter (200–400 m) reducing the vertical mixing and therefore the dilution of pollution. Similar changes are also evident over the eastern Asian region. Recent studies have reported an additional role of complex chemical processes in the persistence of haze episodes. Increased humidity can substantially change the chemical properties of aerosols through these complex processes, which can drastically reduce the visibility in high aerosol mass loading scenarios (Cheng et al. 2016; Gunthe et al. 2020). An example of early morning haze versus clear sky conditions over a tropical megacity, Delhi, India, is shown in Fig. 12.5 (adapted from Dhaka et al. 2020).

In complete contrast to winter haze, dry springs and summers experience intense photochemistry involving NOx, CO and VOCs to produce O_3 in urban and rural environments, called as the photochemical smog. Depending upon precursor concentrations (NO_x and VOCs) and solar radiation, O_3 production takes place through complex and non-linear chemistry (Seinfeld and Pandis 2006). O_3 pollution is especially stronger during dry summer conditions, as shown in Fig. 12.2 due to intense photochemistry. NO participates in O_3 chemical destruction also, and therefore, net O_3 concentrations can be higher in the downwind regions than those over the emission sources of fossil fuel and biomass burning. Higher fossil fuel burning

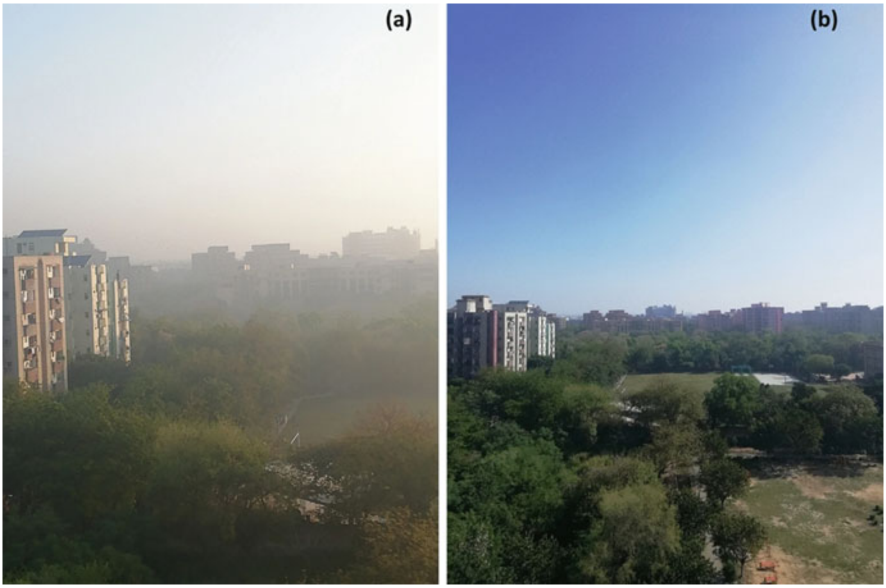

Fig. 12.5 An example of (**a**) early morning haze and (**b**) clear sky condition over a tropical megacity, Delhi, India (adapted from Dhaka et al. 2020 available at https://www.nature.com/articles/s41598-020-70179-8 as per https://creativecommons.org/licenses/by/4.0/)

over China causes high O_3 events exceeding 200 μg m^{-3} more frequently mainly during the warm season as compared to several other industrialized regions in the world (Lu et al. 2018). Higher temperature during summer months fuels the chemistry and can also enhance biogenic emissions of VOCs resulting in higher O_3 concentrations (Coates et al. 2016). Biomass burning was shown to enhance O_3 levels above the air quality standards during spring and autumn seasons over northern Indian region (Kumar et al. 2016; Ojha et al. 2019). In addition to contributions from fossil fuel and biomass burning, fertilizer-induced NO_x emissions from soil also contribute to O_3 chemistry, especially over the agricultural regions (Chameides et al. 1994). Nitrous acid (HONO), a reservoir of NOx and HOx mainly formed during night, injects a pulse with sunrise (Seinfeld and Pandis 2006). Recently, new sources of daytime HONO are revealed (Kleffmann 2007), which could influence O_3. Similarly, the gas-phase reactions between Cl and VOCs can also increase the production of O_3 (Riedel et al. 2014). In a nutshell, photochemistry intertwined with the meteorology and concentration of precursor gases drives the O_3 pollution. Most of the studies dealt with gas-phase chemistry, but the role of heterogeneous chemistry (reactions on the surface of aerosols, for instance, during thick fog events) also needs to be investigated more in future.

During the El Niño conditions, sea surface temperature is warmer than usual in the Eastern Pacific. This causes changes in the precipitation pattern over the tropical belt. Precipitation reduces and Southeast Asia (especially, maritime continent) and Australia experience drought conditions. In effect, prolonged drier and hotter conditions prevail over Indonesia and Australia. These conditions are conducive for triggering fires over forest regions. Extreme forest fire events have been observed over Indonesia and Australia during El Niño years (e.g. 1997, 2006). Millions of people suffered the effects of air pollution resulting from the forest fires of 1997–1998 over Indonesia. Neighbouring countries (Malaysia and Singapore) experienced thick clouds of smoke and haze. Thailand, Vietnam and the Philippines also felt haze. This was due to extremely dry conditions over forest under the drought influences linked with El Niño (Glover and David 2006).

It is clear that air pollution episodes are results from a variety of man-made and natural factors. Besides regulations on the industrial emissions and efforts to avoid accidental leakages, significant efforts are needed to monitor the air quality over global and regional scales. Contributions of anthropogenic and biomass burning emissions have still been uncertain due to uncertainties in the emission inventories and limited abilities of models to reproduce the measurements. Ozone pollution is anticipated to be stronger in the future because climate warming can offset the potential benefits of emission reductions (Coates et al. 2016). Occurrences of heatwaves and concurrent high ozone pollution can lead to more severe health effects (Stedman 2004). Controlling the biomass burning emissions from both natural forest fires and man-made such as crop residue burning would involve consideration also of socio-economic aspects of a particular region. In view of these, it remains a major challenge to formulate the policies to minimize occurrences and impacts of pollution episodes by taking unfavourable meteorology and climate change also into account for more effective control measures.

12.5 Some Perspectives on Control Measures and Outlook

Numerous acts and regulations have been brought in worldwide to minimize the occurrences and impacts of the air pollution episodes (e.g. Jacobson 2002; Brimblecombe 2017). Here, we discuss some current perspectives and outlook on control measures of pollution episodes. Measures to control air pollution involve a diversified approach requiring the source and process-oriented steps and considering the socio-economic, scientific and cost-benefit aspects. The conventional control systems rely on source-based pollution control strategies, e.g. control of emissions from point and mobile sources or the efficiency improvement of processes (e.g. combustion efficiency) to reduce the emissions (Saxena and Sonwani 2019). Air pollution from large-scale industries, vehicular exhausts and indoor air pollution sources have been a prime focus of air pollution control and management, whereas relatively less emphasis has been on the impacts of natural phenomena (forest fires, volcanoes, secondary formation of aerosol particles, etc.). The important air pollution episodes, which require special attention, are season-specific haze and smog, dust outbreaks and occasional leakage of toxic gases from industrial units. Localized observation and high-resolution modelling studies have suggested a strong interplay of both source strengths and meteorological phenomena in the development of regional haze (e.g. over northern India, Indonesia and East China). Sudden spikes in the concentration of $PM_{2.5}$, CO, SO_2, NO_2, NH_3, etc., attributed to the burning of crop residue or forest biomass, lead to the formation of haze and smog. The control of these types of pollution events requires important policy interventions and effective management via alternate use of residual biomass or temporal adjustments in crop harvesting periods. The provincial governments in the northern Indian states of Punjab and Haryana have enacted laws against the open burning of crop residue and also provided subsidies for not burning as a preventive measure to reduce haze during post-monsoon. A similar inter-governmental framework has been designed among the countries in the Southeast Asian region. Dust outbreak is another such air pollution episode that requires more preventive measures rather than its direct control due to its natural origin. Although it is difficult to control the long-range transport of dust, nevertheless, its resuspension can be significantly checked with suitable landscape management policies. The development of green belts in residential and commercial areas would help in reducing ambient dust through different processes such as filtration, interception and absorption on plants. The green belts are reported to be effective in gaseous pollution tolerance (Sikarwar et al. 1999; Saxena et al. 2010, 2011). The mandatory developments of green belts for every commercial, residential project of larger areas and industrial infrastructural construction can help in controlling the resuspension of dust transported from distant sources. Chaulya (2004) and Garg et al. (2015) provides recommendation on several plant species that can be used for green belt development to reduce ambient air pollution.

It may, however, be challenging to develop green belts at locations with a large impervious area like cities and other urban settings. In such conditions, green roofing over buildings has significant potentials of intercepting dust and other pollutants. Deutsch et al. (2005) estimated the removal of 58 metric tons of pollutants including aerosols with 100% green roofing. Similar results were observed by Currie and Bass (2005) in Toronto with the removal of 7.9 metric tons of air pollutants annually with 109 ha of green roofs in the city. The implementation of such practices should be emphasized in regions like India and China experiencing rapid urban sprawl and land-use changes. The implementation of the green roofing concepts should be stressed upon through acts and legislations to reduce ambient air pollution. Occasional leakage of toxic gases and other pollutants from industries can also be more controlled through firm legislations and protocols. The key protocols that ensure the control of occasional accidents from leakage include periodic leak detection inspections, maintenance of records of previous leaks and setting up future stringent safety goals. These measures would ensure the prevention of unanticipated pollution episodes. The remote detection of leakage through portable measurement systems can help in preparation for any such accident.

It is of vital significance to depend more on renewable energies and make all possible efforts to minimize fossil fuel burning in the future. Lelieveld et al. (2019) argued that this would have a remarkable effect on the global air quality and save millions of lives, besides helping to limit the global warming. In addition to various control measures, it is also crucial to improve our understanding of the chances of occurrence of air pollution episodes in the future. More efforts with monitoring and modelling of air quality would help in availing better forecast (Kumar et al. 2018) and hence better preparedness. Satellite-based measurements are being used to successfully retrieve the distribution of $PM_{2.5}$ over large geographical regions (Dey et al. 2020), which would especially be useful over regions with sparse observations and strong spatial heterogeneity. Assimilation of satellite-based measurements is shown to significantly improve the skills of model forecast systems in predicting the short-term air quality (Kumar et al. 2020). Further improvements in the emission estimates, improved meteorology, and chemistry schemes would be valuable in better understanding the air pollution drivers over local to regional scales and designing the control measures.

12.6 Summary

Historically, the air pollution episodes have been driven by unusual combinations of emission with meteorological condition. For example, the Great Smog of London (1952) was driven by coal burning emission and limited atmospheric ventilation in the winter, whereas the photochemical smog over Los Angeles (1943) was due to intense photochemistry involving vehicular and industrial emissions during summer. Additional major episodes were caused by sudden emissions from accidental leak in industry, volcanic eruptions and forest fires. The health impacts of pollution during such episodes were unprecedented and therefore initiated the development and implementation of policies for prevention and control.

The observational and modelling studies unravelled a variety of mechanisms causing pollution episodes, besides providing the recommendations for formulation of effective control strategies. In this line, numerous national and international efforts have been initiated for providing data sets on air pollution and deriving health impacts over local, regional and global scales. Nevertheless, pollution episodes are being experienced both over major cities and in the form of widespread haze across larger geographical areas (e.g. NCP, IGP). Both the NCP and IGP regions have been identified as the global hotspots of elevated $PM_{2.5}$ during winter conditions. In contrast, the photochemical smog is experienced to be most severe during the dry spring-summer conditions associated with high ozone levels, which also spreads over rural and remote regions. Besides the meteorological conditions and anthropogenic emissions, air pollution is also found to be exacerbated by intense forest fires and crop residue burning. Recently, regulations have been placed to curb emissions from anthropogenic sources and crop residue burning, besides stringent safety measures to prevent accidental release of toxic pollutants from industries and chemical plants. In addition, monitoring of air quality using ground-based network is also expanded to cover the larger geographical areas complimented by the satellite-based instruments.

Despite significant progress on monitoring, modelling and implementation of policies, the intensity and frequency of extreme pollution are on the rise. More studies are therefore needed to fill the data gaps and to validate the satellite retrievals and model simulations, especially over developing regions. Minimizing the usage of fossil fuel is suggested to help both in reducing pollution and in mitigating climate warming. In future, natural emissions may also rise due to climate warming, which could offset some benefits of reduction in the anthropogenic emissions. Hence, further studies on pollution impacts are needed, which also account for the role of climate variabilities leading to frequent pollution episodes. In the end, assimilation of satellite and ground data with models for accurate forecasting of pollution episodes would help towards better preparedness and to minimize health impacts.

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Increasing Atmospheric Extreme Events and Role of Disaster Risk Management: Dimensions and Approaches

13

Madhavi Jain

Abstract

Under most future emission projection scenarios, global temperature rise is imminent. Rising temperature is closely interlinked with balance in energy and water budget. As per the Clausius–Clapeyron equation, atmospheric moisture rises as 7% per °C rise. This means that both temperature and precipitation extremes such as heatwaves, floods and droughts will be more frequent and intense. Multiple atmospheric extremes events such as heatwaves with low moisture availability could have severe compounding impacts, e.g. increased risk of forest fires, droughts and dust storms. Moreover, global population is increasingly becoming more urban. Most future urban population growth is projected to be in the densely populated cities in Asia and Africa. Temperature and precipitation extremes are often exacerbated due to the presence of dense urban areas and are presented as urban heat islands, CO_2 domes, urban flooding, smog, etc. Cities, in general, show more vulnerability towards atmospheric extremes.

In order to mitigate such disasters, it is crucial to identify vulnerable hotspots and demographic groups most likely to be affected. The chapter outlines various disaster mitigation and adaptation strategies. Importance of science and decision support systems, data availability and sharing, early warning systems, timely information dissemination and post-disaster management are highlighted.

Keywords

Atmospheric extreme events · Temperature · Precipitation · Urbanization · Disaster vulnerability · Mitigation strategies

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13.1 Background

From 1999 to 2018, more than 12,000 extreme events were recorded worldwide (Eckstein et al. 2019). Adapting to and mitigating extreme atmospheric events fuelled by climate change is quite possibly the greatest challenge presented to mankind in the twenty-first century. Not only do such disasters cause tens of thousands of deaths each year, but they also incur huge monetary and gross domestic product (GDP) losses. Nearly, half a million people died as a direct result of these events between 1999 and 2018, and they further coasted countries ~USD 3.5 trillion (Eckstein et al. 2019). Looking closely, the global number of climate-related disasters in the recent times increased from 428 per year (1994–1998) to 707 per year (1999–2003) (Prasad et al. 2008). Moreover, atmospheric extremes pose a danger to all sectors of the society—agriculture and biodiversity, food and water security, health and livelihood, small and large businesses, and culture and tourism (Wernberg et al. 2013; Thornton et al. 2014; Thomas et al. 2019). Such disasters affect both the rich and the poor, although the poor are much more severely impacted (IPCC 2012; Fankhauser and McDermott 2014). Therefore, it becomes imperative to study (1) how 'normal' atmospheric conditions are changing and what it means for the future, (2) what different types of atmospheric extremes exist, (3) which regions and socio-economic groups are more vulnerable to their impacts and finally, and (4) what strategies can be implemented to manage disaster risks and increase resilience. This chapter briefly introduces the reader to all these key concepts. It also focuses on the importance of identifying key vulnerable hotspots and demographic groups that are highly likely to face severe adverse effects of such events.

13.2 Atmospheric Dynamics and Feedbacks

Under normal atmospheric conditions, a balance in the amount and distribution of energy is maintained. Almost all aspects of planetary weather and climate systems are governed by radiation budget balance and the normal functioning of feedback systems, e.g. hydrological cycle (Trenberth et al. 2009). However, since the industrialization era, the earth's air chemistry and atmospheric composition have recorded major changes—most notably in the concentration of carbon dioxide (CO_2). CO_2 atmospheric concentration increased from 280 parts per million (ppm) in 1750 to 410 ppm in 2019 and is projected to reach ~600 ppm by 2050, given current emission trends (Soba et al. 2020). Various anthropogenic practices such as fuel combustion, industrialization, biomass burning, deforestation and land-use changes have inarguably led to significant increase in levels of CO_2, carbon monoxide (CO), methane (CH_4), nitrous oxides (NO_x), tropospheric ozone (O_3), volatile organic compounds (VOCs), chlorofluorocarbons (CFCs) and other trace gases such as sulphur hexafluoride (SF_6) (IPCC 2014; Uprety and Saxena 2021a). Apart from greenhouse gas (GHG) emissions, aerosol column burden is yet another concern. Fine ($PM_{2.5}$) and coarse (PM_{10}) particulate matters (PMs) are added to the troposphere by natural and anthropogenic sources and get transported via winds to long-range distances (Saxena et al. 2021; Sonwani et al. 2021). Properties such as radiative heating or cooling depend upon aerosol physical and chemical properties, particle residence time, amount and distribution in the atmospheric layers (Quaas et al. 2004; Andrews et al. 2011; IPCC 2014).

The earth's radiation budget and as a consequence the global water budget (hydrological cycle) are greatly affected by such changes in the atmosphere (Trenberth 2011; Brown and Caldeira 2017). Trenberth et al. (2009) provide a detailed schematic of the incoming shortwave radiation from the sun, its distribution, outgoing long-wave radiation emitted from the earth and the net energy stored. The presence of various types of clouds, amount of water vapour, gases and aerosols in the atmosphere, along with albedo and thermal properties of various land covers types, e.g. forest, water bodies and urban areas, determine the amount of radiation that is absorbed, transmitted or reflected (Trenberth et al. 2009). In a globally polluted environment, the atmospheric burden of GHGs such as CO_2, CH_4 and N_2O increases tremendously. These gases have a high global warming potential (GWP) and global temperature change potential (GTP) (Myhre et al. 2013). Readers are encouraged to go through the extensive data assembled by Myhre et al. (2013) on GWP, GTP and atmospheric lifetimes of major and trace gases found in our environment.

Meanwhile, on the land surface, evapotranspiration process accelerates when the surrounding air has a high sensible heat. In an effort to lower down the Bowen ratio, moisture from plant systems and from the soil beneath is rather converted to latent heat (Jain et al. 2017). Thus, a higher fraction of moisture content enters into the atmospheric system, creating a moisture deficit over many land regions. Coupled with continued rise in ambient temperature and lack of moisture for further surface evaporation (and evapotranspiration), many regions face increased risk of droughts, forest fires and sometimes dust storms (IPCC 2012). Apart from this, these areas are also likely to experience extreme heat stress, severe heatwave events and slowly a new normal of elevated temperature. As per the Clausius–Clapeyron equation, low-level moisture shows a ~7% increase for every degree Celsius (°C) rise in temperature (Allan and Soden 2008). In order to complete the hydrological cycle, this excess water vapour (temporarily stored in the atmosphere) requires a sink. The sink is often presented in the form of heavy and extreme precipitation events, e.g. severe thunderstorms, tropical cyclones and stronger hurricanes where all the excess stored water vapour is suddenly released (Trenberth et al. 2003). Heavy and extreme precipitation events are therefore significantly intensified and more likely under a warmer climate, leading to more floods and large-scale inundation (IPCC 2012). The presence of cities and urban agglomerations often exacerbates the atmospheric extreme events. For example, most cities already face higher night and daytime temperature than their rural surroundings. They are also major sources of air pollution. Thus, the effects of any heatwave event are often amplified for urban residents due to the urban heat island (UHI) effect. Similarly, lack of porous soil surfaces or water reservoirs due to rampant concretization overwhelms the city drainage systems. In this case, even few minutes of a heavy precipitation event are capable of creating flood-like situations, which would be rare in a rural setting.

13.3 Increase in Frequency and Intensity of Atmospheric Extremes

As discussed, anthropogenic activities are significantly causing changes in the global radiation and water budget. Better computational abilities, deeper knowledge of atmospheric dynamics and better data availability have continuously helped scientists simulate atmospheric extremes with higher accuracy (Tippett 2018). Most numerical weather predictions and climate model outputs unanimously agree that atmospheric extremes will be more common under almost all future climate scenarios (IPCC 2014). Temperature and precipitation are the two most important variables that largely govern short-term weather and long-term climate patterns on local, regional and global scales (Trenberth et al. 2009; IPCC 2014; Brown and Caldeira 2017; Tippett 2018). In fact, shifts from 'normal' temperature, precipitation and associated land–atmosphere feedback systems cascade into a multitude of extremes that have far-reaching, unprecedented and devastative effects (IPCC 2012). Various large- and local-scale atmospheric extremes are discussed in detail in the following sub-sections.

13.3.1 Large-Scale Atmospheric Extremes

13.3.1.1 Heat and Cold Waves

An atmospheric heatwave is a deadly temperature stress event that lasts from a few days to many consecutive weeks. To name a few, the Chicago (1995), European (2003 and 2019), Indian subcontinent (2007, 2015 and 2019), Australian (2008 and 2019), California (2016) and Siberian (2020) events are well-known examples of severe heatwaves in the recent decades. Unlike other extremes, e.g. hurricanes, tornadoes, floods and forest fires, the death toll from heatwaves is not always immediately obvious, but it is still one of the leading causes of weather-related mortality (Robinson 2001; Peterson et al. 2013). According to the World Health Organization, in 2015 alone, an additional 175 million people were exposed to heatwave events compared to previous year averages (WHO 2020). Compared to 1971–2000, the global heatwave exposure (95th percentile) under a combined representative concentration pathway and shared socio-economic pathway (RCP8.5-SSP3) is likely to increase ~18–37 times by 2071–2100 (Liu et al. 2017). In other words, with increasing emissions, less sustainable development and a disparate population growth between developed and developing countries, the global heat exposure will quantifiably amount to ~1200 to 2300 billion person days. The mortality risk also depends on factors such as individual and community acclimatization to prolonged temperature extremes, means of thermal comfort, i.e. heating and cooling mechanisms and access to affordable health care (Robinson 2001; Kovats and Hajat 2008; Kent et al. 2014). Heatwaves are in part exacerbated due to UHI formations (see Sect. 13.3.2.1).

Simply speaking, a heat (cold) wave is an extended period of above (below) normal climatological temperature that causes unusually high stress to the human

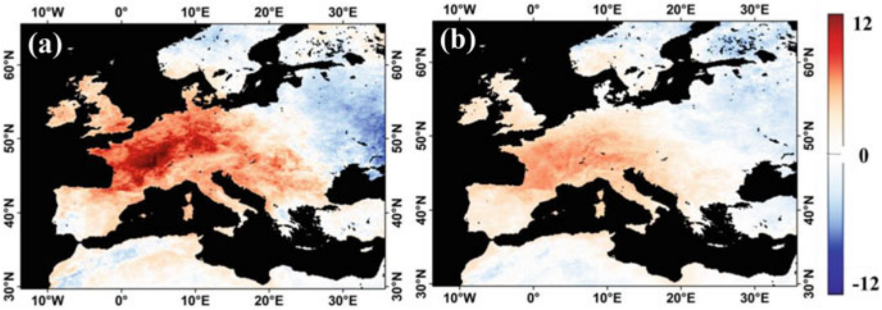

Fig. 13.1 MODIS (**a**) day and (**b**) night land surface temperature (LST; °C) anomaly over Europe for August 2003, compared to 2000–2010 August mean. Map is prepared via NASA earth observation online platform (https://neo.sci.gsfc.nasa.gov/) and ArcGIS ver. 10.6 mapping software. Only land surface is represented, and sea is masked (in black)

body (Robinson 2001). No singular definition of heat and cold waves exists in literature as most regions fine tune this concept based on geographical and climatological set-up. The degree of deviation from climatological normal, heat thresholds (75th or 95th percentile) and minimum days needed to classify the event as a heat (or severe heat) wave is therefore highly subjective (Robinson 2001; Kent et al. 2014; Liu et al. 2017). Steadman (1984) combined temperature and relative humidity to estimate the apparent temperature (temperature felt by the human body as opposed to actual temperature), which was later modified and termed as the 'heat index' by the National Weather Service. Many other such heat indices have been developed since then.

The famous 2003 summer European heatwave blasted through most European countries with extreme sweltering and record-breaking temperatures. Night-time temperatures at some European locations were noted to be several degrees higher than their climatological daily mean (Black et al. 2004). By the end of the event, almost 70,000 deaths were officially reported (WHO 2020). Figure 13.1 shows MODIS day and night land surface temperature (LST) anomaly over Europe during August 2003, compared to its decadal (2000–2010) mean for the same month. A clear and extreme deviation (>5 °C and reaching ~12 °C over some European regions) from the decadal average temperature (for both day and night) can be noted for August 2003. If some climate model predictions are to be believed, then the atmospheric conditions presented in the 2003 European heatwave would become the 'new normal' by the year 2100 (Black et al. 2004). Similar deadly heatwaves struck the Indian subcontinent in the summer of 2015, with temperatures crossing 45 °C at many places and killing more than 2500 people in India and ~700 in Karachi (Pakistan) (Wehner et al. 2016). According to the authors, both events had clear anthropogenic signatures in the heat indices. Apart from human-induced factors, strong dry winds called 'loo' blowing from north-western parts of Indian subcontinent, high humidity and significantly less pre-monsoon precipitation contributed to increased severity of the event (Pattanaik et al. 2017). In all likelihood, temperature extremes across the world, in particular heatwaves, are expected to be more frequent, intense, longer in duration and wider in spatial expanse in the future (Robinson 2001). Mishra et al. (2017) in their study over India highlight that severe heatwave events (such as 2015 heatwave) are likely to increase 15 times by 2050 and 92 times by 2100 if global temperatures increase by 2 °C. Cold extremes at a global level are likely to decrease in the future, but nonetheless are an important atmospheric extreme event (IPCC 2012). In the USA, average cold wave events were recorded to be the highest during the 1980s and in the 2000s there was almost a lack of cold waves (Peterson et al. 2013). However, increasing instances of weak stratospheric polar vortex since the 1990s means that the cold polar winds are unable to remain confined at high latitudes and creep into the mid-latitudes, causing many cold extreme events in Northern America and Eurasia (Kretschmer et al. 2018). Apart from these, it should be mentioned that marine heatwaves have also become unequivocally more frequent, longer and intense and are expected to follow the trend with changing atmospheric conditions and global warming scenarios (Tippett 2018).

13.3.1.2 Precipitation Modification

During the twentieth century, the global temperatures at the surface rose by 0.74 ± 0.18 °C (IPCC 2014). Moreover, barring the year 1998, all the remaining top ten warmest years on NOAA records have occurred since 2005, and projections suggest that 2020s will outrank (high confidence) previous records (Arguez et al. 2020). Global temperature rise directly leads to glacier and continental ice shelf melting, which in turn causes sea level rise and changes in ocean salinity. As mentioned earlier, a warmer climate has a higher moisture-holding capacity, a phenomenon governed by the Clausius–Clapeyron equation (see Sect. 13.2). Tropics and subtropics show a strong association between increased sea surface temperature (SST), positive El Niño Southern Oscillation (ENSO) and the total column water vapour, which influences precipitation patterns such as monsoons and Walker circulation (Trenberth 2011). Stronger ENSO events are also closely linked with recurrent floods in some African nations (Ward et al. 2010). In effect, all direct and indirect temperature feedbacks alter the ‘normal’ frequency, type, amount, timing, distribution and intensity of various large precipitating systems and extreme precipitation events (Trenberth et al. 2003; Goswami et al. 2006; Kishtawal et al. 2010; IPCC 2014; Tippett 2018). Precipitation commonly occurs as rain, snow or hail, and has embedded inter-seasonal, inter-annual and inter-decadal variabilities (IPCC 2012). Snow accumulates in the winter months and replenishes glacier volume and its slow melting in summer months provide freshwater via rivers, streams and channels. In a warmer climate, precipitation is more likely to be in the form of rain (rather than snow), which will severely disrupt freshwater availability (Groisman et al. 2001). Such a scenario is especially concerning for countries such as India, where the majority of freshwater demand for a billion plus population is fulfilled by glacier-fed rivers.

Global observations suggest that the zonally averaged annual precipitation between the years 1900 and 1995 has increased by 7–12% over Northern Hemisphere (30°–85°N) and by ~2% over Southern Hemisphere (0°–55°S) (Dore 2005).

This asymmetry is mainly due to the distribution of earth's landmass, non-linear ocean–atmosphere coupling and, most importantly, anthropogenic influences. Further, recent decadal observations note that over time moist (dry) regions of the world have become wetter (drier) and that many climate models underestimate the precipitation response to the globally warming atmosphere (Dore 2005; Allan and Soden 2008). There has been a significant increase in both heavy and extreme precipitation events, even when no change or fall in total annual precipitation is noted (Allan and Soden 2008). Similarly, for many increasingly wetter regions in the world too, the total annual precipitation is skewed towards increasing extreme events and such a trend is expected to continue into the future (Donat et al. 2016). Observational data sets for 1951–2003 show the Indian summer monsoon (ISM) over central India region has remained stable, with no significant trends in the number of active and break days (Rajeevan et al. 2006). However, upon closer look over the same region (from 1951 to 2000), Goswami et al. (2006) find a statistically significant trend of increasing extreme events and simultaneously decreasing trend of moderate precipitation events during ISM. Cook et al. (2014) observe that the North American monsoon (NAM) shows small and statistically insignificant changes in total season rainfall under RCP8.5 emission scenario. However, the authors in their Coupled Model Intercomparison Project version 5 (CMIP5)-based simulations find a delayed onset and late season retreat of the monsoon as a response of increased GHGs in the atmosphere.

Apart from modifications in large monsoon systems, e.g. ISM and NAM, the twenty-first century is witnessing a higher proportion of severe thunderstorms, tropical and extratropical cyclones, cloud bursts and flash floods, etc. (IPCC 2012; Hawcroft et al. 2018). For example, large-scale moisture incursion in the US west coast, brought on by atmospheric rivers, is expected to have more frequent landfalls with longer spells causing higher precipitation extremes by 2100 (Tippett 2018). The 2017 hurricane season in the Atlantic Ocean was particularly devastating. High ocean heat content (OHC), increased SST and overabundant moisture content provide the perfect recipe to fuel many long and intense tropical storms and hurricanes (Trenberth et al. 2018). The authors find concrete footprints of anthropogenic-driven climate change in the realization of 2017 hurricane Harvey. Substantially high OHC was converted to massive quantity of atmospheric moisture over the Gulf of Mexico, which later on caused record-breaking rainfall and flooding (Risser and Wehner 2017; Trenberth et al. 2018). Urbanization was found to have further exacerbated the rainfall amount and associated flooding in Houston, USA, during this hurricane (Zhang et al. 2018). Behaviour of heavy and extreme precipitation over urban areas is discussed in detail in Sect. 13.3.2.2. Poor land use and land management practices, e.g. urbanization along riverbeds, watershed areas and low-lying coastal areas, deforestation, removal of grasslands, wetlands and coastal mangroves, and creation of dams and other water diversions, add on to precipitation and flood disaster incidences, severity and losses (Peterson et al. 2013). The 2013 Kedarnath flash flood disaster that killed over 6000 people in India is an excellent example in this respect (Allen et al. 2016).

13.3.1.3 Droughts

Drought is a complex and recurring extreme event caused over land that can stretch from few months to many years (Dai 2011). Multiple factors such as sustained high temperature, extended severe heatwave event, high evaporation rate, very less or no precipitation for long periods, overexploitation of groundwater, deforestation and overgrazing can lead to a drought (van Lanen and Peters 2000; Peterson et al. 2013). A drought, be it meteorological, agricultural or hydrological in nature, is essentially the result of a prolonged state of imbalance between net moisture (Dai 2011). When soil moisture falls below a certain threshold, it fails to support plant systems, leaving large areas not suitable for agriculture, and therefore crucial from global food security perspective. Li et al. (2009) used a revised Palmer Drought Severity Index (PDSI) combines effects of drought frequency and severity, crop yield and irrigation extent in order to model future meteorological drought frequencies under various special report on emissions scenarios (SRESs). Their exhaustive study indicates that under increasing temperature, global drought risk by 2100 will enhance, especially in Africa. The authors add that global area under drought is likely to triple compared to baseline figures, and correspondingly, major crop yields will significantly decline. A recent study by Bisht et al. (2019) over India reveals a strong likelihood that the above moderate drought conditions under a warming climate (RCP 4.5 and RCP 8.5) will significantly worse by 2100 as compared to moderate droughts. Compared to 1976–2005, the average drought length, severity and persistence for each successive drought occurrence is likely to keep increasing from near-future (2010–2039), to mid-future (2040–2069) and then to far-future (2070–2099) (Bisht et al. 2019). This would indeed put an excessive amount of pressure on food security of India, considering its massive population. Besides agricultural productivity and food security, droughts are also responsible for huge biodiversity losses, mortality and economic downfall.

13.3.1.4 Dust Storms

Sustained droughts risk depletion of loose fertile topsoil layer through wind erosion, consequently declining soil quality and even leading to desertification in extreme cases. Assessing the eastern Mediterranean soil, Amit et al. (2021) find evidence of long-range Saharan and Arabian fine dust transport occurring since millions of years, and another geologically recent (Pleistocene) dust source from the nearby Negev desert. The authors emphasize that the agricultural productivity of the region was enhanced only after winds rich in coarse silt quartz were supplied. Apart from Saharan Desert and Arabian Desert, the Taklimakan Desert is another major source of trans-continental dust, all three collectively accounting for over 95% of natural dust emissions in the world (Chen et al. 2018). While dust storms carry nutrients to some regions, they also cause additional burden, especially concerning human health and productivity.

One such event, the 1930s ‘dust bowl’ that occurred in the USA and lasted nearly a decade is elaborated. The challenges of the great depression and World War I forced Americans to mercilessly plough and harvest the Great Plains region in 1920s, well beyond its ecological limits (Worster 2004). What started as an ecological blunder slowly turned into the worst drought in its climatological history. The absence of rains in 1930, successive droughts beginning 1931 and recurring intense heatwaves in the following years left the ground devoid of any soil moisture by the mid-1930s (Warn 1953). The long intense drought stretched to almost 20 states, and winds carried away any unanchored soil, which as result of dust aerosol precipitation suppression further exacerbated the drought (Dai 2011; Cook et al. 2014). Worster (2004) details that as many as 179 dust storms recorded in April 1933 were sourced from the drought-stricken areas. Between 9 and 11 May 1934, about 350 million tons of loose brown earth was swept up in the atmosphere by high-level winds creating a 'black blizzard' and many such blizzards, e.g. Black Sunday followed in the years thereafter (Warn 1953; Worster 2004; Cook et al. 2014). By its end in 1939 (with the onset of good rains), the 'dust bowl' event had caused loss of more than 850 million tons of earth, thousands of deaths from heat, starvation and dust pneumonia, migration of almost 2.5 million people and economic losses that ran in millions of USD each day (Worster 2004). Model simulations suggest that by 2050, extreme drought conditions similar to the dust bowl event will likely occur over south-west USA, Southeast Asia, southern Europe and large regions in African and Australia (Dai 2011). The conditions are expected to keep worsening under climate change and remain largely irreversible for about a millennium even after emissions have been curbed (Romm 2011).

13.3.1.5 Forest Fires and Biomass Burning

Forest fires are yet another example of an extreme event that will significantly get impacted by future changes in climate (Jain et al. 2021). Figure 13.2 shows the global fire burn area map for 2015. It includes both forest and agricultural fires across all biomes (Giglio et al. 2018). Fires start due to natural (e.g. friction between dry trees in summer and lightning strikes) or anthropogenic (e.g. accidental small fire or intentional burning which turned massive) cause. Central African and sub-Saharan

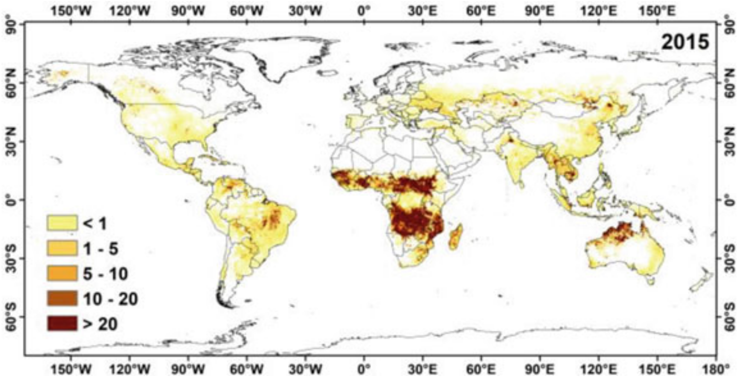

Fig. 13.2 Map showing global area (in thousand ha) burning due to all fires (forest and agricultural) for the year 2015. Map plotted at 0.25° × 0.25° spatial resolution using ArcGIS ver. 10.6 (*data source:* https://sedac.ciesin.columbia.edu/data/)

region (Fig. 13.2) shows large-scale controlled fires due to extensive biomass burning. While many argue that slash and burn practices, intermittent and other seasonal fires help restore ecosystem productivity and control pests, they have numerous detrimental effects pertaining to air quality and health (Bauer et al. 2019).

In general, frequent and large-scale fires of any type tend to cause loss of biodiversity, elevated local temperatures, poor visibility and increased secondary effects related to pollution and smoke. Besides this, widespread fires also force evacuation and cause property damage. Area under fire, its intensity (amount of energy released), time of the year (summer fires are generally more intense due to low moisture in vegetation and a drier climate), fire type (ground surface, canopy crown or a mix) and fuel type and amount (firewood and biomass properties) determine the severity of any forest fire event (Flannigan et al. 2000). Compared to the twentieth century, twenty-first-century forest fires in California are significantly bigger ($>$12,000 ha burn area) and start earlier in the season, a shift likely due to climate change (Collins et al. 2019). Combined with a 1 °C temperature rise and a significant decrease (-30%) in autumn rainfall since 1980s, the frequency of extreme fire weather (95th percentile) days in autumn is twice as likely now (Goss et al. 2020). The 2020 autumn California forest fires have burnt an area $>$1.3 million ha and are yet to be fully contained but have already been recorded as the largest wildfire in its history (Forbes 2020). Prolonged lightning strikes initiated the fires, but an extremely dry weather with persistent heatwave conditions and winds turned it into a major extreme event (Temple 2020). The intense heat in wildfire hotspots further created pyro-cumulonimbus clouds, which creates risk of expansion of existing fires due to downdraft winds or entirely new fires due to more lightning strike activity (NASA 2020). In addition, the smoke from these fires has travelled thousands of miles to cities on the US east coast and even as far as Europe, causing high BC and CO levels along with poor visibility and health issues (Los Angeles Times 2020). Similarly, the frequent intense arctic and boreal fires have been linked with increased atmospheric CO_2 seasonality coupled with increasing land-use land cover disturbances, changes in forest types, albedo and net radiation (Wang et al. 2020).

13.3.2 Regional and Local-Scale Atmospheric Extremes

Atmospheric extremes are without a doubt a cause of concern for the entire world, but its effects are felt more in cities. Our world is now predominantly urban, as per the United Nations by another decade almost 67% population would be living in a city (UN 2018). Also, the morphology, dynamical (energy physics, hydrometeorology, etc.) processes and the microclimate within cities are very different from the natural landscape (Oke 1997; Zhou and Chen 2018). The next subsection addresses how cities tend to exacerbate temperature and precipitation extremes and air pollution-related events.

13.3.2.1 Urban Heat Island and CO_2 Domes

Urban and suburban areas are typically warmer (2–10 °C) than their adjacent rural surroundings (Oke 1997; Rosenzweig et al. 2006; Kishtawal et al. 2010; Zhou and Chen 2018). This is especially noted on calm and clear nights, with the most intense formations usually occurring during summers (Arnfield 2003). When urban development replaces natural elements with asphalt, glass, bricks and steel, it greatly modifies the thermal and radiative properties such as energy balance, albedo, surface roughness length, wind and water flow patterns and the urban canopy layer characteristics (Arnfield 2003; Huong and Pathirana 2013; Zhou and Chen 2018). After sunset, buildings slowly keep emitting radiation that was absorbed during the day, while natural landscapes tend to remain cooler. Reduction in evapotranspiration also causes elevated sensible heat fraction in dense urban morphology (Vardoulakis et al. 2013). Thus, on top of global temperature rise, warmer urban areas face an additive local climate change effect, generally increasing energy demands. Vardoulakis et al. (2013) estimated a 36% increase in cooling demand during peak summer, for a small city in Greece. Such demands turn out to be exceptionally high in megacities, simply because of their massive population size. To meet the increased energy requirements of warmer cities, more GHGs are inadvertently added into the atmosphere. At the same time, cities have another unique phenomenon called CO_2 domes.

Extensive urbanization processes are directly (e.g. vehicular, commercial and industrial emissions) and indirectly (e.g. cement production) responsible for higher CO_2 concentration (IPCC 2012; Uprety and Saxena 2021b). In their pioneering work over Phoenix (Arizona), Idso et al. (1998) observed CO_2 concentrations over urban core during winter season to be 50% higher as compared to nearby rural counterparts. Further extending their work, Idso et al. (2001) note significantly higher CO_2 concentrations on weekdays than weekends supporting the transportation and commercial building emission hypothesis. City-induced average peak CO_2 concentration enhancement at near-surface boundary layer was found to be over 40% during weekdays. Astonishingly, on some weekdays the urban centre CO_2 concentration measurement even crossed 650 ppm, while the rural concentrations were approximated at 350 ppm (Idso et al. 2001). High pollution levels and anthropogenic heat also tend to create an inversion layer over the city, which further intensifies UHI (Rosenzweig et al. 2006). Both UHI and CO_2 domes are diminished or dispersed in high wind conditions. These ‘normal’ urban microclimatic conditions (higher temperatures and CO_2 concentrations) cause a domino effect when larger atmospheric extreme events such as heatwaves strike the cities. Urban people are likely to face more pronounced repercussions such as reduced thermal comfort, heat-related health issues, increased fatalities especially in older and socio-economically weaker sections of the society and lowered work productivity (Kovats and Hajat 2008; Vardoulakis et al. 2013).

13.3.2.2 Extreme Precipitation Events and Urban Flooding

Changes in global precipitation patterns and associated increased variability have resulted in frequent, short duration, and large or extreme rainfall events that occur more over certain regions (Dore 2005). In cities, such quick and large volume spells have the potential to overload drainage systems and lead to urban flooding. As most city surfaces are concretized, water is unable to percolate down and instead flows as surface runoff in the designed storm drains. Conversely, soil surfaces in rural areas readily absorb water and any additional runoff gets channelled into catchments, e.g. ponds, lakes, wetlands and rivers. The absence of infiltration, catchments and natural storage along with reduced resistance of water flow in urban areas puts excessive pressure on the city drains (Huong and Pathirana 2013). Whenever the drainage capacity is unable to keep up with the precipitation influx, it leads to water inundation. Characterizing extreme precipitation events, their intensity, frequency and distribution is therefore critical to managing urban flood risks (Zhou et al. 2017). Recent decades have witnessed growing episodes of urban flooding, even with a couple of hours of intense rainfall (NDMA 2010). Moreover, many studies highlight the role of urban microclimate in increased and stronger local precipitation over cities. Based on long-term observational data sets, Kishtawal et al. (2010) conclude that urban areas of India have shown a significantly increasing frequency (climatological trend) of heavy and extreme precipitation during ISM. They further state that heavier (lighter) precipitation rates are more (less) likely in urban areas compared to rural counterparts. Urban enhancement in severe thunderstorms (precipitation intensity >50–70 mm/h) leads to flash flood situations in urban areas (NDMA 2010). Many concurrent studies suggest that with time, rampantly urbanizing cities across the world have reported a significant increase in their episodes of extreme precipitation events (Mishra and Lettenmaier 2011; Shastri et al. 2015; Zhou et al. 2017; Wu et al. 2019). This is attributed to a higher sensible heat flux, higher moisture-holding capacity, increased availability of cloud condensation nuclei through pollutant aerosols and increased surface roughness in the urban areas (Trenberth et al. 2009; Pathirana et al. 2014).

While urban flooding can occur in any city in the world, developed countries are usually better equipped to handle the situation. In developing countries, it is not uncommon to witness cities flooded for many hours or days due to an extreme precipitation event. Moreover, special attention needs to be focused on the highly populous Asian and African cities, which are currently witnessing rampant urbanization and are projected to continue in the future as well (UN 2018). One of the most notable examples of urban floods caused by an extreme precipitation event is the 2005 Mumbai floods in India. On 26 July, an unprecedented amount of rainfall brought the entire city on a standstill—roads were submerged, public transportation was stopped, and even the Mumbai International Airport had to be shut down. The financial capital of India suffered the worst flood in its entire recorded history, leaving two-thirds city inundated, more than 500 people and 6300 animals dead and an estimated loss of USD ~1.7 billion (MMRDA 2006; Gupta 2007; Ranger et al. 2011). Figure 13.3a shows NASA Tropical Rainfall Measuring Mission (TRMM) satellite-derived image of cumulative precipitation over western India on 26 July 2005. Orange and red areas depict regions that received >200 mm rainfall, which by the India Meteorological Department (IMD) is classified as a very heavy rainfall event (Gupta 2007). The event was heavily centred across Mumbai city.

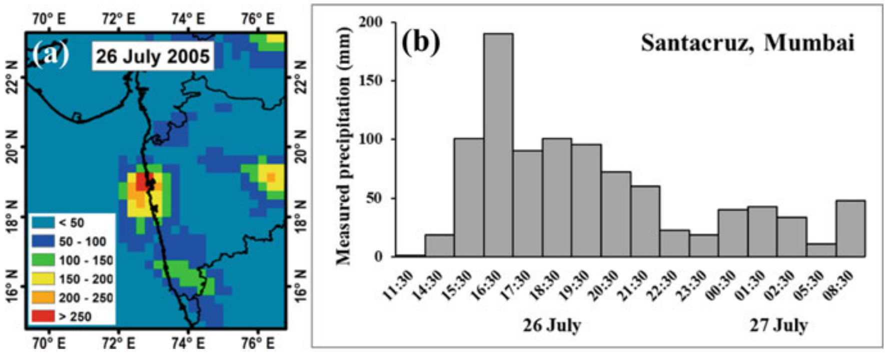

Fig. 13.3 (**a**) Cumulative precipitation (mm) over western India on 26 July 2005 derived from NASA 3-hourly TRMM_3B42_7 data set at 0.25° × 0.25° spatial resolution. Map plotted using ArcGIS ver. 10.6 (data source: https://disc.gsfc.nasa.gov/) and (**b**) hourly measured precipitation (mm) at Santacruz station in Mumbai

From 0830 (local time) 26 July to 0830 (local time) 27 July, Santacruz IMD station situated in northern Mumbai recorded 944 mm total rainfall, while the Colaba station situated ~25 km away experienced only 73 mm rainfall (Kumar et al. 2008). Figure 13.3b shows the hourly measured precipitation (mm) at Santacruz station. More than 100 mm/h rainfall was received consistently from 15:30 local time to 20:30 local time with 1-h recording as high as 190 mm rain. Combined with inadequate drainage and high tide event along its coast, the city water overflow was unable to recede for days (Gupta 2007). Indian cities in particular face intense pressure to manage urban floods in the future due to extremely high population densities, huge amounts of dust and sediment influx clogging drains and the compact and densely aggregated city structure. Ranger et al. (2011) further highlight that by the year 2080, chances of a 2005 Mumbai-like event striking will be doubled and associated losses could triple.

13.3.2.3 Crop Residue Burning and Smog

Rising background air pollution levels in cities, especially fine aerosols ($PM_{2.5}$), are being increasingly linked with higher morbidity and mortality rates (Samet et al. 2000; Greenstone and Fan 2018). In an exhaustive study over China, it was found that 165 cities out of 190 were unable to meet its national ambient air quality standards for $PM_{2.5}$ (Zhang and Cao 2015). Another recently published air quality life index report concludes that sustained PM pollution over the Indo-Gangetic region (one of the most polluted and populated regions in the world) has shortened its residents' life expectancy by ~7 years (Greenstone and Fan 2018). Black carbon (BC) is emitted when traditional fossil fuels, low-grade coal, dung and fuelwood, and agricultural biomass are poorly burnt. These fine aerosol particles readily absorb solar radiation, drive melting of glaciers, cause global dimming and reduce precipitation (Gustafsson and Ramanathan 2016). Seasonal crop residue burning (CRB) and slash and burn agricultural practices emit hazardous quantities of smoke, soot, primary pollutants and other toxicants. In two agriculturally dominant Indian states viz. Punjab and Haryana, ~20.3 Mt and ~9.6 Mt crop residues were burnt, respectively, during the year 2017–2018, resulting in a combined emission of 235.8 Gg PM_{10} and 194.1 Gg $PM_{2.5}$ from both states (Singh et al. 2020). The authors further highlight that ~34.8 Tg and ~17.3 Tg of CO_2 equivalent GHGs were emitted from these states, respectively, due to CRB. These pollutants travel long distances depending on wind speed, wind direction and varying particle scavenging rates. Such transboundary pollutants often get trapped in cities and add on to their existing air pollution problems (Saxena et al. 2021). Smog (smoke plus fog) is another atmospheric extreme increasingly faced by many urban areas and big metropolitan cities. During winters, dissipation of emitted and transboundary pollutants is inhibited due to colder temperature and episodes of smog are common (Badarinath et al. 2007). Creation of an inversion layer noted in some highly polluted cities is also responsible for amplifying severe smog events (Saxena et al. 2020). A recent study over India reports that CRB causes economic losses greater than US$300 million each year, and a tripled risk of acute respiratory illnesses (Chakrabarti et al. 2019). It is further noted that CRB abatement in northern India would prove to be highly cost-effective in the long run, with a 5-year period disability-adjusted life year equivalence estimated at ~US$1.53 billion. Lastly, anthropogenic point and non-point sources of pollution emit varying quantities of NO_x, CO and non-methane hydrocarbons, which under favourable temperature and other meteorological conditions, e.g. clear skies and low wind speed, are able to photochemically form secondary pollutants, e.g. tropospheric O_3 and peroxyacetyl nitrate (PAN) (Rappenglück et al. 2000). Secondary air pollutants also have severe health repercussions (Bernstein et al. 2004). Multi-nodal agencies should therefore evaluate all these risks prevalent in the urban setting while formulating future disaster mitigation plans.

13.4 Vulnerability to Disaster

While the number of atmospheric extremes and their severity is likely to increase by the end of this century, their adverse impacts on human and animal lives, infrastructure, society, economy and environment are expected to not affect nations equally (Black et al. 2004; Li et al. 2009; Tippett 2018; Eckstein et al. 2019). Some regions and countries are likely to have higher vulnerability and exposure to extreme events, and consequences are often multiplied by lack of disaster preparedness, high population density, poverty and low incomes, low accessibility to disaster relief and health services, low adaptive capacity and lack of timely information dissemination (IPCC 2012). Demographics have a key role in deciding disaster vulnerability. Morbidity and mortality rates differ with age, gender, class, race, ethnicity and migrant groups (IPCC 2012). Figure 13.4 shows the global population density map projection for 2020 (CIESIN 2018). Some regions such as India and China are inherently vulnerable to higher mortality risks simply because of their extremely high population density (>1000 persons per km^2 in some areas, Fig. 13.4). Low

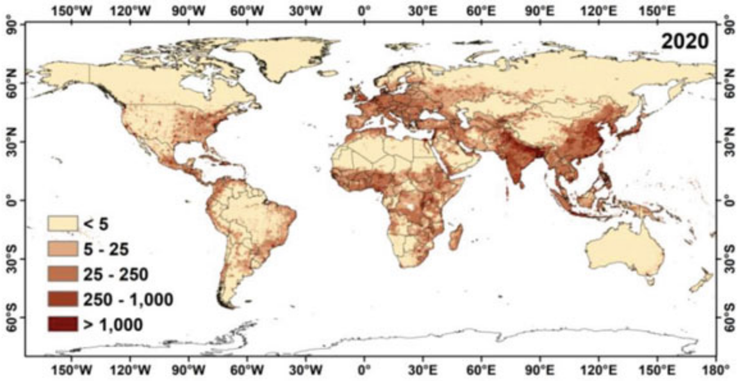

Fig. 13.4 Global gridded population density (persons/km^2) estimated for the year 2020. Map plotted at 0.25° × 0.25° spatial resolution using ArcGIS ver. 10.6 (*data source:* https://sedac.ciesin.columbia.edu/data/)

income and highly populated Asian and African countries are likely to face severe devastative effects needing longer recovery periods (Li et al. 2009; Ward et al. 2010; IPCC 2012; UN 2018). However, developed countries are not immune to disaster losses by any means with 2003 European heatwave, 2005 hurricane Katrina and 2017 hurricane Harvey in the USA, being some well-known recent disasters. Not considering the regions' adaptation capacity, some key factors such as topography, climatic biomes and geographical features govern exposure risk. Many coastal cities are vulnerable to hurricanes, cyclones and typhoons. Some are also increasingly facing submergence risks due to global sea level rise. Impacts could range from temporary displacement to permanent shifting of an entire city to a different location. For example, about 80% of Maldives sits at <1 m sea level height and is extremely vulnerable to submergence if IPCC projected global sea level rise (0.3–1 m by 2100) occurs (Stojanov et al. 2017). At the same time, mountainous terrains are also vulnerable to disasters and, additionally, difficult to access and provide rapid disaster management.

Furthermore, atmospheric extreme events are likely to cause multiple disaster events and could have severe compounding impacts (Trenberth et al. 2003). For example, prolonged heatwaves compounded with low moisture availability significantly increase the risk of forest and bushfires, severe drought and famine conditions and are likely to exacerbate UHIs in cities (Dai 2011; IPCC 2012). From seed sowing to crop harvest, different stages of plant growth are majorly dependent on direct and indirect climate feedbacks (IPCC 2014; Ray et al. 2015; Lesk et al. 2016; Deutsch et al. 2018). Rising heat and cold waves, increasing number of hot degree days, untimely precipitation and monsoon and frequent incidences of intense floods, droughts, thunderstorms, hailstorms, frost, etc., along with certain air pollutants, e.g. tropospheric $O_{3,}$ are projected to significantly hinder crop yields (Tai et al. 2014; Ray et al. 2015; Lesk et al. 2016). In another scenario, abundant precipitation might lead to widespread floods, which then compounds into a breeding ground for many water-borne diseases (NDMA 2010). In order to cope with the increased intensity and frequency of atmospheric extremes likely in the future, disaster risks need to be evaluated based on various emission, population and urbanization scenarios. Risk is defined as multiplicative product of hazard, exposure and disaster vulnerability (NIDM 2019). One such study by Eckstein et al. (2019) estimates the global climate risk index due to atmospheric extreme events. They categorize many south and south-east Asian countries such as Pakistan, India, Nepal, Bangladesh, Myanmar, Vietnam, Thailand and the Philippines as long-term high climate risk countries. High-income countries such as Japan, Germany, Canada and USA (Puerto Rico) have also been highly affected by extreme events in the recent years (Eckstein et al. 2019). The following section discusses various useful strategies in order to prepare, adapt and mitigate atmospheric extreme-related disaster events.

13.5 Disaster Risk Management

13.5.1 Scientific Dimensions and Decision Support Systems

Lack of continuous and high-quality data is often a major hindrance in forecasting any extreme event. This is especially true for developing and low-income countries. In order to manage risks associated with atmospheric extreme events, many countries need to update their knowledge base, infrastructure and resources. This includes rapid and aggressive installation of automatic weather stations, Doppler weather radars and other monitoring systems at national, regional and local levels (NDMA 2010). It should be ensured that such stations have a good network density (especially in climate risk and inherently vulnerable areas), a wide spatial coverage and superior measurement accuracy. In the recent decades, availability of satellite data has proved to be a beneficial tool in continuous global monitoring. However, while some satellite data exist in public domain, there are countries that limit data access causing significant hurdles in conducting scientific research. Free availability of information, ease of data access and inter-agency cooperation should be promoted. Decision support systems are also a key aspect of any disaster preparedness. Various global and regional climate models, and numerical weather prediction models are used by meteorologists to simulate extreme events—their likelihood and other functional characteristics. These models benefit from on availability of robust data, high computational efficiency and immense scientific and technical know-how. Both nowcast and forecast predictions need to improve. Nowcasting provides more imminent warnings (within minutes and hours) of say hurricane landfall or severe thunderstorm, while forecasts are based on projections that are weeks, months and years ahead. Such improvements immensely help authorities to issue timely disaster-related warnings to the public and plan for disaster mitigation. On the other hand, long-range projections and probabilistic distributions (10, 20, 50 or 100 years) greatly assist planners, administrative authorities and concerned nodal agencies to include climate-associated risks (e.g. flood and drought return periods) into environmental impact assessments (EIA), city plans along with fine-tuning region-specific climate risk management and disaster risk reduction strategies (NIDM 2019). Such projections can identify the probability of frequent and rare atmospheric extreme events in the future.

Geographical information system (GIS) incorporates remotely sensed and ground data sets, e.g. weather, land use, terrain, socio-economic profiles, city maps, traffic and other data, and is a helpful tool for visualization, interpretation and modelling. Usually, global and regional climate models consider land surface is considered a time-invariant input when in reality it is quasi-dynamic. This means that urban and population impacts are not properly accounted for or are severely underestimated. In this regard, Stewart and Oke (2012) proposed local climate zones that include parameters such as building heights, canyon widths and anthropogenic heat flux to better represent cities. Urbanization patterns for the future can be predicted using various GIS-based models. When inherent model land representation is replaced with such schemes, and are also updated for relevant time frames, then more accurate future projections can be made, especially over cities. Lastly, hotspot assessments should be emphasized as it pinpoints certain regions—whether global, national or within a city that are either more vulnerable to disaster risk or is likely to face severe impacts due to demographics. Diverting more resources towards capacity building and mitigation strategies in such hotspots can greatly reduce atmospheric extreme event-related losses.

13.5.2 Disaster Risk Reduction, Mitigation and Adaptation

On a global level, all countries need to aggressively cut down on their emissions, as increased GHGs are inarguably linked to global temperature rise and precipitation changes. The 2016 Paris climate agreement (COP-21) signatories aim to keep global temperature rise well below 2 °C by 2100, with some countries aiming for 0.5 °C further reduction (Markandya et al. 2018). It brings hope that many countries are actively relying higher on renewable sources of energy, are pushing for reduced emission technologies and are aiming to become carbon neutral by the next few decades. Concurrently, in order to reduce the chances of many extremes environmental awareness plays a key role. Most disasters are exacerbated due to poor land management practices, e.g. unbridled construction along water bodies, overgrazing and deforestation, filling of wetlands, and poorly planned urbanization and agricultural practices (IPCC 2012). It is therefore important to identify key natural elements such as wetlands and grasslands and to conserve them. This not only helps to keep soil bound together but also helps to retain soil moisture, effectively managing droughts, dust storms and floods. In addition, EIAs need to be conducted in an honest, unbiased and scientific manner and strictly implemented. Careful modelling of precipitation systems (e.g. monsoons), temperature extreme likelihood and drought indices in advance can aid farmers in many agricultural-based decisions. As discussed in earlier sections, atmospheric extreme events are most acutely experienced at a local level, where majority of the population resides or infrastructure is involved. The following paragraphs detail some disaster risk reduction, mitigation and adaptation strategies.

Near-surface air temperatures can be sufficiently reduced by urban greening practices. Trees primarily lower Bowen ratio, check moisture imbalance, reduce surface wind speeds and provide shade (Oke 1997). Some noteworthy examples include planting trees in the identified hot clusters, e.g. alongside roads and highways, creating parks inside residential blocks and promoting green (living) roofs and vertical gardens (Rosenzweig et al. 2006). The cooling potential depends on several factors such as tree species, plant size and maturity, surface area (tree canopy and wall or roof coverage) and its location in the urban surroundings (Akbari et al. 1997). The authors find that trees planted on the streets and gardens adjacent to buildings help to save energy by 27–30%. The practice of urban agriculture is on the rise in many cities as it provides many additional benefits apart from reducing overall city temperature (d'Amour et al. 2017; Jain 2021). The second mechanism includes lowering the albedo of urban structures through high albedo roofs and cool pavements (Rosenzweig et al. 2006). Cool roofs are able to reduce indoor temperatures by 2–5 °C and therefore provide increased thermal comfort and energy savings (NRDC 2019). A very recent study by Li et al. (2020) proves efficacy of $CaCO_3$-acrylic base paint in combating UHI through radiative cooling. The synthesized paint has ~96% solar reflectance, 0.94 sky–window emissivity, cooling power greater than 37 W/m^2 and the ability to reduce noon ambient surface temperature by >1.7 °C. Urban heat island can be also be greatly minimized by increasing canyon space in dense urban areas, using materials that radiate lesser heat during night, promoting energy-efficient architecture and green buildings. Pavement watering cooling strategies have been found to be effective in combating heatwaves (Hendel et al. 2016). After the 2010 Indian heatwave that caused additional ~1350 fatalities (NRDC 2019), the Ahmedabad Heat Action Plan 2013 was introduced as the first extreme heat event early warning system in South Asia (Masood et al. 2015). It involves a multi-pronged approach including public awareness programmes, community and social media outreach, early warning systems based on IMD temperature forecasts, healthcare capacity building and adaptation measures such as city-wide mandatory and voluntary cool roof implementations (NRDC 2019). The report also updates that ~2380 additional fatalities (heat stress-related) were avoided post the successful implementation of this action plan.

In case of precipitation extremes, the first challenge is to redesign, expand and timely desilt city drains so that they can support added pressures due to future climate change. This should take into account up-to-date city (or ground station)-specific intensity distribution frequency (IDF) curves, extreme precipitation event climatology, flood return year periods and future extreme event model estimates (NDMA 2010). Mitigation strategies such as increasing green space, rainwater harvesting, check dams and non-concretized pavements reduce burden on drainage system by slowing surface runoff, and instead recharging groundwater. Drought forecasts both short term and long term can aid crop management practices, speedy allocation of drought relief funds to farmers, timely water resource reallocations, improved water resource management policies in future and development of water recharge and harvesting projects (Bisht et al. 2019). On the other hand, forest fire management requires strong decision support systems to locate high ignition risk zones through forest characteristics and anthropogenic drivers as well as redistribution of higher fire risk forest types and strictly limiting burning of forest debris (Sturtevant et al. 2009). Alternatives such as composting of crop residue, mechanization and improved technology use and production of biochar from agricultural waster present effective sustainable management practices to curtail CRB (Bhuvaneshwari et al. 2019). A technology developed by a premier agricultural institute in India makes use of economically cheap biomass decomposition tablets that when sprayed over crop residue stubble, speeds up decomposition and forms manure (Deccan Herald 2020). Thus, along with air pollution reduction it co-benefits farmers in increasing agricultural productivity. Other than the above-mentioned strategies, emergency shelters that can withstand extreme events such as hurricanes and tropical cyclones need to be set up in vulnerable areas. Such centres should be sufficient in number and have ample capacity to hold displaced populations and vulnerable groups. In case of cooling centres for heatwave events, the locations need to be carefully planned, taking in the fact that the poor and homeless are the most vulnerable. The importance of indigenous knowledge of local populations and stakeholder involvement can be immensely helpful in assessing climate-related changes experienced over generations, capacity-building and fine-tuning disaster mitigation strategies to suit local needs (IPCC 2012). Moreover, NIDM (2019) calls to categorically segregate present and future atmospheric extreme event-related disasters (sudden and slow onset) into ‘avoided, unavoided or unavoidable’. For some extremely high disaster risk regions, this means that migration may be the only adaptation strategy left.

In summary, each country needs to identify and update data gaps, recognize information requirements in context of short- and long-term climate risk management, define status quo from national to sub-community levels, examine disaster risks and carry out context-specific risk tolerance assessments for each sub-region and, lastly, implement feasible risk reduction, mitigation and adaptation strategies (NIDM 2019). As a recent example, India adopted its first national-level disaster management plan in 2016, which recognizes and incorporates three landmark climate and sustainable development agreements—the Sendai Framework for DRR 2015–2030, sustainable development goals 2030 and the recently signed 2016 Paris climate agreement (COP-21) (NDMA 2016). The plan specifically aims to make India a disaster-resilient country through its comprehensive disaster prevention, mitigation, quick response and fast recovery approach. It also seeks to improve disaster risk governance and invest more in DRR, early warning systems and post-disaster management, while assigning specific roles and duties of government bodies at all levels (NDMA 2016).

13.5.3 Early Warning Systems and Post-disaster Management

Many countries, including India, already have detailed disaster management and mitigation plans available. At ground level, however, implementation of these policies is lacking or is not stringent enough. Moreover, most developing countries lack proper early warning systems and timely dissemination of information. Due to lack of timely warning, people can neither prepare themselves for the imminent disaster nor are they able to reach designated emergency shelters. Such circumstances increase the death toll multi-fold. Warning systems require robust information based on scientific assessments (discussed in Sect. 13.5.1 and speedy information dissemination through various platforms, e.g. print media, television news updates and weather warnings on mobile phones). The power of social media continues to be an untapped resource, more so in developing nations, in terms of disaster preparedness, early warning system and post-disaster relief. Post-disaster handling requires joint efforts from multiple sectors and government bodies. This means provision of adequate emergency medical services, distribution of food rations and basic necessities, deployment of military to assist with evacuations and providing financial aid to rebuild livelihoods. With the inevitable increase in atmospheric extreme events in the future, we must aim to better adapt, increase resilience and quickly mitigate climate disasters.

13.6 Summary

Mounting scientific evidence strongly suggests that atmospheric extreme events, e.g. heat and cold waves, droughts, floods and forest fires, are significantly increasing in number, frequency and intensity throughout parts of the world and will continue to do so in the future. The chapter introduces the reader to how ‘normal’ atmospheric conditions are rapidly changing, causing a significant imbalance in energy and water budget. In a globally polluted environment, the atmospheric burden of GHGs such as CO_2, CH_4 and N_2O increases tremendously, causing warmer temperatures. The role of temperature–precipitation feedbacks and interlinked land–air processes in exacerbating atmospheric extreme events is discussed in detail in this chapter. In future, atmospheric extreme events are likely to cause multiple disaster events one after the other, e.g. heatwave-associated drought and forest fire, and they could have severe compounding impacts. For each atmospheric extreme event, selected case studies from around the world and over India are discussed in order to highlight the dangers of such disasters and the importance of disaster mitigation. Not only do these disasters cause tens of thousands of deaths each year, but they also incur huge monetary and GDP losses. The chapter further discusses the importance of identifying key vulnerable (1) hot spots, e.g. cities, coastal areas and mountainous regions, (2) demographic groups, e.g. low-income, elderly and migrants, and (3) nations, e.g. India, China, Canada and USA that are highly likely to face severe adverse effects of atmospheric extreme events. Lastly, the chapter outlines various disaster risk management strategies by highlighting the role of scientific dimensions, e.g. data, models and forecasting along with various decision support systems. Disaster risk reduction, mitigation and adaptation involve aggressive GHG reduction, reversing poor land management practices, implementing strategies such as cool roofs, city drainage redesigning and most importantly preparing short- and long-term climate risk assessments at national to city level. Comprehensive disaster prevention plans, mitigation strategies, early warning systems, quick response and fast recovery approaches are needed to become resilient to climate disasters and atmospheric extreme events in the future.

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14

Disaster Preparedness and Emergency Response for Air Pollution and Related Health Extremes

Anjali Barwal, Sonal Bindal, and Anil Kumar Gupta

Abstract

Over the past few years, air pollution has become a growing problem with an increasing number of acute incidents of air pollution in many cities across the world. As a direct consequence, air quality is contributing extreme risk to public health, accounting for about one in every nine deaths per year. Sudden and extreme air pollution episodes are creating disaster like situations causing an immediate public health emergency. Every year, as per the World Health Organization (WHO), about seven million people die tragically from air pollution-induced diseases around the world. Approximately four million such deaths occur in the Asia-Pacific region only. Now, it is not possible to perceive air pollution as an isolated environmental problem. It is high time that sudden air pollution management should be implemented into state and city planning processes. There is an urgent need for a concerted approach consisting of the generation and compilation of well-structured and exhaustive databases with geospatial locations on air pollution. There is also the requirement of effective representation and well-timely dissemination of air quality information, use of accurate and complex inferences to make significant implementation in air quality-related policy decisions.

Keywords

Air pollution · Public health emergency · Disaster management · Anthropogenic disasters · Air pollution episodes

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14.1 Introduction

Air is mainly composed of dynamic fusion of gases (nitrogen, oxygen, etc.), water vapour and particulate matter. There has been tremendous variation in the air quality composition due to the increased industrialization and development in civilized human society (Mackenzie 2016). The composition of various gaseous air pollutants including dust particles, volatile organic compounds, and heavy metals is constantly increasing because of unmanageable solid and fossil fuel combustion. The chemical composition, reaction sequence, time and mechanism of all these pollutants differ considerably (Singh 2020; Saxena and Naik 2018). These pollutants have different toxicological impacts on human health, depending on exposure period and concentration, as illustrated in Fig. 14.1.

Globally, air pollution contributes substantially to various disease burdens, premature mortality, morbidity, reduced life expectancy, etc., with a greater impact in developing countries than in developed countries (Balakrishnan et al. 2019). The World Health Organization (WHO) report estimates that worldwide around seven million people die every year from various diseases such as stroke, heart disease, lung cancer, pulmonary disorders and respiratory infections, caused by polluted air quality (Schwela and Haq 2020; Sonwani et al. 2021), which means every hour around 800 humans (or say, 13 every minute) died because of the polluted air they breathe. Out of which, around four million such deaths occur in the Asia-Pacific region only (UNEP 2019).

WHO scientists also believe that global warming temperatures could lead to malaria, yellow fever, bone loss, respiratory diseases and other diseases spreading throughout the world. The proliferation of such infections is growing further in warm

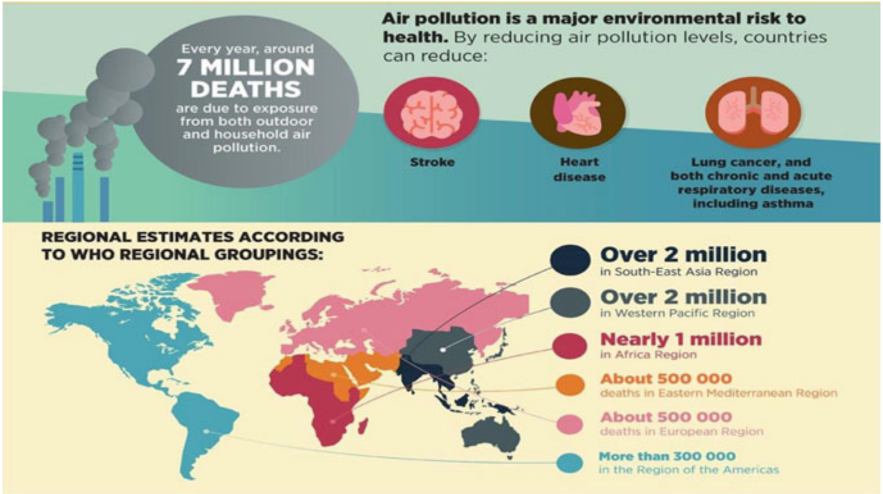

Fig. 14.1 Regional estimate of air pollution and its health consequences (source: WHO PHE Infographics on air pollution, 2020)

and humid environments as pathogens often live under such climatic conditions. Understanding of the geographical distribution of diseases for the health planning of each country is required to notify the regulators of the situation of each disease in the world and to include the necessary health initiatives for local residents in their health policies as well (Javadinejad et al. 2020).

In this chapter, an attempt has been made to examine and assess the various components of air pollution, their effects on human health and way forward to deal with air pollution as a disaster and public health emergency with existing policies and programmes. The identified framework will be useful to all stakeholders and decision-makers as a roadmap while designing the future air pollution mitigation policies from disaster management point of view.

14.2 Air Pollution Risks and Episodes

Asia is home to many extremely polluted cities in the world. As per the United Nations Department of Economic and Social Affairs (UNDESA) World Urbanization prospect report, astounding two-third of the world's population would reside in urban areas by 2050. And in this regard, India would lead the world with over 400 million people living in these urban regions. Evidently, sustainable solutions would be required to impart clean air to breathe and sustain life on the planet (Rodríguez-Urrego and Rodríguez-Urrego 2020). As shown in Fig. 14.2, air pollution is among the top five environmental risks leading to premature deaths globally for 2010 to 2050.

Air pollution episodes in the twentieth and twenty-first centuries have had significant social, economic and political effects. In extreme conditions, episodes of air pollution cause global public concern that is correlated with quantifiable health risks (Sonwani et al. 2022). The major notable episodes of air pollution are mentioned below in Table 14.1.

14.3 Air Pollution as Disaster and Its Preparedness

Disaster is a threat that results in substantial physical injury, loss of life or environmental impacts. Disasters are now known to be the result of insufficient risk management. Life exposure to high concentrations of pollutants over a short period of time can result in unexpected impacts as seen in the events of chemical, petrochemicals and other industrial accidents. Disasters involving extreme air pollution are causing an immediate public health crisis leading to an increased pressure on stakeholders and agencies to provide solutions to protect impacted communities during any such emergencies (Chandrappa and Kulshrestha 2016). During any disaster, the air quality management is dependent on the local community preparedness and external aid. Air pollution can also lead to disasters and disasters can trigger the air pollution as well (Harlan and Ruddell 2011). In both cases, human health and the environment would be affected. Moreover, ambient air pollution is considered as

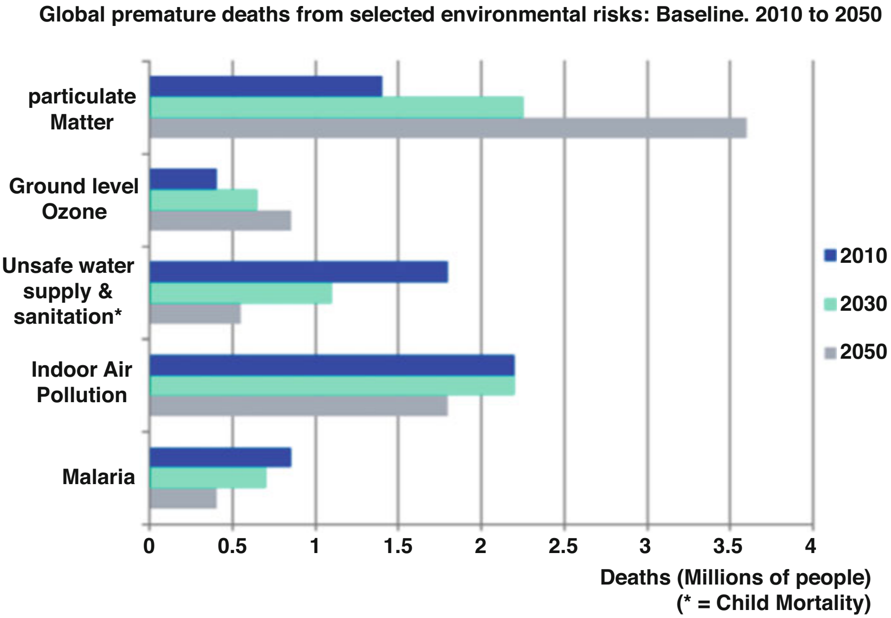

Fig. 14.2 Global premature deaths attributed by the environmental risks (source: Marchal et al. 2011)

Table 14.1 Major global air pollution episodes

S. no.	Major air pollution episodes	Year	Cause
1.	Great Smog of London	1952	Natural
2.	Mount St. Helens Eruption	1980	Natural
3.	Bhopal Gas Tragedy	1984	Anthropogenic
4.	Lake Nyos Disaster	1986	Natural
5.	Kuwaiti Oil Fires	1991	Anthropogenic
6.	Southeast Asian Haze	1997/1998	Natural
7.	Indonesian Forest Fires	1997	Natural
8.	World Trade Center	2001	Anthropogenic
9.	Malaysian Haze	2005	Natural
10.	Southeast Asian Haze	2006	Anthropogenic
11.	North Atlantic Volcanic Ash	2010	Natural
12.	Beijing, China	2013	Natural
13.	Southeast Asian Haze	2015	Anthropogenic
14.	Bushfires in Australia	2019/2020	Natural
15.	Assam's Baghjan Oil Well Fire, India	2020	Anthropogenic

the fifth highest ranking risk factor for mortality, worldwide. There are basically three major disaster components of air pollution as mentioned in Fig. 14.3. These all are interrelated with each other, one drives or subsides the proportion leading to air

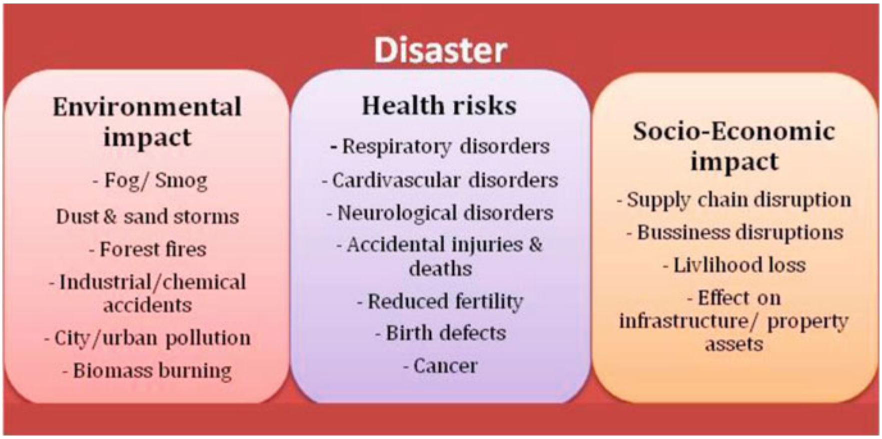

Fig. 14.3 Disaster components and its associated risks

pollution disasters. The environmental impacts such as fog, smog, dust storms, industrial or chemical accidents and biomass burning ultimately lead to various health risks such as respiratory, cardiovascular, neurological disorders, accidental injuries or even deaths (Tigala et al. 2018). Further, the health burden related to air pollution is associated with socio-economic impacts such as supply chain disruptions and livelihood losses. Therefore, there is an immediate need to globally minimize air pollution emissions, as WHO has also cautioned air pollution as a "public health emergency".

Disaster preparedness with respect to air pollution is crucial for individuals, households, businesses and communities, but many of them are often not prepared. The recent air pollution episodes and its related series of health emergencies serve to highlight the importance of individual and community responsibility, local government coordination and continuity strategies to ensure the capacity to respond to and recover from any major incidents. The concept of disaster preparedness encompasses measures designed to improve the safety and security of human lives and livelihood during any disaster damage and disruption, as well as the capacity to interact in post-disaster restoration and early recovery actions.

14.4 Air Pollution Emergency Causes

Major air pollution emergencies can have the following dimensions:

14.4.1 Dense Fog and Smog

Due to dense fog conditions, dispersion of particulate matter becomes difficult as air turns very dense due to the high relative humidity (i.e. more than 90%). Smog is the type of air pollution that affects most cities. Dense fog curbs the visibility and thus affects many human activities including all forms of traffic, aircraft operations and sailing. Moreover, when the fog contains toxic air pollutants, it becomes more harmful to humans and the environment (Saxena et al. 2020a).

Case study In Pakistan's Lahore city, smog had developed on 2–5 November 2016, which shows a very poor Air Quality Index (AQI) when compared to the baseline condition measured during the same time the previous year, i.e. 2015. During smog, the highest pollutant concentration measured was for NOx, which was nearly 17 times higher than the baseline value. The other contaminants (SO_2 and O_3) were four times higher than the baseline value, whereas CO, VOC and $PM_{2.5}$ were two times higher, and PM_{10} was six times higher, respectively. Cool temperatures, calm winds and high humidity were the weather conditions during the smog incident, which eventually triggered the photochemical reaction that caused the smog. The information was gathered from Lahore's tertiary care hospitals, which showed a rise in the number of cases of ocular surface diseases such as dry eyes, irritation, lid erosion, uveitis, conjunctival diseases, corneal diseases and lacrimation. According to the results obtained, only 200 (30%) out of 700 patients were reported in the year 2015, and 500 (70%) were reported in the year 2016 only (Ashraf et al. 2019). The increased air pollution compelled the provincial government to declare the closure of all of the province's schools.

14.4.2 Chemical/Industrial Accidents

Releases of hazardous or toxic substances may affect a broader range of people and locations. Hazardous or toxic substance releases could have an impact on more geographic areas and people. Not all chemical accidents pose the same threat with respect to air pollution. The sudden toxic gaseous discharges can damage the human health and environment or cause corrosivity to the ancient monuments and modern buildings, etc.

Case study Recently, the Vizag accident at the LG Polymers chemical plant in Visakhapatnam, India, that happened on 7 May 2020, due to malfunction in the cooling system of styrene storage tanks, resulted in the release of 3 tonnes of toxic styrene gas into the atmosphere that spread over the entire region. On that accident day, the styrene concentrations in the air in the region were approximately 500 times higher than the prescribed WHO limit of less than 5 parts per billion (ppb). The facility in Visakhapatnam is spread over 240 hectares (ha), including the adjacent residential areas. There is also a revenue village nearby, which has resulted in a higher exposure rate (Hailwood 2020).

Central Pollution Control Board (CPCB) monitors the real-time ambient air quality monitoring stations network of the monitored three volatile organic compounds (VOCs)—xylene (C_8H_{10}), toluene (C_7H_8) and benzene (C_6H_6)—in Visakhapatnam District, which is 14 km downstream of accidental site of gas leakage. The data dashboard helped in compilation of xylene levels up to 18 ppb, toluene levels up to 35 ppb and benzene levels up to 12 ppb, against the CPCB standards, i.e. 5 ppb (annual average) (CSE 2020). This helped in creating awareness around the nearby areas for air quality issues.

14.4.3 Dust and Sand Storms

Dust or sand storms are observed throughout most of the continents. Every year, millions of people are affected by droughts and dust storms (UNEP 2019). Sand storms originate from the semi-arid and arid regions of the world (Sarkar et al. 2019). These are also common events in the Central Asia, Middle-East and south-west Asia's arid and semi-arid regions (Indoitu et al. 2012; Barlow et al. 2016). Sandstorms are caused by radiant heat, high wind speed, scarce or dearth of vegetation cover, soil erosion, low humidity and a high-pressure gradient. Dust enhances aerosol, which affects the quality and visibility of air (Csavina et al. 2014). Longer periods of contact with fine dust particles are one of the important factors in the incidence of lung cancer and heart diseases.

Drought also has an indirect impact on air quality and health, which results in impacting crop failures, habitat loss, significant population migration, soil degradation, widespread livestock deaths, increased diseases such as polio, cholera, diphtheria, typhoid and tuberculosis (Barlow et al. 2016). Therefore, there is a need to consider sandstorms as a disaster and develop policies and guidelines accordingly.

Case study In March 2018, a thick sandstorm ravaged Khartoum in Sudan, pressuring the regulators to cancel flights and shut down schools in the city and other nearby towns. In the same way, cities situated in the south-west of Iran are among the most dusty cities in the world. Drought effects are non-structural and spread over a greater geographical region unlike damage from many other natural hazards (Shinoda et al. 2014).

14.4.4 Urban Air Pollution

Globally, increased transportation vehicles have been recognized as one of the major sources of air pollution in developing countries (Tiwari and Saxena 2021). It leads to a 40–80% range of overall air pollution. Hazardous substances in fossil fuels such as lead, nickel, iron, copper and other catalytically active compounds are taken into account on the surface of incomplete fuel combustion. Between tires of cars with road surfaces and between car brakes and the bowl of the wheel also add a lot of toxic substances to the air (Javadinejad et al. 2020). This is due to the lack of management to reduce adverse environmental impacts and other negative transport effects without reducing the benefits of mobility. This problem is now more urgent due to rapid urban development, especially with smart cities plans in case of India, which in turn is expected to dramatically increase the demand for travel.

The backbone of economic development is infrastructure. Various constructions, repair and demolition activities like clearing of land surface, operation of diesel engines, heavy equipment, burning of fuels and working with toxic materials also contribute to the sudden air pollution.

Case study Beijing, a typical representative of rapidly developing cities, declared war on air pollution in 1998. The obstacle was to find sustainable ways to boost air quality in fastest growing cities in the developing world. For 20 years, Beijing has been maintaining it. Its air quality has enhanced dramatically, and the lesson learned provides a blueprint for other growing urban cities to combat air pollution (Schleicher et al. 2012). Beijing's case offers hope that the problems associated with improving air quality can be tackled during the time of explosive growth and motorization (Hao and Wang 2005).

Beijing introduced more rigorous and strict steps to control air pollution in the year 2013. The fine particulate emissions ($PM_{2.5}$) had reduced dramatically by 35% and 25% in the neighbouring Beijing–Tianjin–Hebei area by the end of 2017. Over this period, Beijing's annual emissions were decreased by 83%, 43%, 55% and 42% for sulphur dioxide—SO_2, nitrogen oxides—NO_x, particulate matter—PM_{10} and volatile organic compounds (VOC), respectively.

In response to extremely serious $PM_{2.5}$ emissions, the Beijing Government has introduced a range of initiatives and a number of policies and steps on the prevention and regulation of air pollution and has taken some concrete action to enhance air quality and to meet the national air quality requirements (Fig. 14.4).

Another significant factor impacting air quality is the weather conditions that restrict the density, dilution, diffusion, transport and transformation of ambient atmospheric contaminants. This further affects the distribution, composition and concentration of atmospheric pollutants.

14.4.5 Biomass Burning

Biomass burning appears to have a high potential to trigger local and regional air quality with higher levels of fine particulate matter (PM 2.5), which could worsen ambient air quality and endanger human health. This massive biomass burning has been increasing over recent years due to human activities. Stubble (crop/agricultural residue) burning is another source of air pollution (Gurjar et al. 2016; Abdurrahman et al. 2020; Saxena et al. 2021). It has been reckoned among the major contributors of air pollution, especially in South Asia. In India, the ambient particulate matter air pollution leads to staggering 670,000 deaths every year (Balakrishnan et al. 2019).

Case study According to the World Air Quality Report (2019), New Delhi (capital city of India) is among the worst polluted cities in the world—ranking 5th. The air quality spikes each year due to farmers burning millions of tons of crop wastes, which affects the ambient air quality of the capital city and NCR (National Capital Region) cities (World Air Quality Report 2019).

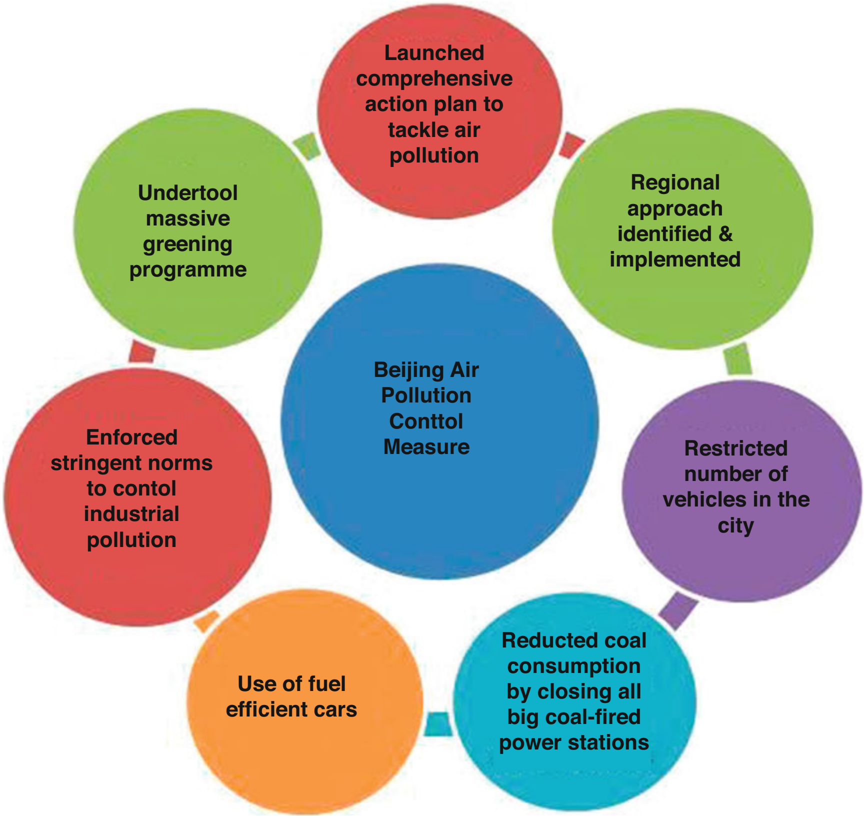

Fig. 14.4 Air pollution control measures adopted by Beijing, China

Regions of Delhi NCR are increasingly struggling with air pollution problems, especially during the late fall and early winter. Weather conditions seem to play a very important role in controlling air pollutants. Northern states of India experience a wintertime inversion layer of cool air that leads to the accumulation of pollutants near the ground level. Delhi experiences a decrease in temperatures and wind speeds from mid-September onwards, favouring the accumulation of air pollutants and rising outdoor pollutant levels. In the northern states like Punjab, Haryana, Uttar Pradesh, Uttarakhand and neighbouring areas, an estimated 20 million tonnes of paddy stubble is burned soon after the monsoon crop is harvested (Jaiswal et al. 2019). During festivals and events such as Diwali (despite some restrictions), the widespread use of crackers has helped to ooze poisonous air into residential areas, workplaces and playgrounds (Saxena et al. 2020b). Both of these variables have contributed significantly to the growing cases of non-communicable diseases (NCDs)—chronic respiratory and cardiovascular problems indicating that NCDs

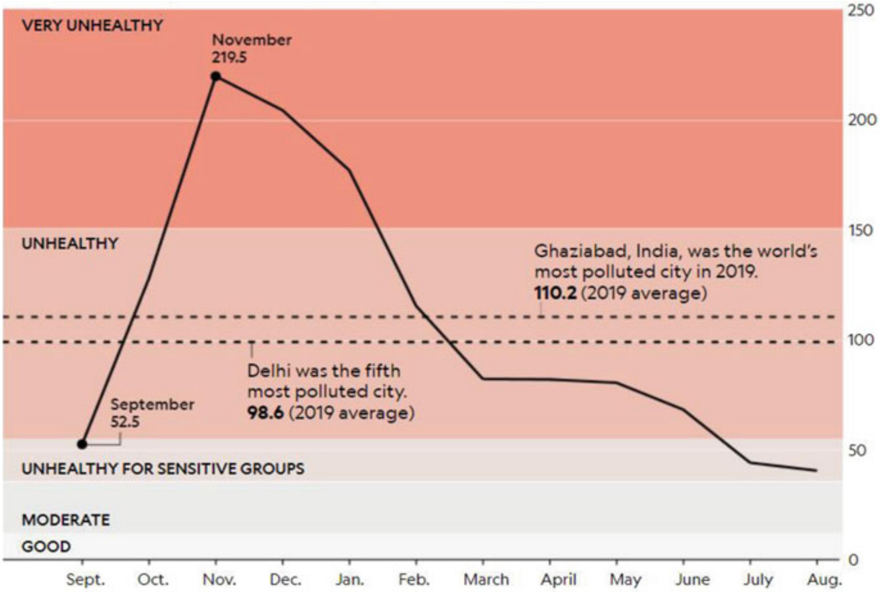

Fig. 14.5 Seasonal PM2.5 air pollution in Delhi, India during the year 2016–2020 (in μg/m^3) (source: Berkeley Earth; IQAIR)

such as cancers and diabetes would lead to over 61% of deaths in India (Tigala et al. 2019).

Figure 14.5 shows the seasonal PM2.5 air pollution in Delhi during the year 2016–2020. Air pollution has led to 24,000 life losses in Delhi in the first half of 2020 including 3 months of the COVID-19 pandemic lockdown (Bhowmick 2020).

The EPCA, or Environment Pollution (Prevention and Control) Authority for Delhi and NCR, is a Supreme Court-appointed committee that has been in charge of all air pollution regulations in the city since 1998. The EPCA, in partnership with the federal and state governments, began implementing the Graded Response Action Plan (GRAP) in 2016. The GRAP has allowed expanded air pollution control so far in 2019. The Delhi government released a health alert/advisory for the first time to protect its residents from health-harming levels of air pollution. In addition to the actions under GRAP, the various governments in the city had declared the following actions: the odd–even rule. Under this scheme, private cars with odd-numbered registration plates were allowed to drive on odd days, and those with even-numbered plates were allowed to drive on even days from 8 a.m. to 8 p.m., except on Sundays. The city government increased the number of buses and metro-coaches and placed a temporary moratorium on surge pricing on app-based taxis like Ola and Uber (Jaiswal et al. 2019). Five key lessons Delhi (or any city facing air pollution) needs to learn to combat air pollution are shown in Fig. 14.6.

Fig. 14.6 Five key lessons Delhi needs to learn to combat air pollution

14.4.6 Forest Fire

Heatwaves combined with drought conditions can result in large wildfires that pollute the air around us (Jain et al. 2021). Forest fires are increasingly becoming a major contributor to air pollution over the past two decades as an indirect impact due to climate change (Vardoulakis et al. 2020). These wildfires may cause sudden rise in outdoor gaseous particles such as carbon monoxide, formaldehyde, nitrogen dioxide and acetaldehyde (Walter et al. 2020).

Case study As per the New South Wales (NSW) Department of Planning, Development, and Environment reports, the recent Australian wildfires have increased ambient air pollution (more than 14 times) during 2019–2020. Sydney has been blanketed in smoke as a result of destructive bushfires, resulting in excessive levels of air pollution. According to an overview of all Australian monitoring stations reported on the World Air Quality Index website, recent events have caused the Sydney area monitoring stations into the top ten of Australia’s most polluted places in 2019. Since the beginning of November 2019, the suburbs of Liverpool and Rouse Hill, as well as Sydney area Richmond, have experienced between 9 and 15 days of unhealthy air quality, some of which were rated as “very unhealthy” by the index as shown in Fig. 14.7 (Walter et al. 2020).

In addition to bushfire smoke’s deadly consequences, it is associated with more risks of illness and increased visits to hospitals due to respiratory diseases. Increased evidence also indicates that bushfire smoke may increase cardiovascular morbidity, psychiatric problems, adverse birth and eye outcomes.

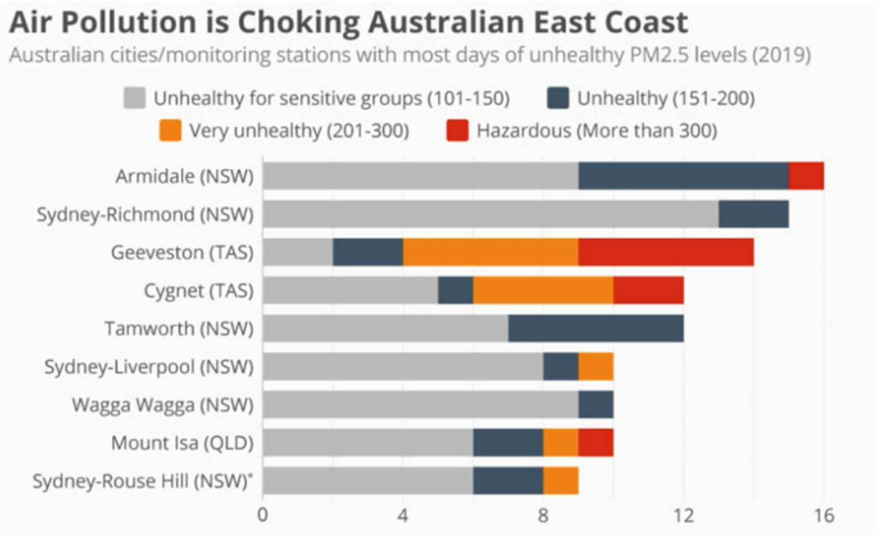

Fig. 14.7 Sub-regional distribution of air pollution due to Australian bushfires as of December 2019

An extensive study conducted in western North America for understanding the impacts of climate and air quality using field and laboratory analysis during 2016–2019 revealed that the combination of dry and warm climate has produced more frequent fires and with larger magnitude in the U.S. West and Canada, irrespective of fire control practices (Fig. 14.8). The fire suppression practices have caused an increase in build-up of fuels, a breakdown in forest ecology and rise in risk at urban wild and bush boundaries. New regulations have been implemented to allow burning. Climate change along with deforestation will only increase this problem. The area burned is more prone to double for every degree rise in temperature due to global warming.

Unfortunately, there is no reliable way to minimize the impact of bushfire smoke on human health, except wearing facial masks and remaining indoors are widely advised (Vardoulakis et al. 2020). However, face mask's performance and effectiveness depend on their filtration ability, person wearing behaviour and characteristics, e.g. facial hair, or length and frequency of wearing a face mask. Sometimes, wearing a face mask can be painful when the bushfires happen in hot weather.

14.5 Air Pollution as Public Health Emergency

Approximately 91% of the world's population resides in areas where air quality exceeds WHO standards (WHO Ambient Air Pollution Report 2016). By reducing air pollution levels, countries and states can reduce the burden of various infectious diseases. The respiratory and cardiovascular effects on human health would become

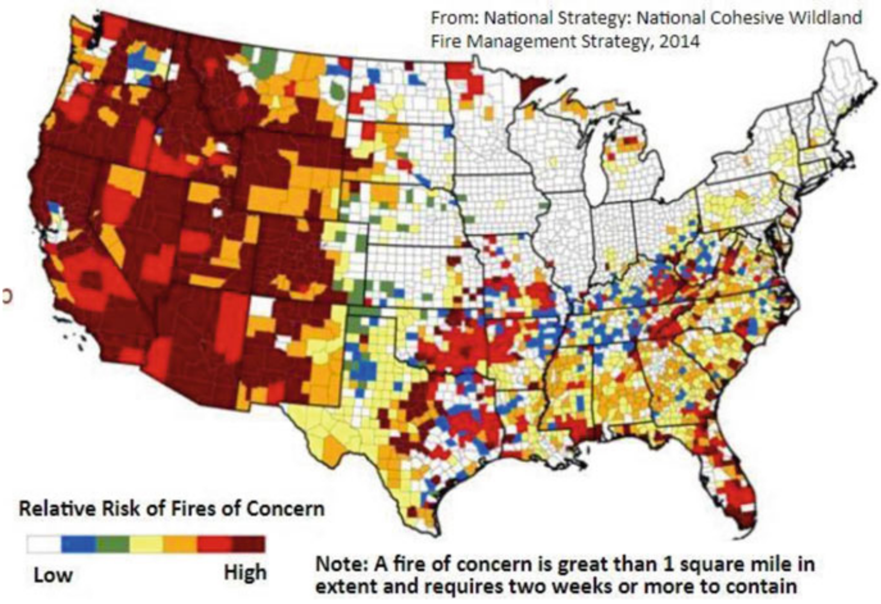

Fig. 14.8 Relative risk of fires in the USA classified from low-risk to high-risk regions

better with the lower levels of air pollution, in both long run and short run (WHO Fact Sheet 2018). Air pollution is a major risk factor for preventable non-communicable diseases (NCDs). Air pollution has a wide variety of health consequences, from irritation of the skin and eyes to extreme neurological, cardiovascular and respiratory disorders such as pneumonia, asthma, bronchitis, tracheitis, chronic obstructive pulmonary disease (COPD), allergic rhinitis, silicosis, emphysema and cancer. Because of the prolonged exposure to high emission levels, it also contributes to a rise in mortality rates (Abdurrahman et al. 2020).

Air pollution is responsible for 29% of all lung cancer deaths and illness, 17% of all acute lower respiratory infections, 25% of ischaemic heart disease, 43% of chronic obstructive pulmonary disease deaths and 24% of all stroke deaths worldwide (McHardy et al. 2020). Many airborne infectious diseases can be transmitted by dust. Researchers assume that inhaling dust particles in humid, dry weather destroys the mucosa of the nose and throat, providing optimal conditions for bacterial infection. Furthermore, dust particles containing iron oxides can increase the risk of infection (WMO 2020).

In addition to these direct effects on individual health outcomes, air pollution has indirect effects on other important health determinants. People cannot go outside to exercise or work during business hours because of dangerously high levels of air pollutants. Every aspect of a person's well-being is impacted. Children under 14 are particularly susceptible to air pollution. Growing children ingest more air per kg of body weight as opposed to adults. As a result, air pollution has the potential to harm any developing organ in a child's body, as well as trigger stunting and mental health issues. But, children are not the only ones who are at risk from air pollution; senior citizens and pregnant women are also at risk. So, air pollution cannot be considered an isolated environmental concern, as it is now becoming a major public health emergency. It is high time that air pollution control and management should become a part of state and city planning processes.

14.6 Existing Policies and Recommendations

There are numerous policies and programmes to resolve the air pollution problem that has been introduced across the world. The performance and effectiveness of these programmes, like any other policy indicator, have been dependent on cooperation and coordination among different stakeholders. Some of the major initiatives launched to combat sudden increase in air pollution in Indian cities have been mentioned below in Table 14.2.

However, the above-mentioned policies state that non-compliance is mostly due to a lack of appropriate monitoring and inspection elements and it also indicates that

Table 14.2 Existing policies and recommendations for prevention, regulation and abatement of air pollution in India

S. no.	Government programmes	Tasks
1	National Clean Air Programme (NCAP), January 2019	National-level strategy to address the country's air pollution problem in a holistic manner with an aim of achieving 20–30% reduction in PM_{10} and $PM_{2.5}$ concentrations by 2024 keeping 2017 as the baseline year for the comparison
2	Comprehensive Action Plan (CAP), 2018	Identifying timelines and implementing agencies for specified actions for air pollution prevention, control and mitigation in Delhi and the NCR
3	Graded Response Action Plan (GRAP), January 2017	For the prevention, regulation and reduction in air pollution in Delhi and the National Capital Region. It distinguishes graded responses and implementing agencies for four AQI categories: moderate to poor, very poor, severe and severe + or emergency
4	SAMEER App, 2016	Where public access to air quality information is provided, as well as the ability to file complaints about air polluting activities
5	Environment Education, Awareness and Training Scheme	To raise environmental consciousness among all segments of society and mobilize public interest in environmental protection
6	Pollution under control (PUC)	Certificate of petrol/diesel-driven vehicles which test for carbon monoxide and hydrocarbon
7	Other policies	• Permission to use only pure diesel as fuel for vehicles with a limit of 500 ppm sulphur • The use of non-polluting compressed natural gas CNG by buses and trucks as fuel • Mandatory blending of 20% ethyl alcohol with petrol and 20% biodiesel with diesel

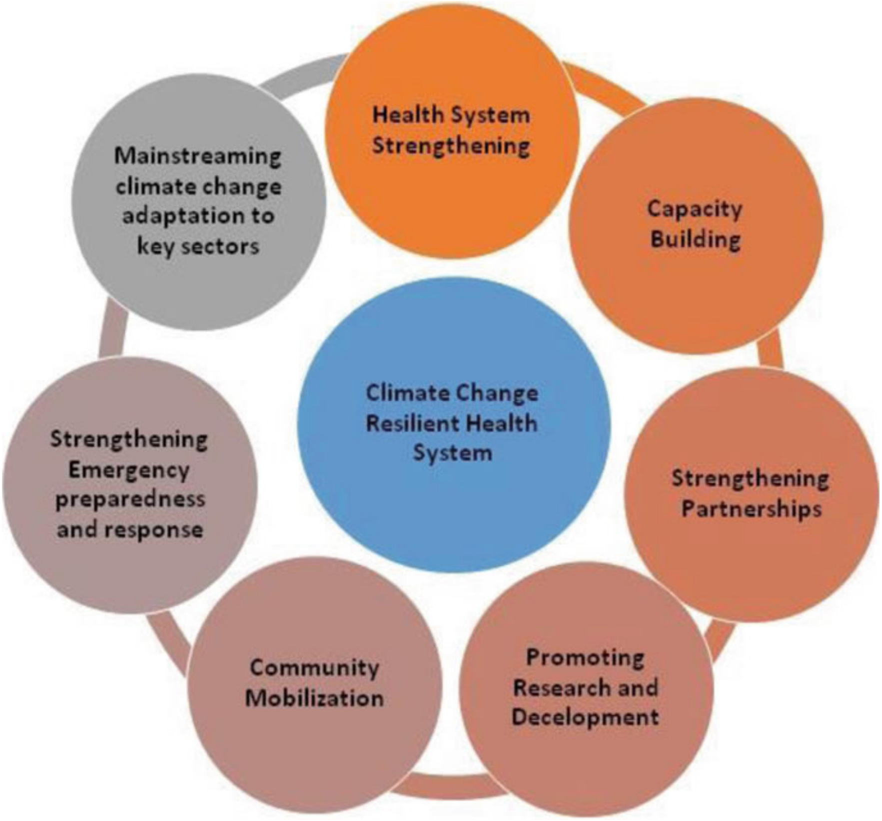

Fig. 14.9 Seven-pronged strategic approach to develop a climate change resilient health system

training should be provided to the workers and daily inspection drives should be carried out.

Moreover, the National Health Adaptation Plan (NHAP) has been designed and developed by the National Institute of Disaster Management, Ministry of Home Affairs, Government of India, to create enabling environment, build the capacity of climate-resilient healthcare system, help institutions strengthen their preparedness and enhance the health system resilience in terms of universal health coverage: early warning, surveillance and community mobilization in the context of any health emergency risk management. The NHAP also proposes a seven-pronged strategic approach to achieve its goal of developing a climate change resilient health system (Fig. 14.9).

Indeed, while the air pollution problem has gained considerable political momentum, India has not been able to make any substantial progress in achieving the objectives set out in the NCAP and other policies and programmes. The momentum was further hampered by the onset of the coronavirus pandemic. The economic fallout of the national lockdown has delayed the objectives of lowering pollution from thermal power plants, transport and other sectors, and transitioning to cleaner energy processes.

14.7 Integrated Approach to Deal with Air Pollution as Disaster

There is an urgent need for a concerted approach consisting of the generation and compilation of well-designed and continuous data on air pollution: its effective representation and timely dissemination to allow a wide range of air quality policy decisions. Big data analytics provides a number of approaches to deal with data sources of monitoring, uncertain sensor data, real-time and predictive analytics, and spatiotemporal mapping and forecasting. Various statistical models have become useful for pooling threats across several locations and measuring spatial heterogeneity, resulting in better control of air quality and its effect on public health.

Despite the popularity of air pollution disasters and the lack of options for reducing contamination and exposure, citizens should seek out ways to protect themselves from pollutants inhalation and expect agencies to include guidelines or even provide preventive measures (Han and Naeher 2006). Face masks are one possible particulate emission intervention, but there is little evidence of their efficacy for community use.

There is an immense need for an integrated framework for dealing with air pollution disasters during emergency situations. Even during the times of emergency, various response and recovery actions were initiated in many countries. However, in India, there is an utmost requirement of an integrated framework where all governing and regulatory bodies should work together to curb air pollution emergencies as shown in Fig. 14.10.

14.8 Conclusion

Many cities around the world are rapidly leading the charge to solve the issue of air pollution and protect public health. It is high time that air pollution should be considered as a disaster and public health emergency. During any such disaster, the air quality management is dependent on the local community's preparedness and external aid. A concerted national initiative would be needed to achieve long-term changes in air quality. The collaboration and coordination at all levels of government are very much important for the effective implementation of various air pollution-related judicial orders, policies, guidelines and crisis management plans. There is an immense need for an integrated framework for dealing with air pollution as a disaster during emergency situations. There is an utmost requirement of an integrated framework on preparedness guidance and planning where all governing and regulatory bodies, stakeholders, businesses, households and communities should work together to curb air pollution emergencies.

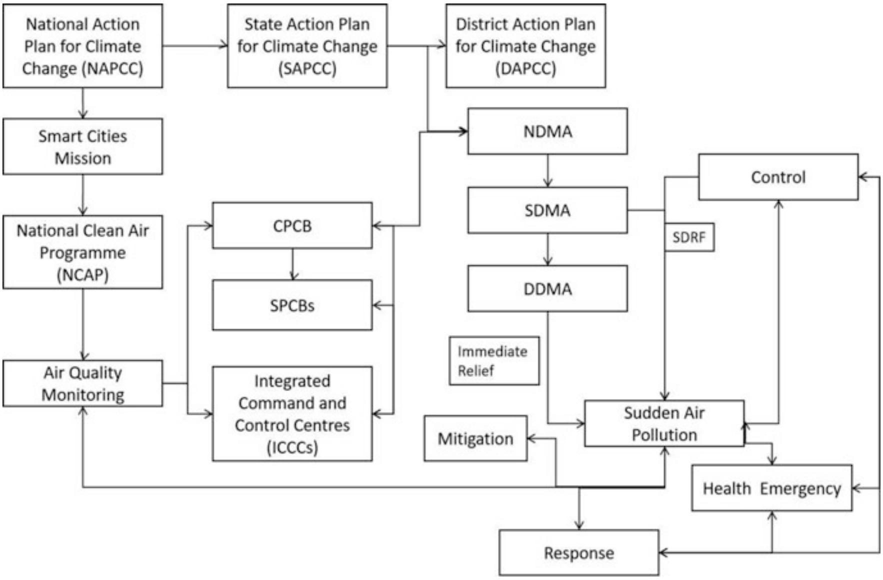

Fig. 14.10 Framework for air pollution as disaster and its response mechanism

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Cost-Effective Technologies for Control of Air Pollution and Atmospheric-Related Extremes

15

Amara Aziz, Hania Maqsood, and Sukriti Kapur

Abstract

Air pollution is a phenomenon harmful to the ecological system and the standard conditions of human existence. In the face of increasingly serious environmental pollution problems, various studies have been conducted on improving air quality better management of air pollution. Air pollution and higher rate of burning of fossil fuels consequently result into adverse weather patterns and atmospheric extremes like sand and dust storms (SDS) and wildfires. This chapter reviews some air pollution control technologies and their cost-effectiveness. We also provide an overview of atmospheric extreme events.

Keywords

Air pollution control · SDS · Atmospheric extremes · Cost-effective technologies

15.1 Introduction

Air quality has severely degraded over the years, causing profound implications for human beings, materials, and ecosystems (Vlachokostas et al. 2011). According to World Health Organization (WHO), more than 80% of people living in metropolitan cities are exposed to air quality levels above the permissible limits. Rapid urbanization and industrialization have lead to an increase in primary atmospheric pollutants,

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such as carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NOx), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), ozone (O_3), and sulfur dioxide (SO_2), especially in developing countries (Manisalidis et al. 2020; Saxena and Sonwani 2019a; Sonwani and Saxena 2022). Several studies have been conducted to study the rise in atmospheric pollutants over the years. Air pollution is known to cause over 0.5 million deaths in developing Asian countries. In India and China, an increase in PM2.5 by 10 $\mu g/m^3$ has been associated with an increase in mortality by 0.6% (Chung et al. 2011). Lelieveld et al. (2001) studied air pollution from south and Southeast Asia. They concluded that emissions during winter monsoon were considerable over this region, with increase in NOx, ozone, BC, and sulfates predicted for the future, owing to an increase in fossil fuel emissions. Biomass burning also is severely known to contribute to NOx emissions in the tropics and subtropics of South Asia (Saxena et al. 2012).

A wide range of air pollution control devices can be used to reduce air pollutants for the sake of prevention of their adverse effects to human health and the environment. Several technological applications aid this purpose. Gravitational settling chambers, incinerators, cyclone separators, selective catalytic reduction systems, electrostatic precipitators, bio filters, scrubbers, and fabric filters are the major technologies used to prevent air pollution (Saxena and Sonwani 2019b). The usage decision of the appropriate control devices depends on the air pollutants type and condition at the sources. If the amount of pollutants emitted to the atmosphere is decreased, the atmospheric concentrations of the pollutants will also decrease. Consequently, exposure to air pollution drops and adverse effects of air pollution on human health and the environment are taken under control.

This chapter aims to discuss common technologies for air pollution control and measurement. We discuss commonly used technologies for air pollution management and their cost-effectiveness.

15.2 Air Pollution Management

Air pollution management is necessary for the elimination or reduction of pollutants to acceptable levels. The presence of airborne gaseous pollutants, suspended particulate matter, and many more in the atmosphere are capable of causing adverse effects on human health, animals or plants, and damage to the environment (e.g., climatic modifications). It needs adequate control because the growing pollution sources in the modern world may lead to irreversible destruction to the environment and humanity.

Most air pollution control systems involve a combination of numerous control techniques. Typically, a blend of both technology and administrative controls is used. However, when there are complex pollution sources, more than one type of technological controls are used.

The selection of the appropriate controls depends upon the problem at hand. Some typical questions that need to be kept in mind before selecting the control methods are:

- What is emitted, and in what concentration?
- What is the most susceptible target?
- What are acceptable short-term exposure levels?
- What are acceptable long-term exposure levels?
- What combination of controls must be selected to ensure that the short-term and long-term exposure levels are not exceeded?

There are number of steps to follow for the pollution control selection methods:

15.2.1 Step 1: Emissions Definition

The first step is to determine the possible pollutants from the source. The next step involves estimating the concentration of each pollutant. These steps are keys to designing a control program.

15.2.2 Step 2: Define the Target Groups

All vulnerable targets must be identified. This includes all flora, fauna, humans, and property. In each case, the most vulnerable member of each group must be identified.

15.2.3 Step 3: Determination of Acceptable Exposure Levels

Establish an acceptable exposure level for the sensitive target group. Set up short- or long-term exposure levels depending upon the pollutant.

15.2.4 Step 4: Select Controls

Every pollutant is monitored to guarantee that it does not surpass the acceptable exposure level. Additional controls must be added, if it exceeds the acceptable level.

Rather than considering emissions from just mobile or fixed sources, management of air pollution also needs to involve reflection of supplementary factors (i.e., topography and meteorology) that must integrate into a complete program. For example, ground-level concentrations resulting from similar pollutant emission can greatly affected by the meteorological conditions. The sources of air pollution may disperse over a community or a region and their effects may be felt by, or their control may include, other than one administration. Moreover, air pollution is an issue beyond boundaries. Emissions may be generated at a different source and induce effects in another region by means of long-range transport.

15.3 Technological Control Measures for Air Pollutants

The basic equipment types used for the control of air pollution are:

- Cyclones (inertial separators), fabric filters (baghouses), wet collectors (scrubbers), and electrostatic precipitators for particulate matter
- Incinerators, adsorption units (adsorption beds), and catalytic (catalytic combustion) for gaseous pollutants

15.3.1 Particulate Matter Control

15.3.1.1 Cyclone

The cyclone is renowned technology that is primarily used for coarse and medium-sized particles collection. It works by downward forcing of a gasified suspension. By centrifugal force, the particles move in the outward direction by colliding with the external wall and then slide toward the bottom of the cyclone. There, the gas converges its downward spiral and then moves upwards in an inner smaller spiral. Clean gas is released from top of the cyclone and the collected particles are ejected from bottom of the cyclone by a pipe closed by a rotary valve. The cyclone collector is shown in Fig. 15.1.

Effective recovery of the products can be done using cyclones, finding a wide variety of applications in vaporous cleaning fields. These devices are low-maintenance, inexpensive, and work at high temperature and pressure. Cyclones show an efficiency of 90% for particles bigger than 10 μm, but have lower efficiency

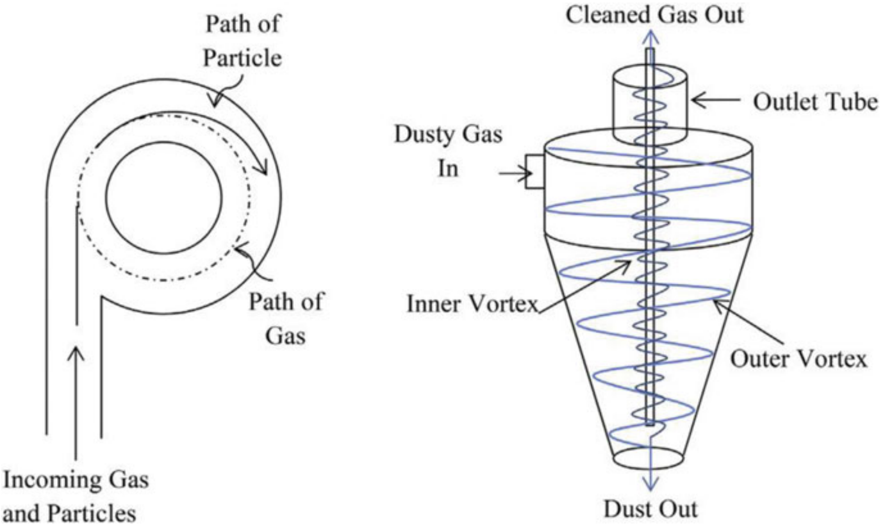

Fig. 15.1 The cyclone collector (Source: J. He et al. 2017)

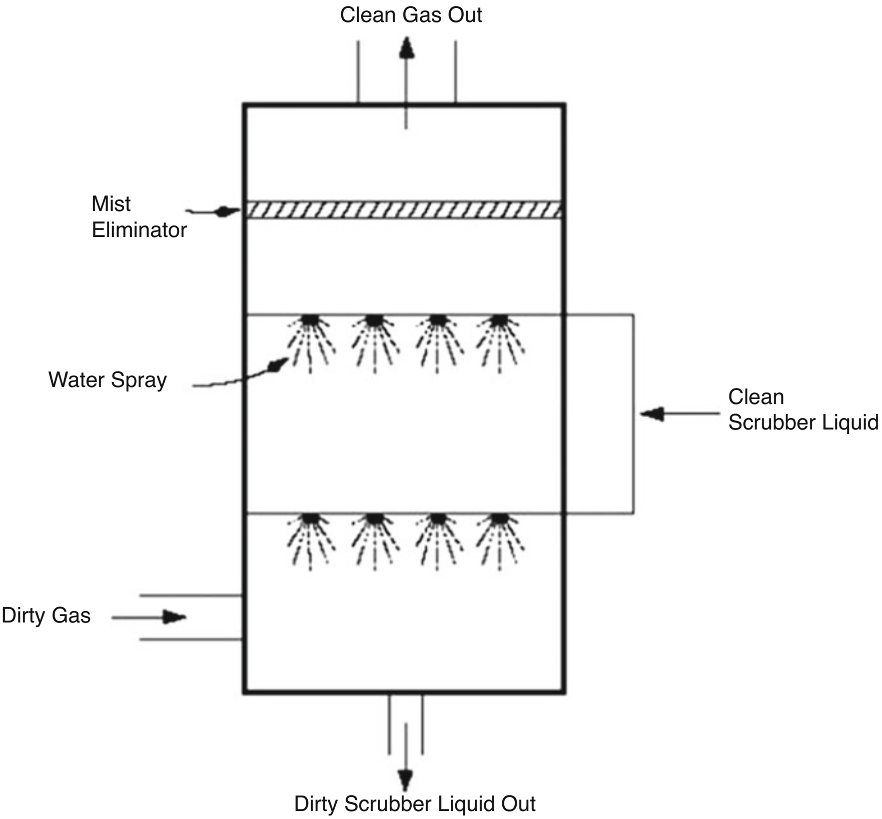

Fig. 15.2 The wet scrubber chamber (Source: EPA Fact Sheet 2016)

for smaller sized particles (Leith and Jones 1997). Additionally, removing sticky particles having higher moisture content cannot be achieved with the cyclone method.

15.3.1.2 Wet Scrubber

Wet scrubber systems are used for the control of mists, fumes, heavy metals, acid gasses, suspended dust, and trace organics. The device contains multiple scrubbers, attached together, which allow for an effective removal efficiency as compared to a single unit (Cooper and Alley 2011). The wet scrubber is shown in Fig. 15.2.

A direct contact is established between the adsorbent liquid (mostly water) and the particles. Based on the contact between the two, the particles leave the gas phase to be adsorbed onto the liquid phase. The adsorption can either be liquid or gaseous phase, depending on the properties of the particle. The removal efficiency depends on a multitude of factors, such as:

- Pollutant solubility in the selected scrubbing liquor
- Pollutant concentration in gas phase
- Gas and liquid phases flow rates
- Contact surfaces of gas–liquid phase
- Recycling of the solvent and liquor shedding efficiency

15.3.1.3 Electrostatic Precipitators

One of the most efficient and famous means of air pollution control is an electrostatic precipitator. It is a particle control method in which electrical forces are used for the movement of particles out of the gas flow stream on to the collector plates (Treybal 1980). Its processes include:

- The particles ionize like liquid droplets or dry dusts, in air that is contaminated.
- The charged plates attract the oppositely charged particles.
- The deposited particles removal from the plates (Fig. 15.3).

The major difference between other scrubbing methods and ESPs is that in electrostatic precipitators, the parting forces are electrical and are directly applied to the droplets or particles themselves; whereas in other methods, the separation forces are typically applied indirectly with the help of contaminated air system. Hence, ESP is capable of small particles or liquid droplets removal at a high efficiency with low energy consumption or low-cost and low-pressure drop (White 1975).

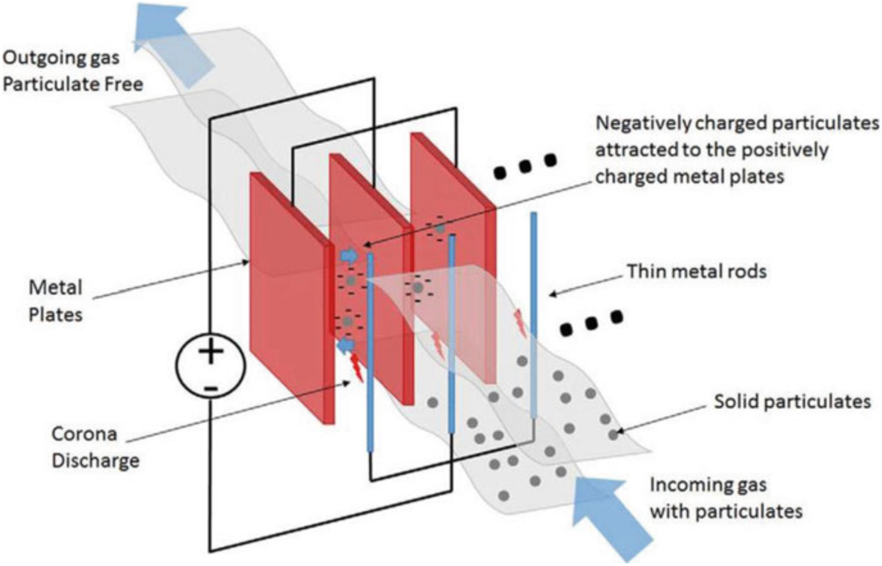

Fig. 15.3 Schematic representation of an electrostatic precipitator (Source: Becker et al. 2005)

15.3.1.4 Fabric Filtration

Fabric filtration is a physical technique in which a gas stream comprising of solids passes through a permeable fabric medium holding the solids. This process might function in a group or semicontinuous mode in order to remove the solid particles, which are retained, from the filter medium. These systems are also designed to function in a continuous way.

The polluted stream of gas is passed through filter bags that are parallelly positioned, and retain the solid particles onto them. The fabric filter is categorized in two simple groups, depending on the properties of fabric, i.e., felt and woven. Felt fabrics are commonly used in high cleaning systems, whereas woven media are used in low-energy systems. These devices operate at an efficiency close to 100% and thus are effective in pollutant removal.

The advantages and disadvantages of particulate matter control techniques are summarized in Table 15.1.

15.3.2 Gaseous Pollutants Control

15.3.2.1 Adsorption

In adsorption, the molecules of a fluid stick to the surface of a solid material called adsorbent. This method is commonly used to recover volatile solvents, i.e., benzene, toluene, and chlorofluorocarbon, process gas streams drying, and control the odor. The molecules in the airstream are captured and removed, even if they are present at low concentrations. This process is exothermic. Chemical adsorption or chemisorption encompasses an actual chemical bonding by the reaction of adsorbate with the adsorbent. This leads to generation of new chemical bonds such as at the surface of the adsorbent.

15.3.2.2 Absorption

Absorption is a chemical or physical process in which ions, molecules or atoms go in the bulk phase. It involves the transmission of a gaseous pollutant from the air in the water. The water must be capable of either serving as a solvent for the pollutant; moreover, to capture it with chemical reaction.

15.3.2.3 Condensation

Condensation is a separation process for the conversion of one or more volatile components of a mixture of vapor to a liquid with the help of a saturation process. By adequate lowering and increasing the pressure and temperature respectively, any volatile components can be converted to liquids. It requires less installation cost, little equipment, and less maintenance, but the problem of water disposal, lower efficiency, and further treatment is still needed.

15.3.2.4 Incineration

Incineration (thermal oxidation) is a largely used technique for the control of air pollutants such as VOCs. It is the process of converting the VOCs and other gaseous

Table 15.1 Advantages and disadvantages of particulate control methods (Source: Buonicore and Davis 1992)

Advantages	Disadvantages
Cyclone	
• Low capital cost • Minor maintenance problems • Ability to operate at high temperature • Small spaces required	• Comparatively low efficiencies for particles collection with smaller size than 10 mm • Not used for sticky materials
Wet scrubber	
• Low capital cost • Require small space • Collect sticky and particles gases • Process at high-temperature and high-humidity gas streams • Highly efficient for collecting fine particles	• Improper water/effluent disposal • Problems of corrosion • High pressure drop difficulties • Solid accumulation problems at the wet–dry interface • Comparatively high maintenance costs
Electrostatic precipitation (ESP)	
• Low maintenance and operation costs • Higher collection effectiveness of coarse and fine particulates • Low consumption of energy • Dry dust collection • Pressure drop is lower • Collect capacity is higher	• High capital cost • Highly sensitive to variations in gas stream • Difficulties with particles, with extremely high or low resistivity • Ozone production as by-product • Require large space for installation • Highly trained maintenance personnel required
Fabric filtration	
• Simple operation • Simple maintenance • No corrosion issues • Highly efficient in collecting coarse and fine particulates • Insensitivity to gas stream variations • Highly efficient in collecting smoke and gaseous contaminants	• Explosion problems • Require high maintenance costs • Difficult operation at high temperature • Fabric treatment needed after removal process • Respiratory protection required for fabric replacement • Medium pressure-drop required

hydrocarbon pollutants into carbon dioxide and water. VOCs and hydrocarbon fume incineration is typically completed in a special incinerator called an afterburner; and a final disposal procedure converts the VOCs to water, carbon dioxide, and inorganic gases. There are two widespread methods of incineration, i.e., catalytic incineration and thermal incineration.

15.3.2.5 Carbon Sequestration

Lower levels of carbon dioxide in the atmosphere can be achieved by effective energy use and using alternate sources of energy (e.g., nuclear, wind, tidal, and solar power). Furthermore, making use of carbon sequestration for storing carbon dioxide underground, in forests and oceans is of utmost importance. Sequestration in forests and oceans depends on natural procedures such as forest growth (Uprety and Saxena

2021). Storage of carbon dioxide underground; a technique which is also called geo sequestration or carbon capture and storage includes driving the gas directly into underground geologic “reservoir” strata. This would involve the removal of carbon dioxide from power plant flue gases, which is an expensive process.

15.3.2.6 Biological System

For controlling air pollutants, mainly volatile organic compounds (VOCs), the biological phenomenon includes the utilization of microbes. It involves the immobilization of air pollutants on a biologically active solid surface. The key role of the process is that the microorganisms used the gaseous contaminants as a source of nutrients and energy, which consequently destroyed and transformed the pollutants into harmless metabolic by-products, i.e., carbon dioxide and water. The procedure through which microorganisms transform or destroy pollutants includes:

- Initially the microbial liquid film on which microbes grow, the gaseous pollutants must be absorbed into the cells of microbes and then it will be metabolized.
- The by-products, i.e., CO_2 must be released from the cells and disperse outside the liquid film.

The key elements required for the design and implementation of biological processes in order to control air pollutants include (Crocker 2000):

1. Identification of the pollutant type and its amount in air stream
2. Utilization of the appropriate microbial culture along with its suitable medium
3. Moisture control
4. Suitable residence time for air stream flow rate
5. Maintaining pH, nutrient levels, and temperature

Biological mechanisms include **Bio filter** and **Bio scrubber.**

15.3.2.7 Bio Filter

It is a biological process which utilizes an organic or synthetic media to culture and nourish the microbes without the utilization of an aqueous flush system.

15.3.2.8 Bio Scrubber

This process uses an inorganic or synthetic media to provide a structural base for culturing the microorganisms requiring a continuous water level or an irregular amount of carbon nutrient that supports the microbes. This method offers numerous advantages such as effective elimination of contaminants, little or no end product pollutants, simple installations, and cost-effectiveness. However, there is lesser suitability at higher concentration levels, a need for maintaining moisture, and the possibility of becoming blocked by particulate matter or biomass growth. A larger area for plant installation is also required.

15.3.3 Control of Air Pollution by Cost-Effective Technologies

Air pollution is becoming inevitable with greater development and urbanization around the globe, which consequently causes many human health issues, such as respiratory and cardiovascular disorders. Controlling of air pollution issues is hard due to its strong flow ability.

Among all types of control technologies of pollutants, comprising of microbial bioremediation, **phytoremediation** stands out for its advantages resulted from self-maintaining, soil stabilization, and other advantages to meet higher public support (Doty et al. 2007).

15.3.3.1 Phytoremediation of Air Pollutants

Particulate Matter (PM)

Vegetation has been used to protect dust in several areas of the world, by a technique known as phytofiltration. This is a cost-effective technique that involves use of plants to reduce toxic pollutants in air. Leaf area, orientation, and shape are some of the structural features that help in effectively capturing dust from the surroundings.

15.3.3.2 Inorganic Pollutants

NO_X

Oxides of nitrogen are considered to be one of the precursors of photochemical reactions taking place in the atmosphere. Deposition, either wet or dry, on the roots or foliage can influence plant systems. Nitrogen Dioxide, on entering plants, is metabolized to organic components such as amino acids. Nitrate, nitrate reductase, or other enzymes in plants can potentially play an important role in this process (Saxena and Srivastava 2020).

SO_2

Approximately 70% of SO_2 in the air comes from fossil fuel burning. SO_2 reaches into plants primarily by stoma, and can be employed in a reductive sulfur cycle in plants. They are transformed into lower oxidation state of sulfur oxides in cell walls. Adenyl-5-phosphosulfate, a protein carrier carries sulfite and sulfide as the intermediates in the reduction pathway. The end products are cysteine or other organic components.

15.3.3.3 Organic Pollutants

Formaldehyde

Formaldehyde, a universal air contaminant, is highly detrimental and is classified as a mutagen and carcinogen constituent. In the 1980s, a NASA's study in the USA discovered that lower concentrations of formaldehyde in atmosphere can be removed by plant leaves, while higher concentrations can be first filtered by activated carbon and then the plant roots and related microbes degrade and integrate remained toxins

(Wolverton 1988). At sufficiently low concentrations of formaldehyde (8.5 mg m^{-3}), shoots of spider plants can absorb free sugars, lipids, cell-wall components, organic acids, and amino acids. Formaldehyde can be oxidized and then degraded in C1 metabolism in phytodegradation. In soybean cell cultures, serine and phosphatidylcholine are known to be the main metabolic products for formaldehyde (Saxena and Ghosh 2015).

15.4 Air Pollution, Climate Change, and Atmospheric Extremes

There is a natural connection between climate change and air pollution since air pollutants and greenhouse gases originate from the identical source, i.e., fossil fuel combustion (Jacob and Winner 2009; Dennekamp and Carey 2010). In reality, combustion processes release greenhouse gases, like methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and air pollutants, like sulfur dioxide (SO_2), particulate matter (PM), carbon monoxide (CO), and nitrogen dioxide (NO_2).

When it comes to defining air quality, pollution and climate change trends are commonly seen to counterbalance each other. While a lot of countries are adopting pollution control strategies to reduce their emissions, climate change often leads to an increase in pollutant levels (Dennekamp and Carey 2010).

The correlation between air quality and climate is notable for ozone. Ozone levels are directly driven by weather, since ozone-generating photochemical reactions of air pollutants (nitrogen oxides; methane; volatile organic compounds, VOCs) need high temperatures and bright sunshine, conditions typical of summer months (Engardt et al. 2009). High temperatures are often associated with dry weather conditions, which significantly contribute to high ozone levels during heatwaves through a drought stress on vegetation that inhibits stomatal uptake of ozone (Jacob and Winner 2009; Ordóñez et al. 2005).

Anthropogenic emissions of ozone precursors are expected to decrease in developed countries, but not in the developing ones. A large increase in ozone concentration is expected to take place in Southern Europe, owing to climate change. This increase is likely to be higher than the reduction in ozone precursors, causing an overall increase. Background ozone concentrations are also predicted to increase due to a higher frequency of forest fires (Engardt et al. 2009).

Particulate matter, based on its chemical composition, is affected differently by climatic factors. Higher global temperatures result in a reduction on nitrate PM concentrations, but also increase sulfate aerosols, owing to faster SO_2 oxidation (Jacob and Winner 2009; Sonwani et al. 2021; Sonwani and Saxena 2021). However, under climate change, the nitrate burden is predicted to increase along with all other aerosol species, except sulfates. Over Europe, the predicted increase in overall aerosol concentrations will be by 20–40 $\mu g \cdot m^{-3}$ relative to the present-day values (Liao et al. 2006). Changes are driven by precipitation changes since wet deposition represents the primary PM sink, but also by increments in water vapor that increase oxidation of SO_2 and sulfate concentrations. Air stagnation conditions represent another important factor that will increase PM concentrations in polluted regions

(Chidthaisong 2005; Jacob and Winner 2009). Climate change-related increase in wildfires will also influence particulate levels (Krawchuk et al. 2009; Spickett et al. 2011); an increased fire risk in Mediterranean countries is expected, especially in areas with high forest cover (Chidthaisong 2005). The 2003 heatwave in Europe is emblematic since it was associated with both record wildfires and high PM levels (Jacob and Winner 2009). Particulate matter with a diameter less than 2.5 μm, commonly known as $PM_{2.5}$ is a major concern during wildfires. These particles have a long lifetime (in the order of days) and can travel larger distances (Naeher et al. 2007). Owing to climate change, wind patterns are predicted to change in the future, which will impact transport of particulate matter (Chidthaisong 2005).

Several primary and secondary pollutants have the potential to increase global warming, either directly or indirectly. Pollutants that are directly released as a result of combustion processes are known as primary pollutants, which include carbon monoxide, nonmethane VOCs, nitrogen oxides, sulfur dioxide, black carbon, and organic carbon aerosols. Secondary pollutants (e.g., ozone) on the other hand, are not emitted from a source, but formed in the atmosphere. Due to large quantities of greenhouse gases emitted, wildfires are known to directly contribute to global warming (Viswanathan et al. 2006). CO, NMVOCs, and NO_x cause an increase in warming, whereas nitrates, organic carbon, and sulfates have a cooling effect (Smith et al. 2009).

As Earth's climate has warmed, a new pattern of more frequent and more intense weather events has extended around the globe. These extreme events are identified based on the past record of weather in a specific region. They consider extreme weather events to be those that produce unusually high or low levels of rain or snow, temperature, wind, or other effects. Usually, these events are deliberated extreme if they are unlike 90 or 95% of comparable weather events that happened before in that same area.

The extreme events give rise to global warming that can further contribute to the intensity of heat waves by enhancing the chances of very warm days and nights. Warming of the air also increases evaporation that can exacerbate drought. More droughts result in dry fields and forests that are inclined to catching fire, and increasing temperatures mean a lengthier wildfire season. Global warming also increases water vapor in the atmosphere, which can lead to more repeated heavy snowstorms and rain.

A moister and warmer atmosphere above the oceans makes it probable that the toughest hurricanes will be stronger, probably be larger and produce more rainfall. Additionally, global warming causes sea level to rise, which increases the amount of seawater, along with more rainfall, that is pushed on to shore during coastal storms.

Understanding the impacts of global warming on extreme weather is significant because it can help notify choices about risk management. For example, if a community well aware of the fact that the increased rainfall due to global warming has converted a 500-year-old flood to a 100-year-old flood, different choices will then be made regarding land management, construction, or floodwall buildup.

15.5 Control Technologies for Atmosphere Extreme Events

15.5.1 Wildfire Control Technologies

Wildfires are a complex mixture of particulates, liquids, and gaseous components. The impact of fires is generally calculated regarding the PM2.5 concentrations in the atmosphere as it is mainly present in fire smoke (Finlay et al. 2012; Dennekamp and Abramson 2011), and is considered as the root cause for health-related issues. Fine particles are generated directly during the burning process and later resulted from the released gases by condensation and atmospheric chemical reactions. Throughout the wildfires, the concentration levels are mostly exceeding the air quality standards, i.e., 24-h mean PM10: 50 μgm^{-3} and 1-year average mean PM2.5: 25 μgm^{-3} (Naeher et al. 2007; Finlay et al. 2012; Dennekamp and Abramson 2011). The atmospheric extreme event is recognized in regard to a certain threshold, i.e., the 99th percentile of particulate distribution. This allows extreme events to be differentiated from conditions in which already present pollution sources are dominant.

Researches on health impacts of wildfire usually change for certain atmospheric conditions. Meanwhile the ambient temperature is typically higher during wildfires; there is also a possible opportunity for the co-occurrence of heatwave and wildfire situations which has huge effect on public health. This interaction can be described by fluctuations in temperature determined by smoke constituents, sunlight, emissions, water vapor, and related with other air pollutants (Naeher et al. 2007). Moreover, atmospheric conditions effect smoke dispersal and transportation (Viswanathan et al. 2006). Other wildfire impacts comprise visibility damage and ozone production (Azevedo et al. 2011); these aspects may also interact with PM concentrations in detecting health impacts (Ovadnevaitė et al. 2006).

Generally, the present indication proposes impacts of wildfires mainly on public health. The greatest operational challenge in these researches regards the evaluation of exposure; in most cases, PM concentrations from air quality monitoring units are utilized, but these are restricted to specific areas and are, thus, poorly representative of actual exposure. The recent method of using burnt areas from satellite data appears to be more effective in detecting high-risk parts. Furthermore, wildfires are occasional events and their impact depends on regional settings; hence, results are not simplified till date no proper consensus is developed to evaluate the exposure of dispersal process of smoke (Henderson et al. 2011).

Wildfire causes chaos and severe destruction of forestland and wildlife. It also has severe impacts to humans and buildings. Traditional control technology utilizes fire-retardant chemicals which not only pollute the atmosphere but also harmful to the marine wildlife. But the new control technology is better in terms of environmental protection but it is also cost-effective in comparison to the old technology. The use of frozen carbon dioxide which is commonly known as dry ice and it is abundantly available in millions of tons in many areas of the world. This control technology is far cheaper and environmentally friendly as compared to the use of fire-retardant chemicals (De et al. 2019).

15.5.2 Unmanned Aerial Vehicles (UAVs)

In recent years, many Unmanned Ariel Vehicles (UAVs) have been employed to combat forest fires. This has proved to be an efficient substitute for piloted aircrafts in times of such emergencies (Yuan et al. 2015).

15.5.3 Wireless Sensor Network (WSN) Technique

Global attention is being paid to wireless sensor network (WSN) for quick and easy indications of wildfires. WSN is capable of distinguishing between smoke of fake and real fires, indicating alarms and communicating distress signals. The sensor can indicate the presence of CO_2, NO_2, temperature, pressure, and relative humidity in the atmosphere, and is a useful device for wildfire detection (Okokpujie et al. 2019).

15.5.4 Spacecraft Technique

Advanced high resolution radiometers and imaging spectroradiometers are often used for timely response on wildfires (Nakau et al. 2006).

15.5.5 High-Tech Sensor and Camera Devices

High-tech sensors are often able to identify the nature of the smoke, temperature of fires, which makes them effective for early identification of wildfires. They are able to contact the control room on the amount of smoke in the area by means of different algorithms, and help in controlling the fire (Alkhatib 2014).

15.6 Sustainable Control Technology for Atmospheric Extreme Events

15.6.1 Carbon Dioxide Technology

Dry ice (solid CO_2) and liquefied CO_2 can help greatly control wildfires by cutting off oxygen supplies. Immediate clearing of areas around the fire and covering them with 2–3″ thick chunks of dry ice and liquefied CO_2 are recommended. Liquefied CO_2 from helicopters, when sprayed on such fires, creates a thick layer where oxygen is displaced. To protect the household communities within 200 m of the fire lines, dry ice chunks need to be spread on the inside, outside as well as the roof of the vacant house. Liquefied or CO_2 gas can be spread around the house, and dry inflammable stuff removed. However, a disadvantage of this method is that dry ice is not produced cost-effectively and we may need to look into other technologies to combat such large-scale disasters (De et al. 2019).

Desert Dust Storms Control Technology: Deserts are a known cause of dust storms globally, with North Africa (the Sahara) being the main contributing area (over 50%). Dust particles derive from the earth's crust and affect air quality, in particular PM10 and coarse particulate (PM2.5–10) levels (De Longueville et al. 2013; Karanasiou et al. 2012). Dust storms, similar to wildfires, are transported over large distances, following specific trajectories and changing chemical composition on the way. These episodes can cause PM concentrations to peak in areas having lower emissions (Niemi et al. 2009). For example, during Saharan dust events, PM_{10} concentrations surpass 100–150 $\mu g \cdot m^{-3}$ in rural areas, much higher than the EU daily limit (Middleton et al. 2008).

Dust storms from North Africa have a significant impact on air quality and human health, especially in Europe and the Mediterranean (De Longueville et al. 2013; Karanasiou et al. 2012). PM on dust days is proven to be higher than nondust days, as confirmed by mortality numbers or hospital admissions for respiratory causes (Jiménez et al. 2010; Samoli et al. 2011; Perez et al. 2012). On the contrary, Athens saw a greater effect on nondust days, while Cyprus observed no effect (Middleton et al. 2008). Studies from Asia and Australia evaluated impacts of dust storms on respiratory diseases such as COPD, asthma, pneumonia, etc. However, evidence relating hospital admissions to particulate matter levels is largely contrasting and unknown (De Longueville et al. 2013; Karanasiou et al. 2012).

It is also important to take into account meteorology when assessing the impacts of wildfires. Cyclones and anticyclones, along with rainfall, may cause long-range dispersion of air masses (Niemi et al. 2009). Dust storms tend to occur during high ambient temperatures and high ozone levels; however, not many studies have quantified the impacts of dust storms on human health, except one (Thalib and Al-Taiar 2012).

Analyzing the effect of dust storms on the environment has several challenges, as specific mortality or morbidity cannot be analyzed due to the low frequency of dust days. Additionally, in urban regions, dust storms are underestimated many times due to the presence of anthropogenic sources in the area (Karanasiou et al. 2012).

15.7 Climate Implications of Sand and Dust Storms (SDS)

Sand and dust storms have drastically damaged our environment by suspending tiny sand and dust particles, called as dust aerosols, in the atmosphere. Sand and dust storms have local and global effects on climate changes, while climatic changes in turn can alter the location and intensity of dust sources in the world. The threats caused by SDS are of great importance for environment as well as for public health because wind erosion can occur in most environments and desert dust events often involve long-range transportation of air particles ranging from 10^6m of distance (Akhlaq et al. 2012). So, environmental pollution control technologies are designed to alleviate SDS hazards for disaster risk reduction and for SDS impact mitigation. Although many SDS hazards are well-known, the processes involved and their impacts are not all equally understood. Development and implementation of mitigation policies, in order to address larger impacts of SDS mainly include transboundary pollution, are needed to be designed (Ginoux et al. 2001).

15.8 SDS Hazards

Sand and dust storms generate various hazards for humans and these are categorized according to the three main procedures of the wind erosion mechanism based on entrainment of particulates, their transportation, and their deposition (Middleton 2017). The SDS hazards are soil loss, nutrient loss, crop roots exposure, and undermining structures.

15.9 Control of Wind Erosion on Cropland

When the top most layer is displaced, it signifies as soil erosion mainly caused by wind and it is highly harmful to crop yield and productivity (Larney et al. 1998). Thus, various methods are designed to control wind erosion and these generally classified into three categories:

- **Soil management techniques**—Several soil management practices help provide a sustainable seed bed for controlling weeds and facilitating plant growth (Triplett and Dick 2008).
- **Protective barriers**—Walls or fences placed at right angles to the wind direction help break the erosive force of winds and prevent wind erosion (Wang et al. 2010).
- **Agronomic measures (crop management practices)**—An effective rule for controlling wind erosion is to maintain sufficient vegetative cover. Using residues from harvested crops can also help protect soil from wind (Skidmore 1986).

15.10 Control of Wind Erosion on Rangeland

Methods for controlling wind erosion on rangelands are largely comprised of preventive measures designed to reduce the pressure of grazing. Livestock may be excluded from pastures, a ban often enforced with fencing (Vetter 2005).

15.11 Controlling Blowing Sand and Mobile Desert Dunes

Mechanical removal, dissipation, reduce sand supply, and deposition promotion are the control measures for blowing sand and mobile dunes (Watson 1985).

15.12 Control of Wind Erosion at Mining Operations

Wetting mine trails, covering or capping with gravel, topsoil or synthetic materials, and erection of protective barriers as windbreaks are some of the techniques employed in this process. Renewable biopolymers and chemical suppressants developed from petroleum are widely used for mitigative purposes, in regions where water is at a premium (Chen et al. 2014).

15.13 Impact Mitigation of SDS and Its Policies

The encounters related to SDS have resulted in many policies in many areas of the world, specifically in those areas that have experienced issues related to wind erosion. The importance of these policies has strong focus on SDS at all levels. These include UNCCD Regional and National Action Plans and international air pollution policies (e.g., The Convention on Long-Range Transboundary Air Pollution).

15.14 Conclusion

This chapter analyzes air pollution control technologies that meet the sustainable environmental objectives in combination with other control technologies. Air pollution poses serious problems to public health and environment and their combined impacts resulted into extreme atmospheric conditions. Due to rapid climate change, the implications for air quality need to be better understood both for the purpose of air pollution control and societal consequences of climate change. Measuring the associated impact of climate change and air pollution should be an important part in designing, developing, and implementing technologies for effective air pollution control. This chapter briefly touched on the potential effect of air pollutants originated from the burning of fossil fuels which resulted in atmospheric extreme conditions, i.e., wildfires, dust storms, and how these impacts can be mitigated by control techniques. Further research is needed to establish greater outcomes and examine important factors that are associated to the developmental actions to combat air pollution in the long-term.

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16

Ecological and Natural-Based Solutions as Green Growth Strategies for Disaster and Emergency Management of Air Pollution Extremes

Sharfaa Hussain and Raza R. Hoque

Abstract

Air Pollution, across the globe is worsening despite efforts. It is an international concern due to its transboundary nature and its impacts on regional and global scale. Pollutants that are emitted to the atmosphere become an active participant in atmospheric reactions thereby altering the atmospheric processes. These alterations facilitate threatening air pollution episodes, what we call as "Air Pollution Extremes". These extremes harmfully effect human health and the environment. There are mooted proposals from the researchers to consider the air pollution extremes as disasters. Disaster management institutes and agencies are to be given with responsibilities on this regard. Air pollution extremes namely, fog, smog, and dust storms have been responsible for multiple deaths per event and serious environmental havoc. World Health Organization (WHO) regards air pollution as a prime factor for human mortality and is to be blamed for seven million deaths in the world every year; therefore, control measures are imminent. Though countries already have in place the legislations and regulating authorities for the control and mitigation of air pollution, many Asian countries like India are still struggling. In this chapter, a two-way "green approach" has been discussed—lowering the source strength, i.e., keeping a check on emissions right at the source and mitigating the pollution that has already been released to the atmosphere. Adopting "green concepts" in economic development and better city planning, and strategically built green covers could be a promising alternative to avert extreme air pollution.

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Green growth strategies · Air pollution extremes · Natural-based solution

16.1 Introduction

For the past several decades air pollution has been an important issue for atmospheric scientists and policy makers. Air pollution has been in the political agenda in many countries including India and there has been international concern due to its transboundary nature and impacts to the dimension of regional to global scale. There are three major concerns—(1) public health, (2) effect on biota and agriculture, and (3) changing composition of trace constituents of air thereby changing the atmospheric processes.

The world nations have recognized air pollution as a threat to human well-being (Shaddick et al. 2020; Mannucci and Franchini 2017; Saxena and Srivastava 2020) and, therefore, some of the pollutants, e.g., particulate matter (PM), sulfur oxides (SOx), nitrogen oxides (NOx), surface ozone (O_3), and some hydrocarbons like benzene and benzo(a)pyrene (B(a)P) have been identified as criteria pollutants (Saxena and Sonwani 2019a). The criteria air pollutants are regulated by the state agencies irrespective of whether the countries are developed or developing, rich or poor (Saxena and Sonwani 2019b).

Air pollution does affect plant growth and it interferes with the processes of photosynthesis, which would mean that air pollution could have direct impacts on the national and global crop productivity. There are reports of air pollution and associated productivity loss (Burney and Ramanathan 2014; Tai et al. 2014; Avnery et al. 2011), and large populous countries cannot ignore this challenge (Saxena et al. 2019; Kulshrestha and Saxena 2016).

As the pollutants are emitted into the atmosphere, they take part in the atmospheric processes and consequently bring about changes in the earth's radiative budget (climate impacts), chemistry of precipitation (acid deposition), and oxidative pathways leading to building up of photochemical oxidants (photochemical smog) in the air, which is a vicious chemical cycle that lasts for several days with severe visibility impairment and deteriorating air quality. Severe episodic air pollution events, historically known as smog episodes, claimed many lives due to recurrent episodes in London (Read and Parton 2019; Luckin 2003; Kelly and Kelly 2009), Glasgow (Bower et al. 1994), and other cities.

Today, it is understood with fair bit of uncertainty that air pollutants, more precisely the carbonaceous aerosol, have implications on the cloud seeding and the weather modifications (Garvey 1975; Guo and Zheng 2009; Guo et al. 2015; Rosenfeld et al. 2008). Extreme rainfall and long spell of dry days are often regarded to have been fallout of carbonaceous aerosol emissions. Cloud bursts and flood have been reported from varied geographical regions of the world (Gupta et al. 2013; Dimri et al. 2017; Kumar et al. 2018; Minea 2013). It is, thus, with little doubt that human action has led to tremendous pressure on the atmosphere and other components of the environment leading to visible global impacts, which is why Paul Crutzen had proposed that the present era be named as Anthropocene (Crutzen 2006; Steffen et al. 2007; Monastersky 2015).

Air pollution in many countries is taking the form of a disaster and hence there has to be a ready-to-use disaster risk management plan. A country's government body should formulate laws and acts that check and regulate air pollution. Disaster management authority that can strategize predisaster, immediate postdisaster, and recovery steps taken during a disaster is a necessity. With evident degrading air pollution green concepts came into play. These concepts refer to socio-economic development keeping sustainability and "easy on environment" nature in mind. Today, the term "green" is often prefixed to any process that does minimum damage to the environment, e.g., green industry, green technology, green fuel, green energy, green methods, etc. Green concepts provide an ecological and natural-based solution to tackle and minimize air pollution. In 2008, World Bank first proposed the idea of nature-based approaches (Tzoulas et al. 2020) and it received tremendous support from the International Union for Conservation of Nature (IUCN 2012) and the European Commission (EC 2015). Since then, natural-based solution has gained importance since it gives prime attention to how much damage it does to the environment. This chapter talks about air pollution and its extremes, how anthropogenic actions have lead air pollution to a disaster and how we can mitigate air pollution and its extremes through ecological and natural-based solution as green growth strategies. The aim of the chapter is to use the approach of nature-based solutions that use ecological and environment-friendly methods in urban planning and management to mitigating air pollution.

16.1.1 Air Pollution and Its Threats

From smog enveloping the cities to smoke hanging indoors, air pollution persists everywhere posing a threat to human health and climate. According to the World Health Organization (WHO), air pollution is responsible for about seven million deaths across the globe, every year and for the record, every nine individuals out of ten breathe in polluted air. The WHO also predicts that there will be an additional 250,000 death cases from 2030 to 2050 owing to air pollution and climate change (WHO 2014). The deaths caused by air pollution can be attributed to serious health issues like chronic obstructive pulmonary disease, acute respiratory infections, etc. Studies show that more than 80% of people inhabiting in urban areas breathe in air that exceeds the WHO air quality guidelines (Sonwani et al. 2022). People from parts of developing country and underdeveloped countries suffer from a combined exposure of both indoor and outdoor pollution. It is expected that by 2030, poor air quality will become one of the eminent environmental cause for premature death (WHO 2014). Long-term exposure to polluted air increases the risk of respiratory illness, cardiovascular disease, and cancer (e.g., Dockery et al. 1993; Jerrett et al. 2009; Krewski et al. 2009; Pope III et al. 2009), thereby increasing the annual acute mortality rate. Additionally, their resultant extremes have the potential to obstruct daily activities, and henceforth calls for strict control measures like Paris temporarily banned vehicles having even-numbered license plates (Porter et al. 2015). Similar policy was also adopted in Delhi with a regime of odd or even number vehicles to run on odd or even number day of the week (Tiwari et al. 2018; Kumar et al. 2017; Sehgal and Gautam 2016; Rao et al. 2017). Air pollution, though a global issue, has large differences in severity. The low-income countries topped the list of air pollution severity. The year 2017, (Fig. 16.1) witnessed an estimated five million deaths globally (Ritchie and Roser 2017). Figure 16.2 shows how air pollution driven deaths vary spatially. It is clear that death rates are 100 times higher in developing countries than Europe and North America.

Air pollution also imposes extensive threats to global food security. With global spike for crop demand due to increasing population, future pollution is expected to leave the global food supply in an extremely vulnerable condition (Alexandratos and Bruinsma 2012). Among various air pollutants, surface ozone (O_3) is explicitly harmful to crop yields (Ainsworth et al. 2012).

16.1.2 Air Pollution: A Brief on Global and National Scenario

Air quality in megacities impacts a significant global population and the affected population will only increase in urban areas over the coming decades. By 2030, the population count in 41 megacities is predicted to rise up to 730 million (UNDP 2015), pointing toward the need to have proper understanding of the influence of dense population on their environment and health of inhabitants. According to the Global Burden of Disease (Lim et al. 2012), ambient air pollution is a major risk factor and global population as large as 96% in the metro cities breathe air with high levels of particulate matter ($PM_{2.5}$) that are above World Health Organization (WHO) air quality standards (Krzyzanowski et al. 2014). Total of 7% of global burden from ambient air pollution comes from the 30 most populated urban areas, while several cities in Eastern and Southern part of Asia have higher per capita effects. Two megacities from India, viz., Mumbai and Delhi are ranked among top ten of populated megacities. It is expected that populations in Delhi and Mumbai will spike from 25.7 to 36.1 million and from 21.0 to 27.8 million, respectively, between 2015 and 2030 (UNDP 2014), thus triggering severity of air pollution. A station-based $PM_{2.5}$ analysis carried out in Delhi found that 69% of samples exceeded the 24-h standards (Tiwari et al. 2013). The average $PM_{2.5}$ and PM_{10} recorded in Delhi during 2008–2011 were 123 and 208 $\mu g/m^3$ respectively and the levels are above standard (Guttikunda and Goel 2013). Mean $PM_{2.5}$ and PM_{10} concentrations in October 2010 were 111 and 238 $\mu g/m^3$, respectively, and hourly O_3 was measured to be above 100 ppb. It was also found that in Delhi, besides multiple emission sources pollutant from outside the capital also enormously contributed to PM (25%) and daytime O_3 (60%) (Marrapu et al. 2014). Major share of India's population ~76.8% is subjected to annual population-weighted mean $PM_{2.5}$ which is higher than the country's National Ambient Air Quality Standards. In 2017, Delhi recorded the highest annual population-weighted mean $PM_{2.5}$ followed by Uttar Pradesh, Bihar,

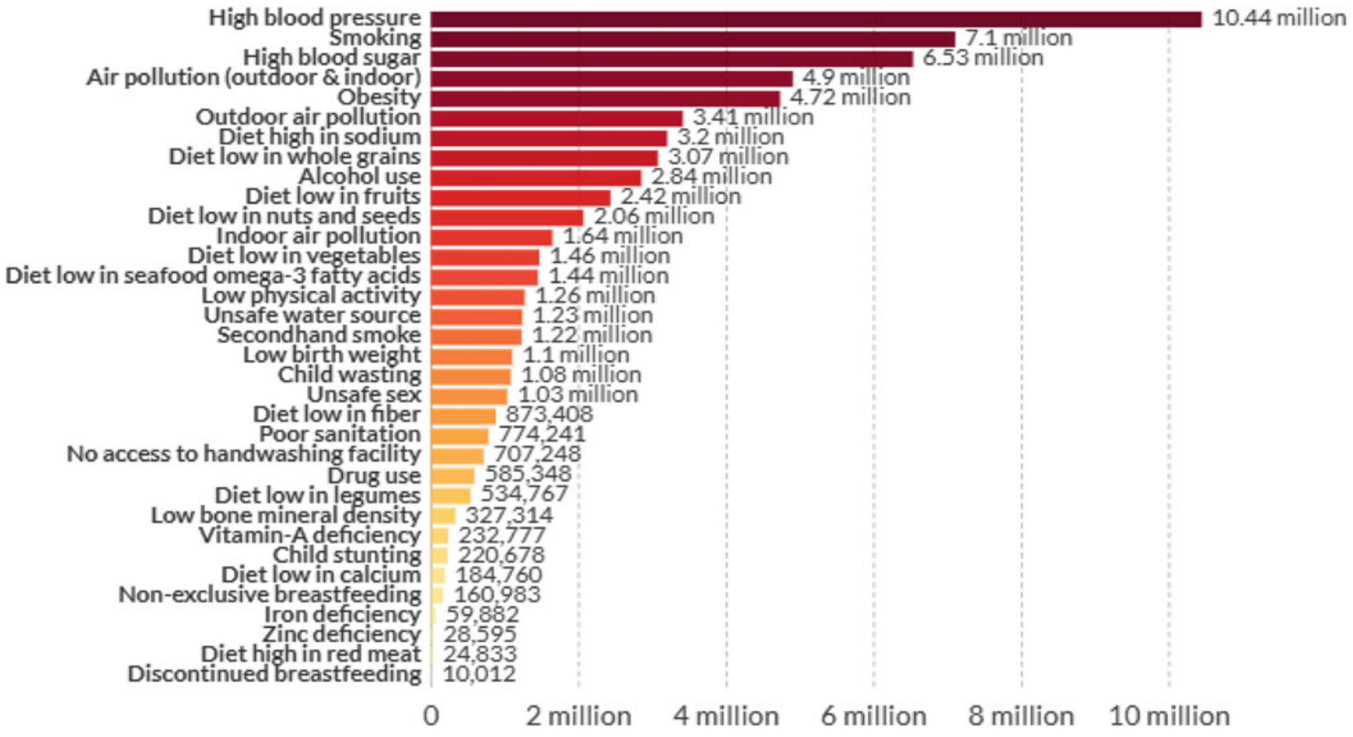

Fig. 16.1 Number of deaths by risk factors across the globe in the year 2017. (Source: IHME, Global Burden of Diseases, Ritchie and Roser 2017)

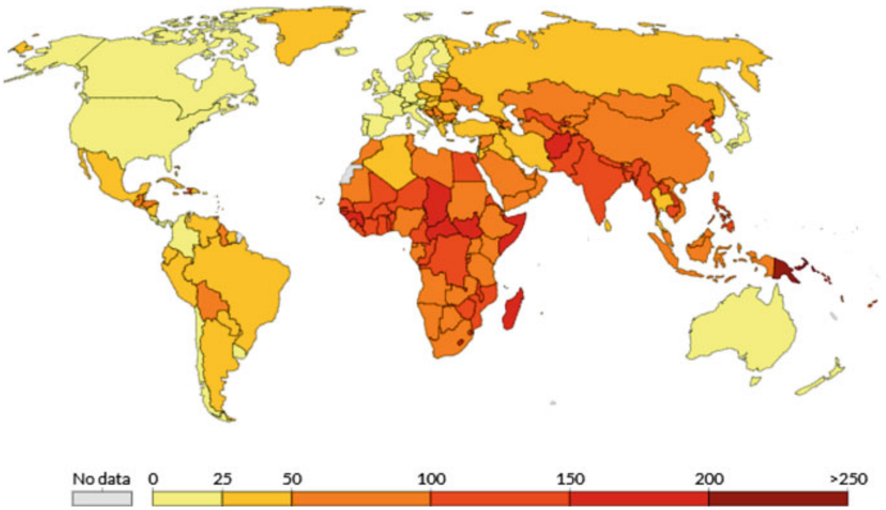

Fig. 16.2 Death rates across the globe due to air pollution from the year 1990 to 2017. (Source: IHME, Global Burden of Diseases, Ritchie and Roser 2017)

and Haryana with an average higher than 125 μg/m^3 (Balakrishnan et al. 2019). Figure 16.3 illustrates the annual and hourly $PM_{2.5}$ levels of some important cities worldwide. Out of eight cities examined, via satellite observations, CO, an important O_3 precursor, showed an increase over 2000–2008 only in Delhi (Pommier et al. 2013). A study found that if global greenhouse gas can be mitigated, we can clear of 0.5 ± 0.2 million demises triggered by $PM_{2.5}$ and O_3 by the year 2030 (West et al. 2013).

16.2 Factors That Influence Air Pollution

The concentration of a pollutants species is a complex function of emissions (source strength), meteorological conditions (allow dispersion, dilution, and transport), atmospheric reactions (lead to degradation of pollutant species), and deposition processes.

Emissions from industries, vehicles, fuel combustion, and biomass burning are some of the common sources of air pollutants which are quite understood well (Bhuyan et al. 2018; Masiol et al. 2017). Emissions from biomass burning and crustal or street dust are major contributors of air pollution in African and Asian region (Bhuyan et al. 2018; Deka and Hoque 2015; Hsu et al. 2014; Chen et al. 2017; Jain et al. 2021). In the Asian context, there are unique types of episodic biomass burning like the *meji* burning of the Brahmaputra Valley (Deka and Hoque 2014; Hoque and Deka 2010), *holika* burning of northern India (Singh et al. 2017), and crop residue burning in Indian states of Punjab and Haryana (Sawlani et al. 2019; Saxena et al. 2021). The crop residue burning adds to the already polluted air of

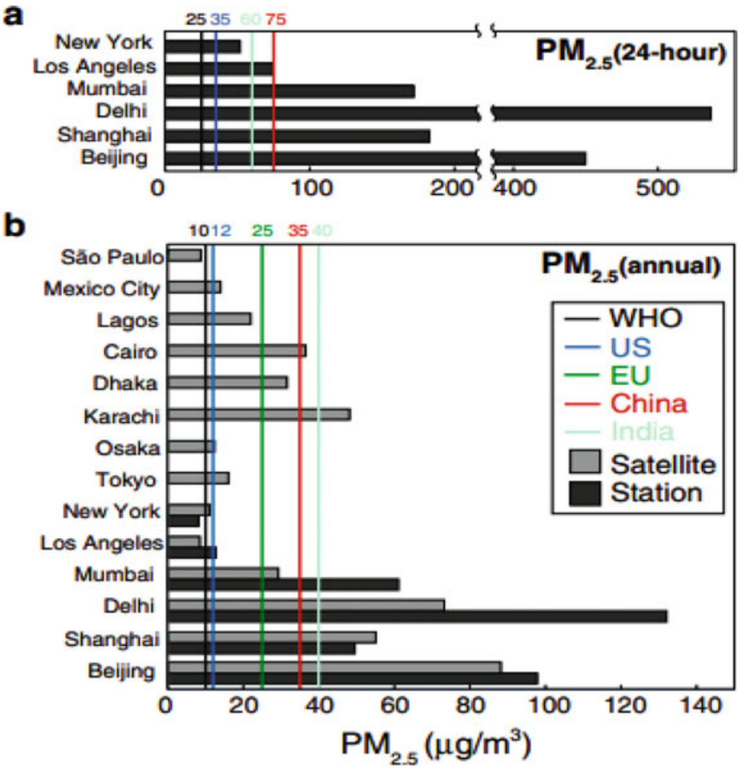

Fig. 16.3 (**a**) Maximum 24-h $PM_{2.5}$ concentrations (μg/m^3) at USA Embassy locations of Mumbai, Delhi, and USA E.P.A. sites in Los Angeles and New York (2014); (**b**) Annual average $PM_{2.5}$ concentrations (μg/m^3) retrieved from stations (2014) and satellite data (2011) (Source: Marlier et al. 2016)

Delhi. It is estimated that 39% of the worldwide population uses biomass fuels for cooking and heating, typically in developing countries (IEA 2011). Household biomass burning emissions add to the ambient air pollution too and the varied biomass types that are generally used have characteristic emission profiles (Deka and Hoque 2015).

Meteorological conditions of an area play an eminent role in the building up of pollutants in the atmosphere. Factors like the prevailing wind, turbulence, stability, and temperature inversions affect the transport, dilution, and dispersion of the pollutants (Shenfeld 1970). Inversions lead to very stable atmospheric condition which does not allow vertical mixing and thus traps pollutants. There is a permanent inversion layer called the “boundary layer” at a height (mixing height), which keeps changing. It would also mean that the pollutant concentrations will be greater when the mixing height experienced is low.

Atmospheric deposition is the permanent loss of pollutant from atmosphere through wet or dry deposition and reduces some part of the total atmospheric loading. Pollutants can be deposited onto vegetation, soil systems, and water bodies. Wet deposition refers to precipitation processes and deposits at a similar speed to every surface (Sehmel 1980; Fowler et al. 2004). Although in dry deposition, the rate depends on the macroscopic characteristics of the surface (Padro 1996; Fowler et al. 2004; Grote et al. 2016). Fowler et al. measured the particle deposition velocity and found that urban trees account for 11 mm/s and grass accounts for 3 mm/s. Of total dry deposition, 70% settles on urban trees and 25% on grasses (Fowler et al. 2004). Attributes like larger surface area, higher transpiration rates, and longer in-leaf periods enhance the process of dry deposition (Padro 1996; Branford et al. 2004; Nowak et al. 2006; Cabaraban et al. 2013; Grote et al. 2016). Lichens and mosses serve as an excellent accumulator for atmospheric dry depositions and, therefore, they are often applied in the biomonitoring studies of air pollutants (Daimari et al. 2013, 2020). Lichens also show the early signs of air pollution effects (Hazarika et al. 2011).

However, we do not have control over the meteorology and other atmospheric processes which influence the extent of air pollution. Though, there are some ways like artificial rain induction; however, this has not been of much convenience because of lots of other uncertainties and introduction of additional chemicals into the environment. It is “only” the source strength of pollution which is generally the focus of policy makers and while making strategies for air pollution reduction, lowering of the source strength has been the priority. Also, it is a wise move to understand the meteorology of a place while locating industries in and around a city which can provide with some relief considering the prevailing winds and other information.

16.3 Air Pollution Extremes

The three air pollution extremes discussed here are fog, smog, and sand/dust storms as per the following:

16.3.1 Fog

Fog is the cloud at the surface level atmosphere. Fog is considered as a hazard because it reduces the horizontal visibility to less than 1 km (George 1951). Increased aerosols in the cities due to rapid urbanization and increased number of automobiles catalyze fog events. Increase in the relative humidity and aerosols of particulate matter are expected to be responsible for poor visibility (Oldenborgh et al. 2018). When visibility is less than 400 m, fog is considered dense or heavy. The northern part of India is conveniently fog prone in winters (December–January). Satellite images detected a sizeable fog layer over Pakistan to Bangladesh during the winter (Gautam et al. 2007; Jenamani 2012; Ghude et al. 2017). In Northern part of India, formation of fog is supported by moisture availability, atmospheric stability, and strong low-level inversions, mostly influenced by a western disturbance

(WD) (Pasricha et al. 2003; Dimri et al. 2015). Atmospheric aerosols also serve the purpose of cloud condensation nuclei (CCN) and alter the life cycle of fog (Ghude et al. 2017; Safai et al. 2019).

Some of the active roads, railways, and airports (Delhi, Jaipur, Lucknow, and Varanasi) of India are situated in this fog prone northern region of India and are severely influenced by heavy fog during the winter months (December–January). Figure 16.4 shows the trends of percentage frequency of visibility in a few cities of India. The threat posed calls for mitigation measures to bring the risk under control. A study showed that, the poor visibility trends during winter in most of the airports in North India showed notable increasing trends amounting to 90%, i.e., almost everyday. On the other hand, the Southern India airports had just 20–30% days with poor visibility (De and Dandekar 2001).

Ecological-based solution to control fog: There is a section of plants that are termed as “fog collectors” because they collect fog from the atmosphere as a source of moisture. There is a detailed discussion in the later part of the chapter about criteria on how to select plants that can collect fog efficiently. It would be smart approach to construct a green belt or vertical live walls with fog-collecting plants in areas that tend to get dense fog.

16.3.2 Smog

The term “Smog” was coined in the early twentieth century and is a fusion of two words “smoke” and “fog”. However, today we know that smog episodes are periods of very high concentrations of air pollutants rendering the air quality poor. The Great Smog of London is one of the earliest recorded and deadly smog events that killed 12,000 people. London then was extensively using coal as the prime energy source and hence emissions from coal combustion made it lethal. The condition worsened due to the subsidence inversion over London region. Subsidence inversion persisted for longer duration and it made a deadly combination with high emission due to strong source strength of air pollutants (coal burning during that time).

There are two types of smog (1) the London type (classical, reducing type) and (2) the Los Angeles type (photochemical, oxidizing type). India witnessed a severe smog event during November 1–7, 2016. Delhi, the capital of India was caught in a severe air pollution episode (SAPE) or the “Great Delhi Smog”. The air quality index (AQI) transcended 500 and the smog layer enveloped the entire capital. Researchers from the University of Hyderabad (UoH), Indian Meteorological Department (IMD), Indian Institute of Tropical Meteorology (New Delhi), Banaras Hindu University, Finnish Meteorological Institute, Finland, Pacific Northwest National Laboratory, Richland in the US, undertook a study that revealed that “air stagnation” catalyzed the event and made it worse. The study also stated that degraded air quality due to high levels of $PM_{2.5}$ has been experienced by Southern Asia. More recently, the winter time intense air pollution haze over Delhi has drawn much focus, which has pushed governments and regulating agencies to the crossroads. The government of Delhi had tried out policies from vehicular

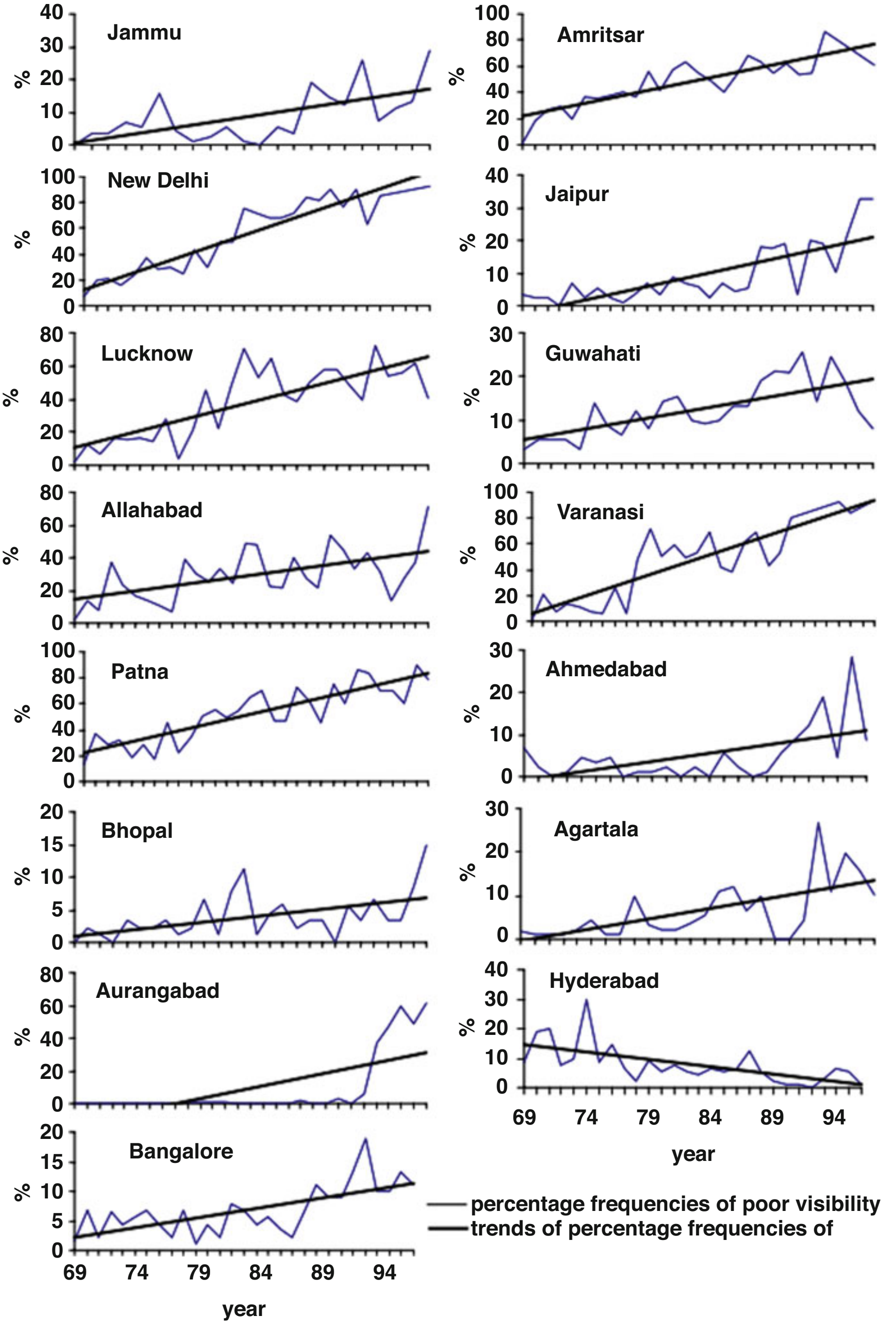

Fig. 16.4 Percentage frequencies of poor visibility and its trends in the Indian cities between 1969 and 1997 (De et al. 2005)

movements to agricultural activities in the rural areas. As an emergency move, the schools were closed and people were advised to stay indoors during the high pollution days.

Smog has been a serious issue in Delhi. The city has been gasping for air every year (Kedia 2017) and root causes are many. Smoke from rural kitchens, vehicular emission, industries, more numbers of vehicles, spike in Compressed Natural Gas (CNG) prices leading to commoners unaffordability, dieselization of cars, jeopardization of nonpolluting public transports, dense population, low investment in public transport and insufficiency of public infrastructure, extensive construction activities, burning of left over crop in adjacent states such as Punjab, Haryana, and Uttar Pradesh contribute together. During the months of autumn and winter, approximately 500 million tons of crop residues are burned in Indo-Gangetic plains leading to mass emissions from biomass burning (Sharma et al. 2010). According to another study, 72% of the total air pollution load in Delhi is from vehicular emissions as calculated using emission factor and activity-based approach suggested by Intergovernmental Panel on Climate Change (IPCC) (Sindhwani and Goyal 2014). Furthermore, during winters, calm winds and low temperatures entrap dust particles and pollutants near the ground setting up smog layer. And then the festival of Diwali, due to fireworks, gives an incremental effect to the air pollution of Delhi.

Natural-based solution to control Smog: Urban air pollution exerts pressure on plants to release stress-induced biogenic emissions (bVOCs) that take part in atmospheric reactions to form secondary organic aerosols (SOAs) and phytochemical smog. Hence, emission profile of plants should be considered while urban plantation. Air Pollution Tolerance Index (APTI) calculates the pollution-tolerant levels of plants and can be used to select plants based on pollution of an area and the plant's tolerance level. There are studies that confirm how some plants can capture particulate matters. So the natural-based approach to mitigate smog would be construction of green belts and extensive plantation of varied plants to tackle all components of smog, considering it is a mixture of fog, pollutants, and particulate matters. Thick lush moss plantation will also be an intelligent approach since moss can entrap access moisture and pollutants from the atmosphere. Details are discussed in the later part of the chapter.

16.3.3 Sand and Dust Storms

Sand and dust storms (SDS) are the occurrence of crystal particles being carried by a strong wind gust. A SDS event takes place when vigorous and turbulent winds gust over parched, loose, fine-grained soil surface that lacks vegetation cover (Middleton and Kang 2017). Strong and speedy wind has the ability to translocate dust for several kilometres and hence dust storms are not just confined to deserts. India was hit by many episodes of acute dust storms, thunderstorms, and lightning and there are reports of deaths due to storms (Illiyas et al. 2014; De et al. 2005). In India such events are common in the western Rajasthan Province, which is covered by the Thar Desert. Dey et al. (2004) reported the effects of a dust storm event in aerosol

Table 16.1 Environmental Hazards to human population caused by wind and dust storms (Middleton and Kang 2017)

Entrainment	Transport	Deposition
Soil loss Nutrient, seed, and fertilizer loss Crop root exposure Undermining structures	Sand blasting of crops Radio communication problems Microwave attenuation Transport disruption Local climate effects Air pollution Respiratory problems and eye infections Disease transmission (humans) Disease transmission (plants and animals)	Salt deposition and groundwater salinization Reduction of reservoir storage capacity Drinking water contamination Burial of structures Crop growth problems Machinery problems Reduction of solar power potential Electrical insulator failure Disruption to power supplies

Table 16.2 Measures for controlling windblown dust (Watson 1985)

Control approach	Examples
Promote deposition	Ditches; fences; tree belts
Enhance transport	Streamlining techniques; creating a smooth texture over the land surface; erecting panels to detect air flow
Reduce land supply	Surface stabilizing techniques; fences; vegetation
Deflect moving sand	Fences; tree belts

parameters and observed a rise in AOD by more than 50% and PM_{10} after a dust storm event. Table 16.1 shows wind erosion and dust storms imposed environmental hazards to human populations.

Natural-based solution to control sand and dust storm: Green fences and tree belts can slow down wind speed and control its devastating nature to a great extent. Sterberg et al., reported that English Ivy can trap suspended particle and has a dust absorption rate of 2.9×10^{10} particles per m^2 for upper side of the leaf (Sternberg et al. 2010). Such plants can be used in areas that are prone to dust and sand storm. Other control approaches are given in Table 16.2.

16.4 Mitigating Air Pollution

A strategic approach to mitigate air pollution is “Reduce–Extend–Protect” (Hewitt et al. 2020). Minimizing emissions right at the source is the prime step of mitigation and can be achieved by lowering the source strength. That is where government regulations and introduction of green concepts come into play. The other mitigating ways are extending the distance between the source and the sink and protecting receptor sites from pollutants. This can be achieved by better planning of urban areas which will target the existing pollution and help reduce it.

16.4.1 Air Pollution Risk Reduction and Management

It is quite obvious that with the over exploitation of natural resources, we are on the losing side and slowly the idea of sustainable development took shape, which was clearly defined by the Brundtland Commission in 1987 (Redclift 2005). The "green concepts" are nothing but sustainable socio-economic development with concern toward the environment. As accepted at the fifth Ministerial Conference on Environment and Development in Asia and the Pacific, green growth is a strategy for achieving sustainable development (Sarkar 2013). With the development in the field of greener technologies that emit less and the adoption of greener fuels, much lowering of the source strengths of air pollution can be achieved. With the introduction of green technologies like electric vehicles, significant lowering of air pollution in our cities could be envisaged, provided the needed electricity comes from zero emission technologies like solar or wind power. If we have to rely on coal-fired thermal power to fuel the electric vehicles, then the purpose would be lost. Also, the most coveted hydrogen fuel could change the air pollution scenario across the world. However, due to high cost of production and technology, the developing countries may not get an easy access to it.

For the air pollution control, countries have put in legislations in place and there are institutions that work under the provisions of the laws. For instance in India, the Air (Prevention and Control of Pollution) Act, 1981 was enacted for the control and abatement of air pollution. At the center, Central Pollution Control Board (CPCB) and at state level, the State Pollution Control Boards (SPCBs) were created under the provisions of the Water Act of 1974, which were entrusted with the responsibilities of control and mitigation of air pollution in India. National ambient air quality standards (NAAQS) have been set for the control. Also the pollution control boards can declare air pollution control zones to regulate polluting units, and a permit regime has been put in place. However, most cities in India are struggling to meet the NAAQS.

From the historical understanding of air pollution, it can be realized with definite terms that extreme air pollution can take a form of a disaster. And, in the case of India, air pollution is going to be the biggest disaster (Bhatt 2018). Therefore, it is good to have a disaster management approach in place for reduction of the associated risks.

Disaster risk reduction is about a systematic array of five key zones of decision building: Risk Identification, Risk Reduction, Preparedness, Financial protection, and Resilient reconstruction. Earlier dealing with disaster only meant coming up with emergency response postdisaster, even so to the climax of twentieth century, researchers were convinced that disasters are not natural and that, the main way of minimizing risk lies in minimizing vulnerability and exposure (GFDRR 2014).

Table 16.3 Activities associated with managing the impacts of disasters (Lal et al. 2012)

Pre-disaster	Immediate post-disaster	Recovery
• Public education • Awareness raising • Warning and evacuation plans • Pre-positioning of resources and supplies • Last minute alleviation and preparedness measures	• Search and rescue • Emergency medical treatment • Damage and needs assessment • Provision of services—water, food, health, shelter, sanitation, social services, security • Resumption of critical infrastructure • Coordination of response • Coordination/management of development partner support	• Transitional shelter in form of temporary housing or long-term shelter • Demolition of critically damaged structures • Repair of less seriously damaged structures • Clearance, removal and disposal of debris • Rehabilitation of infrastructure • New construction • Social rehabilitation • 'Building back better' to reduce future risk • Employment schemes • Reimbursement for losses • Reassessment of risks

Table 16.3 illustrates the basic predisaster, immediate postdisaster, and recovery steps taken during a disaster.

With rising need of disaster risk management in India, the National Disaster Management Act (NDMA) 2005 was enacted. The NDMA holds the responsibility of issuing guidelines and providing with minimum standards of relief to the affected. The Act extends to the whole of India and comes into force when Central Government instructs. The National Institute of Disaster Management (NIDM) has been assigned the pivotal responsibilities to capacity building and policy advocacy, besides other responsibilities, in the issues of disaster management in India under the provisions of the Disaster Management Act 2005. NIDM has in its priority to encourage and create awareness amidst stakeholders, students and teachers of schools and colleges, technical human resources, and others associated with multihazard mitigation, readiness, and response measures (NIDM 2020). NIDM established a network called India Universities and Institutions Network for Disaster Risk Reduction (IUIN-DRR) to work together to tackle disasters. As air pollution is taking a shape of a disaster in the Indian cities and the rural areas around them, it is envisaged that institutions like the Disaster Management Authority (DMA) take connivance and explore possibilities of declaring poor air quality as a disaster. As the NIDM has all the right conditions to handle disasters, extreme air pollution may be a priority for NIDM and take up necessary action (Bhatt 2018).

16.4.2 Green Strategies to Reduce Air Pollution

16.4.2.1 Greening Cities to Mitigate Extreme Air Pollution

Rapid urbanization and population growth have led to increased construction of buildings and skyscrapers with very little space left for greening. A large deal of the deteriorated air quality can be attributed to urban city planning which results into a faulty urban canopy (Ratti et al. 2006; Abhijith et al. 2017). The urban canopy takes up the near-surface volume (Henderson et al. 2016) and interacts with the air flow (Oke 1988). *Green cities, green buildings,* and *green roads* are some concepts that can be strategized together to mitigate the air pollution in urban atmosphere. More and more compact and tall buildings, without enough green cover impair wind flow or deposition of pollutants, thus favor the conditions of heat island formation.

Besides planting trees and grass cover in just streets and parks, other control means like roof greening and vertical plantation have proved useful. A detailed study done on city designs of China, Boya (2012) showed that Beijing's urban planning strategy is in the form of what the author calls as "baking pie" (basically in shape of concentric rings) with green covers surrounding the ring traffic areas. Such green covers are isolated and lack contact with green environment failing to create an independent green system or a healthy microclimate of their own. For a green cover to properly function, they should be connected to form a green belt that acts as the lung of the city, creates a wind channel, and acts as satisfactory sink. This has been mentioned as one major issue for serious atmospheric pollution of Beijing in recent years. Also Sanghai has seen multiple constructions of tall buildings in the recent years. This increase in urban building density restricts natural ventilation and traps the indoor air pollutants and CO_2 thus deteriorating the air quality. Owing to this issue, the author proposed decentralization of the urban spots by breaking down single centers to multicenters, and its functions and populations surrounding them and leaving enough areas for green space.

An ideal green city is not just planning the urban design of the city but also calls for green/sustainable roads and green buildings. Road transport is evidently one of the most economic and widely chosen modes of transport for both good transport and passengers. India has the world's second largest road network of 4.24 million km (MoRTH 2008). The construction of roads also gives out harmful emissions to the atmosphere. Green roads use microsurfacing technique instead of using hot mix where fossil fuel is used both as a raw material and energy source. On an average, hot mix requires approximately 10 m^3 of the natural gas and has about 0.525 kg of carbon. Microsurfacing is in use since 1976 in countries like Germany, Spain, and France and was later introduced to India in 1999–2000 (Ryntathiang et al. 2013). Microsurfacing uses no heat, cold in-place recycling thus minimizing noxious fumes and other harmful emissions, making it safer for the environment and the workers.

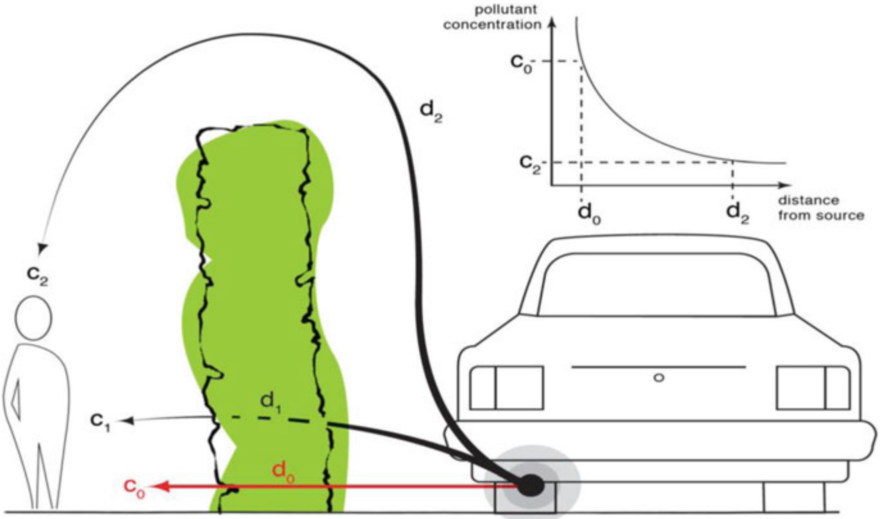

Fig. 16.5 Outcomes of a permeable obstruction (like hedge) in diluting pollutants. Here the child receptor is exposed to pollutant concentrations c_1 and c_2 via paths d_1 and d_2.Through d_1, deposition happens diluting c_1 through d_2 mixing takes place, causing c_2 to decrease. In the absence of barrier live permeable obstruction, the receptor is exposed to c_0, barely diluted over a tiny distance d_0 (Hewitt et al. 2020)

Microsurfacing uses a mixture of polymer-modified asphalt emulsion, mineral aggregate, mineral filler, water, and other additives, properly proportioned, mixed, and spread on a paved surface in variable thick cross-section which resists compaction (ISSA 2005). Sustainable building/green building is gaining importance due to high demand of constructing buildings to accommodate the rising population. Green buildings are healthy, environmental friendly substitutes that provide benefits in terms of energy and CO_2 reduction and improved health situation for building users (Balaban and de Oliveira 2018).

“Landscaping” is an important aspect that helps us achieve a green city. Planting trees have far more benefits than one truly acknowledges. They regulate the precipitation cycle, have profound role in land management and fix carbon. When green coverage exceeds 30%, the heat island effect is reduced to a great extent; when higher than 60% heat island effect is totally eliminated (Boya 2012).

Trees and hedges act like a semipermeable barrier to air flow (Bradley and Mulhearn 1983; Raine and Stevenson 1977; Tiwary et al. 2006; Gromke et al. 2016) and create turbulence thereby increasing dilution (Fig. 16.5).

16.4.2.2 Afforestation

Afforestation/reforestation is simply planting trees in barren areas or areas which had a green cover in the past. Planting trees will not only provide sink for atmospheric pollutants but also regulate wind speed and soil erosion. Planting trees can successfully reduce 25% of atmospheric CO_2 by 2050 via reduction of emissions, by acting as a low-cost sink for atmospheric CO_2 and can also contribute to sustainable development (Niles et al. 2002; Barker et al. 2007). These new plantations, can entrap 205 billion tonnes of carbon, i.e., about two-thirds of the 300 billion tonnes of carbon released to the atmosphere due to anthropogenic activities since the beginning of Industrial Revolution (ETH 2019).

16.4.2.3 Green Belt Development Planning

Green belts in urban cities are considered as the "lung of the city" as they serve as sink for harmful vehicular and industrial emissions, check dust flow, and also bring down noise pollution. All these years, overpopulation has led to insufficient open spaces and green belts in the cities, e.g., the ridge forests in Delhi and the Borivali National Park in Mumbai, served as the lungs of the cities.

In designing a green belt, certain aspects such as wind velocity, assimilation capacity of the ecosystem, tree height, canopy, topography, amount land availability, interspace between pollution source, soil and water quality, nature, and extend of pollutant are considered. Green belts are known to moderate microclimate by reducing wind speed thus reducing building-energy consumption and reducing heat conduction into buildings by reducing solar radiation (Liu and Harris 2008). Plants best suited for green belt construction are: *Acacia farnesiana, Melaleuca* sp., *Pine, Cedar, Junipers, Eucalyptus, Nerium, Acacia auriculiformis, Bamboo, Pongamia pininata, Azaridicta indica, Casuarina,* etc. (GCPC). Roof planting is another approach to achieve green cover in urban areas. It can also collect rainwater and significantly reduce the heat island effect by lowering temperature of the roof.

16.4.2.4 Vertical Gardening

Vertical greening is a constructive and effective plantation method to reduce temperature in urban areas. In case of land unavailability, plant vines are grown through walls, bars, poles, and other buildings. Creepers, air purifying shrubs, etc. are planted with drip watering system installed. It also helps in achieving shading and ambient temperature reduction in summers, isolates noise, absorbs dust, and as a whole dilutes pollution in the area. A study by Pacheco-Torgal et al., demonstrated that a vertical green-living wall filters direct sunlight since 5–30% of the sunlight energy is reflected, 5–20% is consumed in photosynthesis, 10–50% is converted to heat, 20–40% is utilized for evaporation, and finally approximately only 5–30% of the total light passes through the leaves (Pacheco-Torgal et al. 2014), thus blocking the direct sunlight and providing a cooling effect in summer. In winters, the same vertical green layer also acts as an insulation and prevents escaping of heat from inside the building (Hadba et al. 2017). M. Köhler in his study suggested that green facades can capture about 4% of the annual dust-fall in an inner-city area (Köhler 2008). For example, Boston Ivy entraps heavy metals like Al, Cd, Co, Cr, Cu, Fe, Ni, and Pb that are deposited in suspended particulate matters (Köhler 2008; Thönnessen 2002). The lush growth of English Ivy can also trap suspended particle and has a dust absorption rate of 2.9×10^{10} particles per m^2 for upper side of the leaf (Sternberg et al. 2010).

Vertical forests were set up in China, to tackle rocketing urban growth and air pollution crisis. The skyscrapers held 1100 trees and 2500 varieties of plants and shrubs that can facilitate 25 tons of CO_2 absorption per year and production of about 60 kg of oxygen a day (Hutt 2017).

16.5 Selection of Plants

Trees can notably influence the chemistry of urban air by the intake and emission of reactive biogenic volatile organic compounds (BVOCs). There are two potential VOC emissions, viz. “constitutive” (cBVOCs) and “stress-induced” BVOCs (sBVOCs). Owing to their highly reactive nature, BVOCs take part in atmospheric processes and facilitate formation of secondary organic aerosol (SOA). Stress is one core factor that effects BVOC emissions. Biogenic VOCs are released to the atmosphere following biotic or abiotic stress exerted on them (Behnke et al. 2009; Faldt et al. 2003). Urban trees suffer harsh conditions (Calfapietra et al. 2015), like high temperature, high pollutant levels, lack of root space, aeration, nutrient deficiency, and more frequent drought/flood episodes (Calfapietra et al. 2013). These factors together negatively affect plants and enhance emissions of BVOCs. Enhanced sBVOC emissions in turn effect the local air quality (Calfapietra et al. 2013; Churkina et al. 2015; Helln et al. 2012; Papiez et al. 2009). The VOCs react with oxides of nitrogen (NOx) in the presence of sunlight and produce photochemical smog. Ozone and PAN are major constituents of photochemical smog. This brings about a vicious cycle in the cities—the photooxidants injure more plants and the plants emit more VOCs. Thus, when taking up a tree plantation program, the following points may be considered: intended shading climate of area and emission profile of the tree. In the absence of any assessments, it is always good to go for local plants.

The differences in emission rates of different plant species vary significantly. There are plants that emit up to 10,000 times more biogenic VOCs than the atmospherically friendly “low emitters”. The APTI (Air Pollution Tolerance Index) is a scientific tool to help select plant species for urban plantation depending on their pollution tolerance level. The calculation uses four biochemical parameters, viz. total chlorophyll, ascorbic acid, pH, and relative water content. According to a study that evaluated the APTI of four ornamental plant species, viz. *Dracaena deremensis, Tagetes erecta, Rosa indica* and *Dianthus caryophyllus*, *D. deremensis,* and *T. erecta* were found to be tolerant while *R. indica* and *D. caryophyllus* were sensitive to pollution. Based on which, it is suggested that *D. deremensis* and *T. erecta* may be used as sinks for pollutants at highly polluted sites whereas *R. indica* and *D. caryophyllus* were labeled as bioindicators (Saxena and Ghosh 2013).

A research from Delhi suggested a few trees/plants that can absorb high concentration of Suspended Particulate Matter (SPM). The research evaluated APTI values of 20 flora species and suggested that *Azadirachta indica* (*neem*), *Ricinus communis* (castor bean), *Prosopis juliflora* (*kabulikikar, vilayati babul*), *Dalbergia sisoo* (*sheesham*), and *Delonix regia* (*gulmohar*) are tolerant to pollution and can be used in setting up green belts (Singh 2017).

Biomonitoring studies can also tell us a lot about a plant's accumulation capacities. Biomonitoring studies have been done in higher plants, shrubs but more commonly in mosses. Mosses are effective biomonitors, belonging to the lower group of plants called bryophytes. Due to unavailability of true roots, mosses are designed to take up nutrients from the atmosphere, thus evaluating them is an indirect evaluation of atmospheric constituents of that area. Since their cell wall lacks cuticle and possesses cation exchangeable sites, it facilitates metal accumulation above their physiological needs (Tessier and Boisvert 1999). Mosses are resistant to a variety of substances that are otherwise critically toxic for other plants species, they can be found in hot-humid tropical regions and also in chilly cold tundra region and have the capability of undergoing complete desiccation and extreme temperatures as high as 110 °C (Cenci et al. 2003; Fernandez et al. 2006; Dragović and Mihailović 2009). Mosses serve as an eminent bioindicator for high sulfur dioxide (SO_2) concentration, heavy metal accumulation, and various other atmospheric contaminants (Giordano et al. 2004). The popular mosses researched about in articles are: *Hypnum cupressiforme*, *Hylocomium splendens*, and *Pleurozium schreberi* (Blagnyte and Paliulis 2010). Thus, owing to their easy intake of pollutants and heavy metals, growing moss in areas of extreme air pollution can be a great idea to create a vast sink and at the same time pollutant profiling of moss can be adopted as low-cost air pollution monitoring technique.

There are various studies on plants being able to serve as a fog collector. Fog is an important source of water since it allows plants to stay hydrated even during times without rain. The efficiency of plants as fog collectors depend on their leaf shapes, pinnate and perforate shaped leaves have showed higher fog yielding capacity and permeability for air carrying the fog than simple shaped leaf. In case of simple leaf, if air strikes its surface it passes around it because of its impermeability. Thus plants with pinnate and perforate leaves, which also have a lower flow resistance for the air carrying fog, are much better for fog collection (Azad 2016). More and detailed research on efficient plants that can collect fog will help us in selection of plants to construct green belts in fog prone areas. There are also specific studies on plants that can better accumulate particulate matters.

Weerakkody et al. (2018) reported that leaf with small size, complex shape, and hairy, unruly or waxy surface facilitates better PM capture. A study on suitable characteristics of leaf for entrapping traffic-emitted PM (PM_1, $PM_{2.5}$ and PM_{10}) revealed that there was an inverse correlation between leaf size and PM accumulation. In terms of pollutant deposition, evergreen species does a better job than deciduous species, although deciduous species exhibiting longer in-leaf seasons are preferred over deciduous species with brief in-leaf seasons (Abhijith et al. 2017; Sæbø et al. 2012; Smith 2012). The reason being, evergreen species retain functional leaves all round the year, and deciduous species persist without functional leaves typically in winter or dry season. Researches have revealed that gaseous pollutants are managed by stomatal pores through their positive uptake as a consequent of plant photosynthesis and water management processes (Lawson and Blatt

2014). In response to environmental conditions, some plants have shorter stomatal opening time and some have longer opening time. And hence removal of pollutant can be enhanced by selecting plant species with long opening intervals (anisohydric species like Populus and Quercus species) (Barwise and Kumar 2020).

16.6 Conclusion

Despite formulations of environmental policies and risk management strategies, the world is still unable to make a remarkable drop down in the pollutant levels. The serious threats to human health, increasing mortality, and increase in air pollution extremes point to the fact that air pollution is taking the shape of a disaster and therefore disaster management authorities must first consider it as such and strategically formulate full proof policies. Green growth strategies are smart and a convenient approach to mitigate air pollution and hence should be copiously introduced wherever necessary. Natural- and ecological-based solutions are best approaches to mitigate air pollution and its extremes because they are natural and do not cause more pollution. Because if we are to deal with pollution in a way that again has the potential to degrade the quality of environment, the approach will be of no use. Also, we have reached the threshold point of the planet's pollution tolerance due to man-made activities. Hence all we can afford now are natural-based, zero emission, conventional techniques to get back at the existing pollution. Our approach has to spread to all the sources that are responsible for degrading the air quality. Hence strategically built green belts, vertical gardening, and any such urban plantation that has thoroughly checked a plant's pollution tolerance and emission profiles are our go-to natural-based approach. In addition to that what we need is a governing body and disaster management authority that carefully lays out strict regulations in favor of the environment and has a disaster management protocol ready in case of any emergency.

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Policy Implications and Mitigation Strategies for Air Pollution and Atmospheric Extreme Events

17

Disha Sharma

Abstract

Air pollution is a public health concern worldwide. In India, deteriorating air quality is a grave issue causing nearly 1.1 million deaths in 2015 alone (Health Effects Institute, Burden of disease attributable to major air pollution sources in India, 2018). Globally, a significant proportion of human population is breathing poor air. While some megacities experience only episodic increases in air pollution, several Asian cities suffer from the problem chronically. Increases in ambient concentrations of criteria air pollutants above the prescribed air quality standards lead to a deterioration in air quality on different temporal scales. Direct emissions from natural and anthropogenic sources inject primary pollutants and their chemical transformations in the troposphere lead to the formation of secondary air pollutants. The life span of air pollutants can last from hours to decades depending on their chemical characteristics and concentrations at emissions. The need to control and manage the emissions of air pollutants and their ambient concentrations has been addressed through several international and national policy mechanisms that have paved a way for devising control strategies based on scientific solutions. However, these policy actions have not always provided a win-win solution owing to the complex nature of the problem involving multiple sectors and stakeholders. Learning from successful examples of coordinated implementation and timely achievement of objectives (as in the case of Montreal Protocol), it is imperative to build institutions that mature in their approach as the science on the issue develops. This is particularly applicable in the case of air pollution extremes where it is crucial to look for technological innovation while ensuring coordination between multiple agencies. This chapter reviews all the

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existing international and national policies that outline measures to curtail and abate ambient air pollution in chronic and episodic events as well as targeting abatement from natural and anthropogenic sources. The first half of the chapter covers international policies that have been implemented to address the transboundary pollution with global implications. In the second part, policies adopted in India in response to abatement of deteriorating air quality at the state and national level are reviewed.

Keywords

International policies on air pollution · Air quality extremes in India · Air pollution mitigation measures in India · Clean air regulations and laws · India

17.1 Introduction

Air pollution poses a grave danger to human health (Brauer et al. 2013), environment, economy and climate (Von Schneidemesser et al. 2015; Saxena and Srivastava 2020). It is a bigger problem lately, mostly in Asia, causing nearly 1.1 million deaths in 2015 in India (Health Effects Institute 2018). More than 660 million people, equal to almost half of country's population, live in areas that exceed the national air quality standards for $PM_{2.5}$ (40 μg/m^3) and only 1% of total population lives in areas that meet the World Health Organization (WHO) standard (10 μg/m^3) (WHO 2016). While breathing toxic air is a public health emergency, direct emissions of aerosols along with secondary aerosol formation from sulfates and ozone can alter the earth's heat balance and atmospheric chemistry (Li et al. 2019). Poor air quality has a direct impact on the wellbeing of humans along with the potential of altering atmospheric balance and hence is increasingly addressed through policy measures at national and international level.

Air pollution is a policy challenge owing to various factors (World Bank 2008). Multiple sources of emissions from different sectors make it difficult to implement proper sectoral controls which further increase complexity in proposing a policy solution (Dominici et al. 2010). Inter and intra state transport of air pollution makes it have a greater impact on regions downwind of pollution sources. This decreases the willingness of the emitter regions to invest in mitigation, both at national and subnational levels. The transboundary nature of air pollution makes it imperative to have cooperation and collaborations on different spatio—temporal scales at international, national level, and sub national levels to find effective strategies for mitigation. Multiple policy solutions have been proposed over the years in response to gradually and sporadically deteriorating air quality in different parts of the world (Saxena and Sonwani 2019a). The two air pollution categories, gradual increase over the years and extreme events, require different framework for mitigation. Additionally, extremities in air pollution can result from events with regional (volcanic eruptions, wide scale fires, dust storms, etc.) and local (local forest fires, dust storms, agricultural burning, industrial emissions, etc.) implications. Sporadic events require prior preparedness to avert the predicted disaster. Policies to that end need deliberations that ensure consensus building ahead of time in order to avert the predicted air quality extremes. However, the sporadic nature of some of those events, especially from natural sources, makes it a bigger challenge to address extremities in air quality deterioration through policies. This chapter provides an overview of the international and regional cooperation that has resulted from the collective need to address air pollution, from time to time. Specifically, it covers policies framed around criteria and noncriteria pollutants, including SO_2, NO_X, O_3, dust, etc. It also includes the reasons for the success or failure of policy solutions adopted internationally. Institutional framework for guiding mitigation is contextual to consensus building on decision ready science in global and regional mitigation. For India, the role of measures taken to address growing air pollution and response to extreme events, and their implementation within a federal framework are discussed. Although, there exist multiple policy mechanisms for addressing different air quality and related extreme events, their effectiveness is determined by coordination between different stakeholders including government, scientists, policy experts, and the public toward ensuring compliance and measures to curb emissions (Saxena and Sonwani 2019b).

17.2 Global Actions Toward Air Pollution Control

17.2.1 United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP)

Early in 1960s, “acid rain” was identified to be harmful for the forest and water ecosystem that affected trees and fish in the northern hemisphere. Air pollution from emissions thousands of kilometers away from the affected regions was responsible for the acid rain events. Scientific evidence indicated that emissions in continental Europe were causing acidification of Scandinavian lakes (UNECE 1979). The 1972 United Nations conference on Human Environment in Stockholm called for international collaborations to address the issue. In the following years, scientific evidence provided a basis to support the hypothesis that local air pollution could have global environmental implications. As a result, first multilateral agreement to address transboundary air pollution materialized in the form of Convention on Long-Range Transboundary Air Pollution (LRTAP) in 1979 (UNCLRTAP 1979). Initially, 32 countries came together to form a regional framework to address transboundary air pollution and build scientific knowledge about the phenomenon. It was established with active engagement of Europe, North America, and Russia and former East Bloc countries. This was the first international accord that was legally binding wherein air pollution abatement through scientific research and policy solutions was planned on a regional scale.

Over the years, the objectives of the convention have broadened and include more pollutants that negatively affect human health and natural ecosystems (Wettestad

2001). It is a successful example of international and intergovernmental cooperation on issues of local emissions that have a far-reaching impact. At present, there are eight protocols that identify specific measures that need to be taken to reduce emissions. Under the convention, regional cooperation to pool resources for tracking emissions and modeling and measurements exercise is facilitated. Institutional framework under LRTAP has contributed to the decline in emissions of criteria air pollutants in the region. Efforts under the convention have resulted in decrease in sulfur emissions in the region and progressively decoupled economic growth from increasing pollution trend. Collective effort under the convention has been significant in achieving 40–80% reduction in emissions of harmful pollutants (US Department of State). As a result, atmospheric acidic deposition has also reduced and resulted in lower critical loads of acidity in Europe. There has been a drop in nitrogen emissions but not to the same extent as the drop in sulfur emissions. This is attributed as the cause of existing problem of acidity in the forests in Europe (Michel and Seidling 2016). Another accomplishment of the convention has been in controlling lead emissions by nearly 80% between 1990 and 2012 (Lorenz and Becher 2014). The highest reduction rates were reported in the initial period of compliance with the framework, in countries like Finland, Denmark, Spain, Germany, etc. (UNECE 2015).

Following is a brief account of protocols within UN CLRTAP, which provide controls for sulfur, NOx, and ozone emissions:

17.2.1.1 Helsinki Protocol for Reduction of Sulfur Emissions

In 1985, Helsinki Protocol for reduction of sulfur emissions was adopted by the Executive Body of CLRTAP, in Helsinki, Finland (Oslo Protocol 2021). It aimed at a 30% reduction in emissions of sulfur oxides in the atmosphere and their transboundary fluxes (Ringquist and Kostadinova 2005). The base year relative to which the reduction was planned was 1980. Under the protocol, all the signatory parties were obliged to develop strategies at national level, including action plan and programs to target reductions as pledged under the international accord. Additionally, the parties were also required to assess the need for reductions further than what the target laid out under the protocol (Aakvik and Tjøtta 2011). Other protocols addressing reduction in sulfur emissions include the 1994 Protocol on Further Reduction of Sulfur Emissions and 1999 Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone.

The 1994 Oslo Protocol for Further Reduction of Sulfur Emissions came into force in August 1998. It adopted an effects-based approach for planning emissions reduction by Parties to the Protocol. The additional feature of the protocol includes an Implementation Committee consisting of eight parties that is responsible for conducting a period review of compliance and proposal of constructive solutions in cases of noncompliance.

17.2.1.2 Sofia Protocol for the Control of Emissions of Nitrogen Oxides or Their Transboundary Fluxes

The Sofia Protocol for the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes was adopted in 1988 in Sofia (Bulgaria). The protocol established emissions reduction targets for nitrogen oxides with 1987 as the reference year. United States was the only country that chose emission target reduction with respect to 1978. The protocol additionally laid out an effects-based approach wherein the assessment of impacts on affected regions requires scientific analysis and research. It also targets reduction in ammonia and VOCs for their role in eutrophication, photochemical smog, and impacts on human health (Mosier et al. 2002).

17.2.1.3 The 1999 Gothenburg Protocol

The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone in Gothenburg (Sweden) was adopted by the Executive Body in November 1999 (Gothenburg Protocol 2021). Based on scientific research, this is an important protocol that sets limits on emissions on four pollutants—sulfur, NOx, VOCs, and ammonia. The limits sets were negotiated based on severity of emissions and their impacts and the resources available for mitigation (Vestreng et al. 2007). Strict limits on emission pertaining to specific sectors, like industries, electricity, dry cleaning, and vehicles are set. Best available technologies have to be deployed to meet emission limits with the help of collective resources and economic instruments available through the protocol. Upon its full implementation, the protocol would achieve 63% reduction in sulfur emissions, 41% in NOx emissions, 40% in VOC emissions, and 17% in ammonia emissions compared to 1990, in Europe (UNECE).

17.2.2 Montreal Protocol

Montreal Protocol is regarded as one of the most successful international environmental treaties which achieved its objective of prevention of ozone depletion by banning the production and use of ozone-depleting substances that include CFCs, HCFCs, and halons (Montreal Protocol 1987). It is an example of unprecedented level of coordination and commitment shown by the international community. There are many reasons accorded to its success with effective leadership that facilitated collaboration between developed and developing nations being at the helm. Initially, the science on the ozone-depleting phenomenon was not definite and initial estimates of depletion were highly underestimated. Thus, to begin with the framework was modestly designed and was highly flexible to increase or decrease controls as the science developed. With this flexibility, additions were made to the list of chemicals which were to be completely banned rather than being partially phased out (Green 2009). This arrangement built greater confidence in the process. The protocol could achieve a wide scale ratification by putting trade restrictions on countries in the supply chain of banned substances. So, once the producer countries ratified, the consumer countries also followed suit fearing losing trade of the limited supply.

Another reason for the success of the protocol was taking "precautionary principles" even when the science was not fully developed. The approach of common but differentiated responsibilities was also adopted with developing countries given more time to phase out the substances. Another reason for its success was identification of the chemicals and sectors which enabled governments to prioritize actions under the accord. It also provided a framework for long-term planning and innovation in the industry (Velders et al. 2007). It proved to be doubly beneficial as technological innovation led to the production of nonozone-depleting alternatives which had zero global warming potential unlike their former counterparts. Timely assessment and support for compliance also encouraged countries toward early transition using cleaner alternatives.

In 2016, Kigali amendment to the Montreal Protocol was introduced in Kigali, Rwanda. According to this amendment, timelines were proposed for countries to freeze and phase out the production and usage of hydrofluorocarbons (HCFCs) (Kigali amendment, UNIDO 2021). Although, HCFCs do not cause ozone depletion but have a very high greenhouse potential and contribute to climate change. If fully implemented, the Kigali Amendment can prevent 80 gigatonnes of carbon dioxide equivalent (GtCO2eq) being added to the atmosphere by 2050, equated to a reduction of 0.5 °C by the end of the century compared to business as usual (Heath 2017; Polonara et al. 2017; Montreal Protocol 2021).

17.2.3 UN Coalition on Combating Sand and Dust Storms

Sand and dust storms (SDS) are a natural phenomenon linked with land, soil and water management, and climate change. They have the potential to negatively impact the environment by reducing visibility and damaging infrastructure, agriculture, industry, and human health (Sterk et al. 2012). Parts of Africa and the Middle East experience very intense dust storms known by different names such as sirocco, haboob, yellow dust, white storms, and the harmattan. In India, they are referred to as "aandhi". Most active dust sources are found in dry and arid climate zone but can develop anywhere as a result of human influences (Wiesinger et al. 2016). The fluctuation in their intensity and magnitude makes them highly unpredictable and challenging for accurate forecasts.

In 1994, the UN Convention to Combat Desertification (UNCCD 1994) came into being as a binding international legal agreement that linked environmental sustainability directly with developmental pathways adopted in different countries (UNCCD). The Convention focuses on sustainable practices with respect to land use, soil and water management in the arid and semiarid regions, also known as drylands, which are the source regions for dust storms. They also host the most vulnerable ecosystems and peoples accustomed to living in a special habitat. The convention has been ratified by 197 countries. Out of these, some 151 are directly affected by SDS and 45 are recognized as source regions. Poor ecosystem management can create dust sources in any environment. Land degradation and climate change-induced droughts can impact severity and duration of SDS. Thus, the key to mitigate SDS is sustainable developmental planning. Under SDS agreement, parties have to (1) integrate mitigation measures into the subnational, national, and regional implementation of the convention; (2) enhance preparedness and resilience of vulnerable ecosystems and populations to the adverse and negative impacts of SDS; and (3) strengthen multistakeholder platforms and regional initiatives that contribute to addressing SDS. The Global SDS Source Base map developed by the UNCCD secretariat in collaboration with UNEP and WMO provides information for policy development and implementation including risk and vulnerability assessment, modeling, forecasting and early warning, impact, and source mitigation.

17.2.3.1 World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS)

The WMO sand and dust storm project was initiated in 2004 and its Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) was launched by the Fifteenth World Meteorological Congress in 2007 (UNEP 2016). The main objective of the advisory is to help increase the country's ability in timely and accurate forecasts of dust storms. It also provides support for building observation networks and dust storm modeling. International partnerships involving research communities help in knowledge exchange in the affected regions (Nickovic et al. 2015).

17.3 India-Specific Policy Response

India is one of the first countries to include an amendment in the constitution that holds the state accountable for improving and protecting the environment to safeguard public health, wildlife, and forests (Bhave and Kulkarni 2015). The 42nd constitutional amendment adopted in 1976 was in response to the commitments made for managing air quality and natural resources in the country at the Stockholm conference on Human Environment in 1972 (1). Along with the national commitments for protection of the environment, improvement in air quality was also ensured under the Directive Principles of State Policy (Article 48-A) 38 and Fundamental Duties (Article 51-Ag) 39 under the Constitution of India (1). Right to clean air has also been recognized as a part of the right to life under Article 21 of the Indian. The legal provisions guaranteed by the constitution provide a template for policy solutions to different temporal and spatial scales of air pollution that the country engages to address.

Addressing various scales of pollution, the Air (Prevention and Control of Pollution) Act was formulated in 1981. This was the first act that explicitly addressed prevention, control, and abatement of deteriorating air quality in the country. This act came into being in response to the commitment to ensure better air quality made at the international platform, the Stockholm Conference 1972. Under this act, the Central Pollution Control Board (CPCB) was set up with the objectives of monitoring air pollution as India adopted a developmental path in the following decades.

What followed was the sister act, called the Environmental Protection Act 1986. This act was the umbrella act that included protection of environment in general and leads to the formulation of other related rules and laws. The notification for lead free petrol and use of catalytic converters in vehicles to reduce tailpipe emissions was ensured through this act (6). These two provisions are setting stage for present day and future regulations for air quality mitigation in the country. Following is a discussion on the existing policy measures that ensure management and control of air pollution in the country.

17.3.1 The Climate and Clean Air Coalition (CCAC)

This is the first global arrangement aimed at air pollution mitigation involving collaborations between governments, civil society, and the private sector. It targets reduction of short-lived climate pollutants emitted from multiple sectors. It aims at mitigation of near term climate change by providing a platform for devising collective solution through knowledge and resource sharing. The coalition was initially focused on reducing emissions of methane, black carbon, and HFCs, but soon realized the importance of short-lived climate pollutants to support action on greenhouse gas reduction. The objectives under the coalition will be achieved by building national and regional actions and building capacity for mitigation; by raising awareness about the short-lived climate pollutant and their impacts; by promoting best practices and sharing successful examples of control and mitigation; building scientific knowledge for effective actions (CCAC).

17.3.2 National Clean Air Program (NCAP)

The National Clean Air Program (NCAP) was launched by the Ministry of Environment, Forests, and Climate Change in 2019 as an urgent response to curtail and control growing air pollution levels in the country (NCAP 2019). Under NCAP, reduction in air pollution levels in cities is proposed by enabling better monitoring and cross-sectoral collaboration of agencies that can help mitigate the problem. The plan seeks to achieve a 20–30% reduction in concentrations of particulate matter, PM_{10} and $PM_{2.5}$, by 2024, compared to 2017 levels. Initially launched as a 5 year plan, it can be extended if the required outcomes are not achieved in the stipulated period.

17.3.2.1 Structure and Functioning

NCAP seeks intersectoral collaborations and coordination between different ministries and government bodies that are responsible for managing different air pollution emission sources. These include the Ministry of Road Transport and Highway, Ministry of Petroleum and Natural Gas, Ministry of New and Renewable Energy, Ministry of Heavy Industry, Ministry of Housing and Urban Affairs, Ministry of Agriculture, Ministry of Health, NITI Aayog, Central Pollution Control Board (CPCB), and the State Pollution Control Boards (SPCBs), and local bodies. Such cross-sectoral collaboration is also facilitated under the National Action Plan on Climate Change, initiatives on electric vehicles, the Smart Cities Mission among others. The program also seeks to enable partnerships between international organizations, leading technical institutions, philanthropic organizations, and experts from industry and civil society to accomplish its targets. Additionally, the plan incorporates sectoral interventions for control of pollution from major sources including resuspended road dust, vehicular sector and industrial emissions, waste burning, and agricultural residue burning.

17.3.2.2 Challenges

While NCAP is mandated by the central government, the program is very city focused. The 102 nonattainment cities that fail to meet air quality standards for criteria pollutants are required to develop city-specific action plans for air quality control. The plan also entails a budgetary allocation of Rs 300 crores for helping cities build required action plans in the first 2 years. Analysis of the plan by the Center for Energy, Environment, and Water (Ganguly et al. 2020) sheds light on the inherent weaknesses in its implementation. The report shows that the city level plans, prepared in short spans of only a few months, define measures to combat pollution, however lack timelines and priorities in achieving them. Delhi is the only city with a clear legal mandate for implementation of the program, notified by the Supreme Court. Target areas listed for mitigation of pollution in cities fall under several agencies which could result in fragmented accountability. Implementation and timely completion of the program could be jeopardized as a result of poor financial standing of urban local bodies and municipal corporations overlooking the mitigation activities. In the absence of national emission inventory and standard protocol for reporting air pollution emissions, uniform emission targets cannot be set for the country, which would hinder city level source reduction.

17.3.2.3 Key Takeaways

The NCAP is the first effort toward fighting air pollution at the national level, adopting a bottom-up approach starting with city scale mitigation plans involving sector-specific interventions. It also brings together multiple agencies for the first time to collaborate on the issue and coordinate the required measures. However, the city-specific plans need to be more defined in their target setting and timelines for achieving the goals of NCAP. The role of SPCBs in mapping out hotspots within the city by augmenting ground monitoring needs to be supported (Sharma and Singh 2017). NCAP currently does not include a mechanism for quantification of the impact of interventions. Rigorous scientific assessment will have to be carried out to test the impact of the proposed mitigation under the policy. The program sets an example for furthering evidence-based policy solutions for sustained actions to target air quality improvement in country.

17.3.3 Graded Response Action Plan (GRAP) in the National Capital Region (NCR)

National Capital Region (NCR) experiences pollution spikes during winter season owing to increased emissions from periodically active source, namely paddy residue burning, in the neighboring states of Punjab and Haryana. Unfavorable meteorological factors like low boundary layer height and absence of precipitation trap the toxic emissions closer to surface making air quality sore along the Indo-Gangetic Plains (IGP) (Bhatta et al. 2016; Sharma and Kulshrestha 2014). This episode coincides with the festive season of Diwali which also records a spike in criteria pollutants from a few days of firecracker use marking the festivities. Combined effect of agricultural fires, use of firecrackers, and already high emissions, from industrial, vehicular, and residential heating sector, in the region make air pollution surge in this period. Marked at the onset of winters, the increased emissions have led to lingering smog experienced in the NCR in the past couple of years (Tiwari et al. 2018).

Responding to the situation, the Ministry of Environment and Forest, under the directive of the Supreme Court of India in 2016, notified the Environment Protection Control Agency (EPCA) to implement the Graded Response Action Plan (GRAP). The measures under GRAP were notified in 2016 and formulated in 2017; it is the first plan that institutionalized emergency response in case of grave air quality in the NCR. It was an emergency measure proposed to curtail the wintertime air quality deterioration with extremely dangerous air quality recognized under a new category of Air Quality Index (AQI) as "Severe +" or "Emergency" (REF). This emergency response has been prepared by the active engagement of the government officials, scientists, health experts, civil society group, and the judiciary. It is the first plan that has been successful in bringing together multiple agencies responsible for providing a solution to the problem including—pollution control boards, industrial area authorities, municipal corporations, regional officials of the India Meteorological Department, and others. Coordination between the state governments in Delhi, Haryana, Rajasthan, and Uttar Pradesh, states encompassing the NCR, is also provisioned in the plan.

Under GRAP, strict measures to immediately control harmful sources of criteria pollutants are implemented with the provision of penalizing the violators. The national and Delhi government appointed vigilance teams to ensure the plan's implementation and compliance. Some of the measures provisioned under GRAP when AQI is in "Severe+" include barring trucks, other than those carrying essential commodities, from entering Delhi; a complete halt in construction activities, implementing odd even policy for private vehicles, taking additional measures like shutting schools for the duration of high pollution on expert advice (GRAP, CPCB 2016). Applicable since 2017, in 2018, ban on diesel generators was implemented only in Delhi, but in 2019 it was extended to other NCR towns (TOI ref). Rural areas, however, were not included in this ban because of the unreliable power supplies in those areas. Air pollution control measures under other AQI categories described in the GRAP document include closing brick kilns, hot mix plats, banning use of Pet coke as fuel, shutting of Badarpur Power Plant, intensification of public transport and introduction of BS-VI fuel standards in Delhi, mechanized cleaning, and use of water sprinklers on road to control curbside dust resuspension, etc.

GRAP is the first action plan proposed for Delhi that guides action to curtail predicted extreme levels of air pollutants. As an emergency plan, it has been successful in fixing accountability through interagency cooperation and ensuring time bound action. Although, GRAP is a successful example showcasing feasibility of coordination between multiple stake holders on the issue, severity of pollution episodes is still a matter of concern (REF) pointing at a similar provision for long-term pollution mitigation (Gulia et al. 2021).

17.3.3.1 National Policy for Management of Crop Residues

Crop residue burning in India is recognized as one of the major factors responsible for high air pollution levels along the IGP. Unfavorable meteorological conditions exacerbated by calm surface winds, low precipitation, high surface pressure, and low boundary layer height trap the pollutants close to the surface at the onset of winters, leading to smog-like conditions affecting major cities, including Delhi, along the IGP (Guttikunda and Gurjar 2012; Saxena et al. 2021). Over the years, stubble burning in the rice fields of Haryana and Punjab majorly, has become a cause of concern. Use of new machinery for harvesting rice crop and the short window of two available for preparing the field for sowing wheat, generated standing stubble on fields. In the absence of cost-effective alternatives, farmers resort to burning the stubble and the smoke plume generated travels all the way along the IGP. This plume leads to green house gas emissions along with the emissions of other trace gases and aerosols including CH_4, CO, N_2O, NO_2, and other hydrocarbons and large amounts of particulate matter.

The policy (NPMCR 2014) to manage crop residue seeks technical and policy interventions to alleviate the issue in the respective states. It states its objectives as: (A) controlling crop residue burning to prevent loss of soil nutrients and minerals by in situ management of crop residue. (B) It also aims at diversified use of crop residue for various purposes like charcoal gasification, power generation, as industrial raw material for production of bio-ethanol, packing material, paper/board/panel industry, composting and mushroom cultivation, etc. (C) Outreach and awareness about the ill effects of the process. (D) Finding technical and policy solution to address the issue in the long run. The policy seeks to achieve this objective through—(1) Promotion of technologies that would guarantee optimum utilization and in situ management of stubble. (2) Use of residue for other purposes like power generation, as industrial raw material for production of bio-ethanol, packaging material for fruit, in paper pulp manufacturing, biogas generation, etc. (3) Capacity building of stakeholders to opt for alternatives. (4) Suitable laws and incentives enabling farmers to opt for better machinery and participate in public-private partnerships. The policy also proposes a monitoring mechanism at the national level to ensure that alternative measures are adopted and burning incidences reduced.

Institutional challenges for effective mitigation of air pollution through policies:

Despite the provisions to control and abate air quality deterioration in India, there exist institutional challenges that slow the pace of mitigation actions.

(a) In India, it is imperative that the policies adopt a bottom-up approach to effectively target the root cause in each sector. Currently, most of the policies operate in a top-down model which ignores the specificities of the problem and root cause of emissions at the point of emission. For example, in designing crop residue burning policies, farmers should be recognized as a major stakeholder and their participation in the process be ensured.
(b) Public engagement in the issue is missing. The democratic demand for clean air has to be ensured through participation of the common man. Policies should be inclusive of the outreach programs to ensure that the common man's representation while addressing air pollution as a public health issue.
(c) Stringent implementation of the policies, laws, and rules needs to be ensured in order to meet clean air targets at the subnational and national level. Regular monitoring and review of the existing structure should be carried out for efficient policy actions. Also, the laws need to be more composite and adopt a multipronged approach to ensure maximum cobenefits.

17.3.3.2 Way Forward

Air pollution remains a grave environmental problem having larger adverse impacts on the developing countries with limited resources to mitigate the problem. There exist several international and national policy mechanisms that have paved a way for devising control strategies based on scientific solutions. However, these policy actions have not always been a win-win owing to the complex nature of the problem involving multiple sectors and stakeholders, including governments. Learning from successful examples of coordinated implementation and timely achievement of objectives, as in the case of Montreal Protocol, it is imperative to build institutions that mature in their approach as the science on the issue develops. This is particularly applicable in the case of air pollution extremes experienced in India in the winter season, where it is crucial to look for technological innovation while enduring coordination between multiple agencies. Policy solutions can be more effective if they are informed by decision ready science. The institutional and governance challenges to policy solutions are unique to the sectoral emissions and specific sources in each region locally. Even within India, provincial policies adopt a different approach than national policies to target specific sources within a given timeline. Similarly, chronic and extreme air pollution events call for adopting different frameworks. Also, existing policies, laws, and regulations point are the needs of review and increasing interdisciplinary nature of the mitigation measures while adopting a cobenefits approach. However, policy mitigation can be efficient only if the policies are all inclusive, built on a strong science foundation, and engage multiple stakeholders in the process to control and abate air pollution, globally and locally.

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18

Participatory and Collaborative Governance Approach for Management of Atmospheric Processes-Related Extremities

Kamna Sachdeva

Abstract

Management of atmospheric processes-related extremities is a challenging task for all kinds of regulatory authorities. It is a need of an hour to devise a methodology for which collaborative and participatory approach is important, so that micro limits of such extremities can be defined and identified. Unidirectional carrying capacity-based approach has been used by many researchers however multi-disciplinary, multidirectional approach is required where accountability should be in the core. Formulation of policies and its effective implementation with limited empowered work force is near to impossible; hence, bottom-up approach where decentralised and self-governance model is the only hope. The active and passive involvement of stakeholders is part of effective decision-making process, government agencies need people's participation to manage public programs, its implementation and also for the mass awareness. The chapter talk through different approaches with national and international examples to understand effectiveness of participatory model. Participation of different stakeholders in decision-making process and managing the extremities is not straightforward process, hence role of training for state and non-state actors in this respect is important, for better governance and management.

Further to this, role of participatory approach as potential solution to atmospheric extremities and its evolution has also been discussed. Chapter deliberates on different steps of participatory approach and postulates of effective management and response networks for the atmospheric processes-related extremities (APE).

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Keywords

Atmospheric processes · Extremities · Governance · Stakeholders

18.1 Introduction

Atmospheric extremities are unexpected events which have an ability to cause great damage to people, resources and property. As per the Environment report 2020, almost 1300 deaths have been reported in India due to such events in year 2019 and out of which more than 50% of causalities reported to occur due to extreme rain events. Over the decade, these atmospheric extremities have increased many folds, cloud bursts and hail storms frequencies are important indicators of such extremities; hence, planning and coordination are important to minimise the damage (IPCC 2018). The chapter will provide insight of different aspects of governance of such events. The typical governance tools such as meteorological predictions, contingency funds and graded action plans are at place, but for managing the extremities may also need coordinated people's participation, which feeds to the system for better governance and management. The management of such events are not straightforward, because scientific uncertainties and conflicting interest can influence decisions. Hence, active participation of all the stakeholders and citizens in the policy cycle is must (Melica et al. 2018).

Participatory approach where people of the region are part of decision making is gaining acceptance to improve accountability, but in atmospheric processes people participation with self-governance is required (Richardson and Razzaque 2006). Here it is required that people participate in implementation of governance. The main pillars of participatory planning are communication, knowledge distribution, public learning, integration with different sectors and decentralisation of power. The management of APE demands the change of mind set of social and political systems to minimise the risk, people-centric growth model instead of GDP-based, should be promoted. All these pillars need to work together for managing atmospheric extremities such as smog events of Delhi. The smog event management is a success story that has brought all the stakeholders together for policy deliberation and to lead enforcement and implementation of the response plan. Although Delhi being capital, has advantage of having institutional and legal mechanisms at place which is utmost necessary for better governance. The figure describes the plausible steps which can fit into the governance model for managing **Atmospheric Processes-Related Extremities** (Fig. 18.1).

The integration of soft approach with other scientific approaches of risk assessment and management of atmospheric extremities needs planning and training (Palermo and Hernandez 2020). The public participation approaches change the governance model and make it more meaningful (Hernandez et al. 2018). When people start participating in decision making, then improvement in governance will takes place, although it may delay the process due to varied perception of stakeholders (Brink and Wamsler 2019).

Fig. 18.1 Steps involved in effective governance of APE

Arnstein (1969) has given ladder of people participation, which goes from simple manipulation level to full citizen control step. Based on Arnstein model, training on deciding optimum level of people participation is also important so that decision making will not be delayed. André et al. (2006) describe passive and active methods of participation, both are important for managing atmospheric extremities; however, both cannot be implemented at the same time. In passive approach of participation, stakeholders receive information and consulted. On the other side, active participation requires mediation, negotiation and invitation of collaboration. The case of Urban heat Island (UHI) management in Kuala Lumpur (Malaysia) is a good example where involvement of different stakeholders has provided best governance model of urban planning to manage this extreme event (Ramakreshnan et al. 2019). Here focus group discussions have been used as tool to acquire information of awareness level of policy makers on UHI. The outcome of the study indicates the relevance of awareness and knowledge creation among non-government and government actors for effective policy making and urban management practices.

18.2 Rationale and Objective

The first and foremost objective of any kind of regulatory decision is to protect public interest and empowered public with adequate knowledge related to the impacts and risk. In planning and management of atmospheric extremities, the range of solutions viz, public participations, formation of review boards, aim to provide theoretical perspective of participatory and collaborative governance for such events has been adopted. Over the period this has been realised that risk aversion and damage reduction can only be possible by public awareness and adequate knowledge of the process. The enabling environment, organisational development and social participations to promote such instruments are required for effective management of APE. The motivation of this work is to advocate public participation and public empowerment as participatory tool for management of atmospheric processes-related extremities.

18.3 Atmospheric Extremities

In the changing climate regime, atmospheric extremities and its governance has been subject of discussions. Atmosphere itself is dynamic in nature and its processes are interdependent on various feedback mechanisms operating in the system. Synergistic effect of ozone and PM2.5 concentrations is a major concern for various countries; many researchers are working on downscaled models to understand atmospheric extremities. Outputs of GCMs have been used to prepare regional level future emission inventories along with energy pathways to fully characterise the range of possible scenarios for future atmospheric extremities. Based on law of physics, we can predict state of atmosphere but management of its extreme behaviours needs integration of various disciplines such social sciences', human behaviour, community development and management and governance. Although before managing the extremities of atmosphere, we need to have effective predictions of deterministic nature of the atmosphere (Saxena and Sonwani 2019).

However, due to interconnectivity of varied and diverse sub-systems viz; environmental, health, society, etc., atmospheric extremities can become one of the systemic risks. In this kind of risk, inappropriate interactions and institutional setting may lead to disasters in anthropogenic systems. There are many theories such as catastrophe, theory of critical phenomenon and self-governance that have explained how the local failure of links may result in consequential failure of other links. Hence, strengthening of conscious decision making with the adequate public participation is important. Risks posed by air pollution and related disasters can be tackled in various ways, requirement is to provide a clear approach and controls at place to protect our society; however, such approaches generally fail, if community does not participate. First is to prioritise the awareness and provide education to the people about the associated risk and their consequences. The common man should be aware of the hyper-risk (interconnected risk) they are dealing with and the precautionary measures that could be taken in such a condition. Any kind of negligence or lack of governance and poor planning could result to worsen the condition of a hyper-risk. Hence, proper communication and well implementation of emergency response plan and graded action plans are quite essential to minimise the impacts. Information dissemination is a key for Participatory and Collaborative Governance.

Interconnected world has given us the good life as well as the depraved and dangers of the post-modern societies. To tackle the hyper-risks, a reflective response is much needed, including, an individual's knowledge about the process, creating an

Table 18.1 Management participation indexed with public participation spectrum or governance levels in context of air pollution management

Public participation spectrum	Goal of participation in management of APRE
Inform	Lower participation is expected, only unidirectional flow of information. Output and outcomes are not very effective (example AQI information for the public)
Consult and collaborate	This comes in middle level where government consults stakeholders and collaborates with them before implementation of the intervention. This is been seen in the case of stubble burning and associated emissions in Indo-gangetic plain. Farmers have been consulted by the local governments and try to collaborate with them for the solutions. One of the successful interventions is the use of agriculture residue in the biomass-based power plants developed in the vicinity of the problematic regions
Empowerment	This governance effort is at the highest level of the ladder, the self-governance and control of the situation by the active participation of the community is the example of such empowerment SPARE THE AIR the campaign. The program encourages participants to cut polluting activities, specifically in transport sector, in favour of less polluting alternatives. The self-governance model of participation falls in this category: a three-stage model where first stage is to capture perceptions and expectation of the people about any negative externality (viz, smog, bad air quality and storms, etc.), second stage is integration of participatory tool such as training workshop—this step is very crucial and involves two types of participatory approaches; knowledge sharing and willing to learn. Finally, in stage three, where effects and benefits of self-governance will be explained

organised and collective efforts with organised learning and promoting the research in the arena of interconnected risks like atmospheric extremities.

The table given below gives public participation spectrum in the context of atmospheric extremities, this explains at different levels what kind of involvement and participation from local public is required for the better management and risk aversion of extremities (Table 18.1).

18.4 Participatory and Collaborative Governance Model

Assessment of participatory tools is not an easy task but work of Van der Stroom (2017) has provided toolkit which makes it easy to assess, the broad participatory and governance framework is given below which is applicable in different extreme events, the effectiveness of the framework is directly proportional to the efforts of regulatory authorities to seek participation of stakeholders:

1. Communication and sharing of knowledge: It is important to exchange ideas and thoughts with other participants and the response of participants to each other.

This way information is processed and become usable for policy making (Patel et al. 2007; Pelzer et al. 2013).

2. Social Learning: Knowledge of local problems and strategies for the area, this process helps in reframing the perceptions (Pelzer et al. 2014; Reed et al. 2010; Volk et al. 2010).
3. Transparency: There should not be power difference this approach should empower stakeholders to raise voice (Goosen et al. 2007).
4. Integration: Stimulating integration between different contributing factors; this integration will provide better understanding of problem of particular area (Van der Stroom 2017; Volk et al. 2010).
5. Level of Agreement: Conflict resolution and giving consent on appropriate policy decision. This consent can, for example, be on to-be implemented strategies or projects (Hassenforder et al. 2015; Patel et al. 2007).

18.5 Models of Different Countries/Regions

18.5.1 European Union (EU) Model of Air Quality Management

EU's work on long-term benefit approach where main objective levels of air quality which do not harm or pose risk to human health and the environment. The EU acts at different levels to minimise impacts: through legislation; cooperation with sectors responsible for air pollution, as well as international, national and regional authorities and non-governmental organisations and research. The European Commission in 2013 adopted a Clean Air Quality Package which includes innovative measures to curb air pollution. The focused areas are:

- Public display of air pollution data and exceedances
- Trend analysis of air pollution and policy actions on curbing it in Europe
- Investigating the trade-offs and synergies between air pollution and policies in different areas, including climate change, energy, transport and industry

Clean air policy package of Europe

- An updated National Emission Ceilings (NEC) Directive, with emission ceilings for the years from 2010 onward, and new national emission reduction commitments from 2020 and 2030.
- A new Directive on Medium Combustion Plants, to limit emissions of nitrogen oxides, sulphur dioxide and particulate matter from medium-sized combustion installations. The directive proposes emission limit values for new and existing installations.
- Additional actions focusing on air quality in cities, national and local actions supported by EU funds, as well as a reinforced research and innovation agenda.
- It is people-centric package where transparency and accountability are the keys of success although legal binding in the periphery provides support to this approach.

18.5.2 China Model of Air Pollution Control

The control of Beijing's air pollution achievement can be attributed to its governmental structure in some extent and local sustainable development approach viz, strong willingness, clear goal, supportive legislation, plan and policies, implementation and enforcement arrangement United Nations Environment Programme (2019). Engaging the public in these objectives has strengthened environmental protection even further and increased social harmony. The former Beijing Municipal Environmental Protection Bureau recently reformed into Beijing Municipal Ecology and Environment Bureau (BEE) has integrated with more missions on promoting ecological civilisation. They are committed for blue sky, better environment and happy life for the people of the city. They have agenda to practice at local level with full efforts—to connect local goals with vision of 2030 sustainable goals. To establish effective air pollution management system, many policies and reforms have been implemented simultaneously such as subsidies, fees, pricing and other financial practices, to provide economic incentives for the effective implementation of various measures (Figs. 18.2 and 18.3).

Although great air quality improvement has been seen in Beijing but still it faces challenges to control future air pollution and related problems. The way out is continuous improvement of the atmospheric environment and more vigilant approach.

18.5.3 Indian Scenario of Participatory Governance

Air pollution is a big challenge in India; most of the cities violate regulatory standards. It is reported that IGP (Indo-Gangetic Plains) has higher concentrations of surface ozone and particulate pollution (Saxena et al. 2021). Owing to its geographical and agricultural significance, IGP is an important hotspot for analysing the impact atmospheric-induced extremities. The synergetic impact of changing climate and air pollution can make this region very vulnerable for meteorological-related extremities and disasters.

The traditional knowledge and local perspective are important for governments to take responsive decisions for the region. Lack of people participation is impediment for the government; hence, watchdogs through panchayats have been made to ensure participation. Over the period, centralised planning process has moved to participatory governance process in IGP specifically in framing communities of the region. Participatory planning and governance process are providing promising solutions to the climate- and atmospheric-induced disasters in the regions. The hopeful example which can be replicated in disaster management is Community Food and Water Security System which has been formulated by the local farming communities. The model is comprising of field Gene banks and seed bank: where focus is on life-saving crops, which restrain extreme temperatures and stress. Water bank: skewed rainfall is witnessed in IGP region, community driven self-help groups have been created for the promotion of water harvesting and equitable use of water in crisis

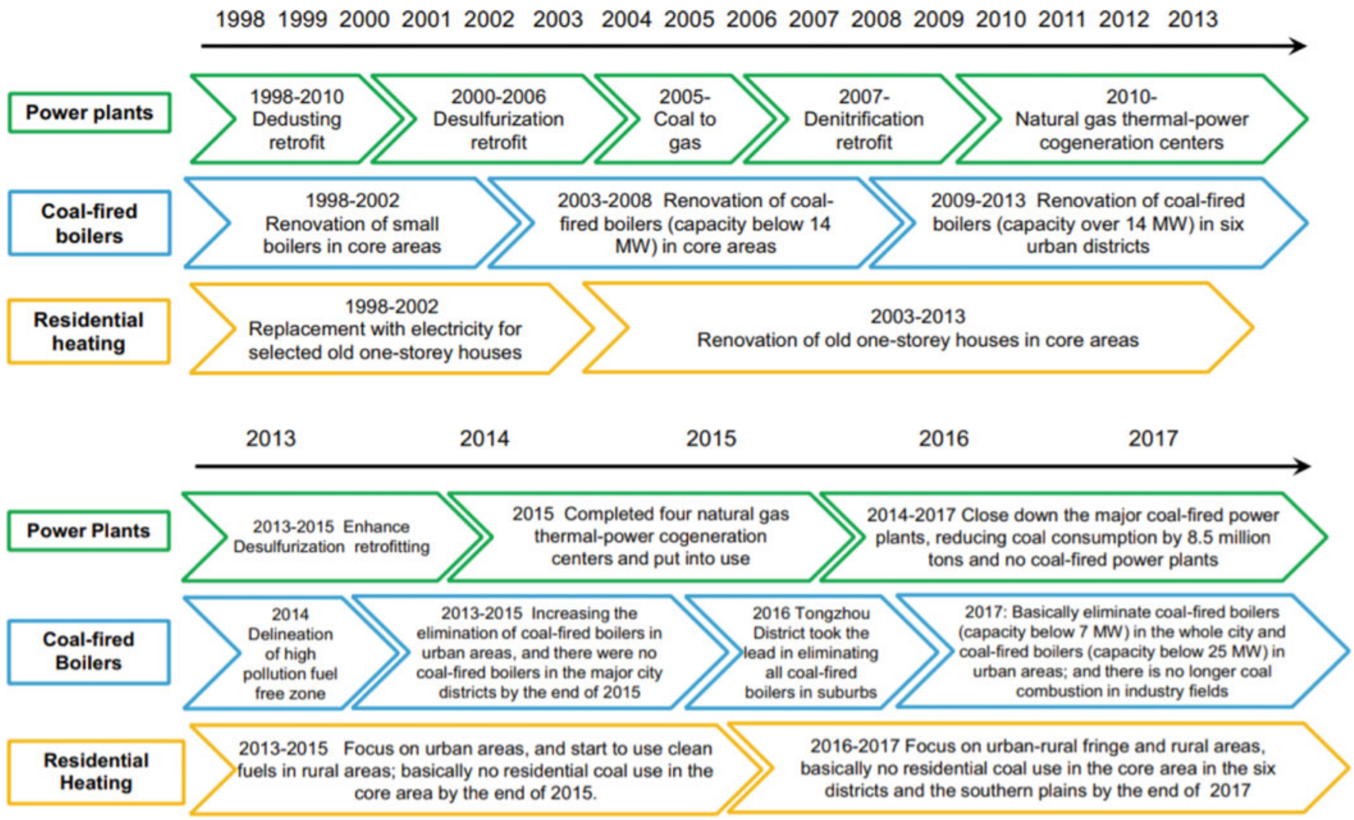

Fig. 18.2 Coal-based emission control measure in Beijing (1998–2017) (Source: Former Beijing Municipal Environmental Protection Bureau, Tsinghua University)

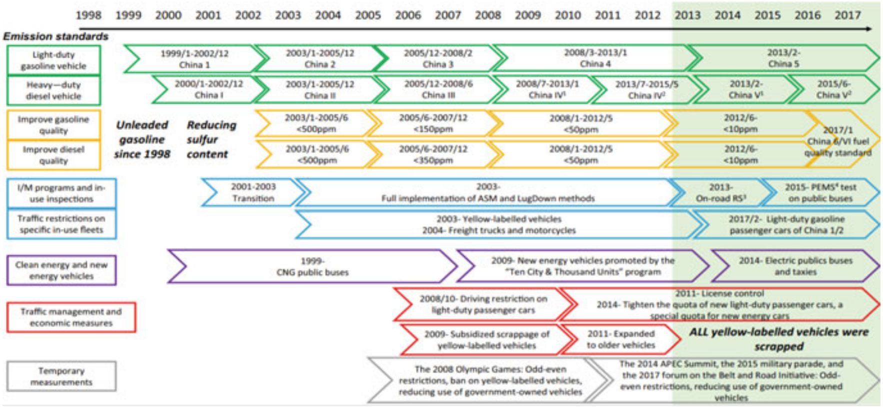

Fig. 18.3 Vehicular control measures review (1998–2017) (Source: Former Beijing Municipal Environmental Protection Bureau, Tsinghua University)

Table 18.2 Important initial steps required for the management-oriented outcomes for the governance of atmospheric extremities

Emission monitoring and advisories	⇨	Informed decision making
Timely and proactive scenario planning		Convincing of governments for action and release of funds for resilience planning

situation. Local level grain banks are another such example where community self-help groups are operated by revolving funds, this model provides sustainable food security in distress time.

18.6 Conclusion and Recommendations

As we know half of the world is facing problem of managing extreme atmospheric events, development drivers such as poverty, malnutrition and poor adaptive capacity pose additional threat to the governance. Even in the regions where economic growth and technological and innovation reforms are at place, finds it most challenging governance issue. Climate change is another driver which makes its management more complicated. Need is to mainstream all the atmospheric extremities in the discussion of climate change governance, else it will increase the cost of mitigation. We are at the stage where best efforts are unlikely to manage the threats of atmospheric extremities, as expansion of energy and urban systems is imperative. Hence, dedicated participatory and inclusive approach is required to protect the vulnerable population. The table given below is suggestive of such model along with steps given in table, citizen awareness and actions can build pressure on institutional mechanisms to act and respond. Non state actors' mobilization is important for better governance and management of atmospheric extremities. All these steps provide empowerment to the good governance system for action (Table 18.2).

In the nutshell, management of atmospheric extremities is a complex process, educating people and ensuring their participation is important. People need to understand how they are affected and what are available solutions for their problems. Government should take responsibility for ensuring the participation to make process inclusive. There is no dearth of access to information, the appropriate evidence based information can be used by the people for influencing the decision of government; hence, it is more effective for governance process to involve people at early stages of management.

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Glossary

Absorption Absorption is a chemical or physical process in which ions, molecules or atoms go in the bulk phase. It involves the transmission of a gaseous pollutant from the air in the water.

Adsorption In adsorption, the molecules of a fluid stick to the surface of a solid material called adsorbent. This method is commonly used to recover volatile solvents, i.e. benzene, toluene and chlorofluorocarbon, process gas streams drying and control the odour.

Aerosol Optical Depth (AOD) Aerosol Optical Depth (AOD) is the measure of aerosols (e.g. urban haze, smoke particles, desert dust, sea salt) distributed within a column of air from the instrument (Earth's surface) to the top of the atmosphere.

Aerosol It consists of very finely subdivided liquid or solid particles dispersed in and surrounded by a gas.

Air Pollution Tolerance Index (APTI) It is one of the important parameters that could be considered for the selection of traffic barrier plant species. It is an important tool to categorize plants based on their tolerances or sensitivity levels into air pollutants. APTI of plants has been described with four biochemical parameters: total chlorophyll, relative water content (RWC), ascorbic acid and leaf extract pH.

Anthropogenic Emissions The emissions which have their origin from man-made activities like vehicular exhaust, industrial activities, domestic activities, etc.

Antioxidant An organic compound that accepts free radicals and thus prevents the auto-oxidation of fats and oil.

Arid region A land region of low rainfall (less than 250 mm/year).

Atmosphere A gaseous envelope surrounding the earth. Atmosphere also contains clouds and aerosol.

Atmospheric Phenomena As commonly used in weather observing practice, an observable occurrence of particular physical (as opposed to dynamic or synoptic) significance within the atmosphere.

Atmospheric Processes Atmospheric processes play the lead role in determining such fundamental properties of climate as the disposition of incoming solar radiation, temperatures at the Earth's surface, the spatial distribution of water in

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the terrestrial biosphere and the distribution of nutrients in the euphotic zone of the ocean.

Bioaerosols Airborne particles produced from microbial, viral, fungal and actinomycete, as well as microbes from organic materials, humidifiers, vaporizers, heating, ventilating and air conditioning systems (HVAC) lead to allergies, infections and poisoning.

Biodiversity Number and relative abundances of different genes (genetic diversity), species and ecosystems (communities) in a particular area.

Bioindicators Bioindicators are living organisms such as plants, planktons, animals and microbes, which are utilized to screen the health of the natural ecosystem in the environment. They are used for assessing environmental health and biogeographic changes taking place in the environment.

Biomass Total mass of living organisms in a given area or volume; recently dead plant material often included as dead biomass.

Biomonitoring Biomonitoring involves the use of organisms to assess environmental contamination, such as of surrounding air or water. It can be done qualitatively by observing and noting changes in organisms or quantitatively by measuring accumulation of chemicals in organism tissues.

Biosphere The part of earth system comprising all ecosystems and living organisms in the atmosphere.

Carbon cycle The term used to describe the flow of carbon through the atmosphere, ocean, terrestrial biosphere and lithosphere.

Carbon sequestration The process of storing carbon dioxide. This can happen naturally, as growing trees and plants turn CO_2 in to biomass (wood, leaves and so on). It can also refer to the capture and storage of CO_2 produced by industry.

Chronic Obstructive Pulmonary Disease (COPD) Chronic obstructive pulmonary disease, commonly referred to as COPD, is a group of progressive lung diseases. The most common of these diseases are emphysema and chronic bronchitis. Many people with COPD have both of these conditions.

Cloud A visible mass of particles of condensed vapour (such as water or ice) suspended in the atmosphere of earth.

Coarse Particulate Matter They are also known as $PM_{10-2.5}$; particles with diameters generally larger than 2.5 μm and smaller than, or equal to, 10 μm in diameter. Note that the term **large coarse particles** in this course refers to particles greater than 10 μm in diameter.

Criteria Air Pollutants The criteria air pollutants include particle pollution, ground-level ozone, carbon monoxide, sulphur dioxide, nitrogen dioxide and lead. These pollutants can harm your health and the environment and cause property damage. Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. EPA calls these pollutants “criteria” air pollutants because it regulates them by developing human health-based and/or environmentally based criteria (science-based guidelines) for setting permissible levels.

Cyclone Separator It is a renowned technology that is primarily used for coarse and medium-sized particles collection. It works by downward forcing of a gasified suspension.

Dew Moisture condensed upon the surfaces of cool bodies especially at night.

Disaster Risk Management Disaster risk management is the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduces existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses.

Dissolved Organic Carbon Dissolved organic carbon is the predominant material that absorbs UV, and rapid attenuation occurs with moderate dissolved organic carbon concentrations (i.e. more than several mg C/L).

Dispersion Modelling Dispersion modelling uses mathematical formulations to characterize the atmospheric processes that disperse a pollutant emitted by a source.

Dobson Unit One Dobson Unit is defined as the number of molecules of O_3 required to create a pure O_3 layer of 0.01 mm thickness at a temperature of 0 °C and sea level (1 atm pressure).

Dry Deposition Primary and secondary particulates are removed by the gravitational force from the atmosphere over time without precipitation, this process is termed as dry deposition.

Dynamic meteorology Dynamic meteorology is usually referred to a meteorology study that focuses on fluid mechanism and thermodynamics of atmosphere since the atmosphere is considered as a continuous fluid medium.

El Nino El Nino is a climate pattern that describes the unusual warming of surface waters in the eastern Pacific Ocean. El Nino is the “warm phase” of a larger phenomenon called the El Nino-Southern Oscillation (ENSO).

Emission Inventory Emission inventory is an important tool for identifying the source of pollutants and quantitative expression of pollution load in a defined area at a particular time.

Environmental Hazard Environmental hazards are generally measured as exposure to pollution such as the amount of dust or sulphur dioxide in the air or the presence/amount of soil or groundwater contamination on the property.

Epidemiology Epidemiology is the branch of medical science that investigates all the factors that determine the presence or absence of diseases and disorders. Epidemiological research helps us to understand how many people have a disease or disorder, if those numbers are changing, and how the disorder affects our society and our economy.

Fine Particulate Matter It is also known as $PM_{2.5}$; particles generally 2.5 μm in diameter or smaller. This group of particles also encompasses **ultrafine** and **nanoparticles** which are generally classified as having diameters less than 0.1 μm.

Fog Fog is a visible aerosol comprising tiny water droplets or ice crystals suspended in the air at or near the Earth’s surface.

Glaze Ice coating that forms when supercooled rain, drizzle or fog drops strike surfaces that have temperatures at or below the freezing point; the accumulated water covers the surface and freezes relatively slowly.

Hail Precipitation in the form of small balls or lumps usually consisting of concentric layers of clear ice and compact snow.

Hydrometeors Hydrometeors consist of liquid or solid water particles. They may be suspended in the atmosphere, fall through the atmosphere, be blown by the wind from the Earth's surface or be deposited on other objects. Snow or water on the ground is, by convention, not considered a hydrometeor.

Indo-Gangetic Plain (IGP) It is also called **North Indian Plain**, extensive north-central section of the Indian subcontinent, stretching westward from (and including) the combined delta of the Brahmaputra Valley and the Ganges (Ganga) River to the Indus River Valley.

Indoor Air Pollution (IAP) Indoor air pollution is dust, dirt or gases in the air inside a building such as your home or workplace that harms us if we breathe it in.

La Nina La Nina, the “cool phase” of ENSO, is a pattern that describes the unusual cooling of the region's surface waters.

Lithometeor A conglomeration of small solid particles (as of dust or sand) that is suspended in the atmosphere and often produces a dry haze.

Mitigation An anthropogenic intervention for lessening, reducing and diminishing the climatic stress and harm caused by adverse effects of climate change. It includes strategies to reduce air pollutants sources and emissions.

Montreal Protocol Montreal Protocol is regarded as one of the most successful international environmental treaties which achieved its objective of prevention of ozone depletion by banning the production and use of ozone depleting substances that include CFCs, HCFCs and halons.

National Clean Air Programme (NCAP) It was launched by the Ministry of Environment, Forests and Climate Change, Government of India, in 2019 as an urgent response to curtail and control growing air pollution levels in the country.

National Health Adaptation Plan (NHAP) It has been designed and developed by the National Institute of Disaster Management, Ministry of Home Affairs, Government of India, to create enabling environment, build the capacity of climate resilient healthcare system; help institutions strengthen their preparedness, enhance the health system resilience in terms of universal health coverage; early warning, surveillance and community mobilization in the context of any health emergency risk management.

Particulate Matter (PM) PM stands for particulate matter and it is a mixture of solid particles and liquid droplets found in the air.

Quiescent Volcano A volcano, which is not active, but is still registering seismic activity. When there is no more seismicity, the volcano is dormant, but still capable of erupting.

Radiative Forcing Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in Wm^{-2}) at the tropopause or top of atmosphere due to a change in an external driver of climate change such as a change in the concentration of carbon dioxide or the output of the Sun.

Rain Water falling in drops condensed from vapour in the atmosphere.

Rime An accumulation of granular ice tufts on the windward sides of exposed objects that is formed from supercooled fog or cloud and built out directly against the wind.

Seamounts They are submarine volcanoes that are extinct and rise abruptly from the sea floor. Despite the fact that no big explosive undersea eruption is yet documented, prevalence of such eruptions is evident from ancient seafloor deposits.

Secondary Organic Aerosol (SOA) Secondary organic aerosol (SOA), formed in the atmosphere by oxidation of organic gases, represents a major fraction of global submicron-sized atmospheric organic aerosol.

Sink Any process, activity or mechanism which involves a pollutant gas or aerosol from the atmosphere.

Snow Precipitation in the form of small white ice crystals formed directly from the water vapour of the air at a temperature less than 32 °F (0 °C).

Source Any process, activity or mechanism which releases a pollutant gas, an aerosol or a precursor of a pollutant gas or aerosol into the atmosphere.

South Asian Monsoon It is an important segment of the tropical monsoon system that mainly lies in the range of the seasonal oscillations of the Intertropical Convergence Zone (ITCZ).

Thermal Inversion Thermal inversion is a natural phenomenon that involves a change in the normal tendency of the air to cool down with altitude.

Tracheobronchial region The tracheobronchial tree is composed of the trachea, the bronchi and the bronchioles that transport air from the environment to the lungs for gas exchange.

Ultrafine Particulate Matter Ultrafine particles (UFPs) are aerosols with an aerodynamic diameter of 0.1 μm (100 nm) or less. There is a growing concern in the public health community about the contribution of UFPs to human health.

Volcano A volcano is a rupture on the Earth's crust through which hot lava, volcanic ash and gases are spewed out during the course of the eruption from a magma chamber underneath the surface.

Wet Deposition Wet deposition is the process whereby atmospheric gases mix with suspended water in the atmosphere and are then washed out through rain, snow or fog.

Wet Scrubber They are used for the control of mists, fumes, heavy metals, acid gases, suspended dust and trace organics.