2 Atmospheric Phenomena: Origin, Mechanism, and Impacts

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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

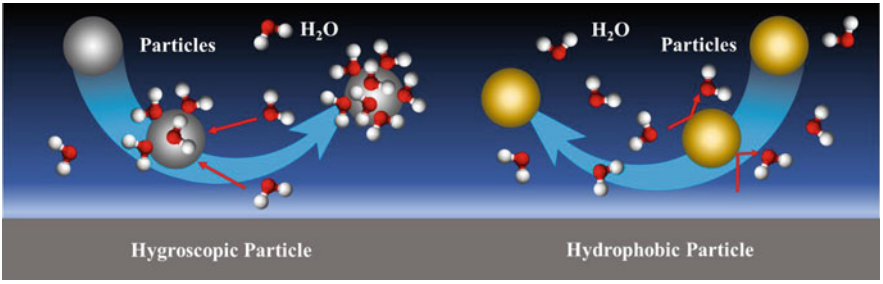

Fig. 2.1 Hygroscopic nuclei and hydrophobic nuclei (modified from: University of Arizona 2018a)

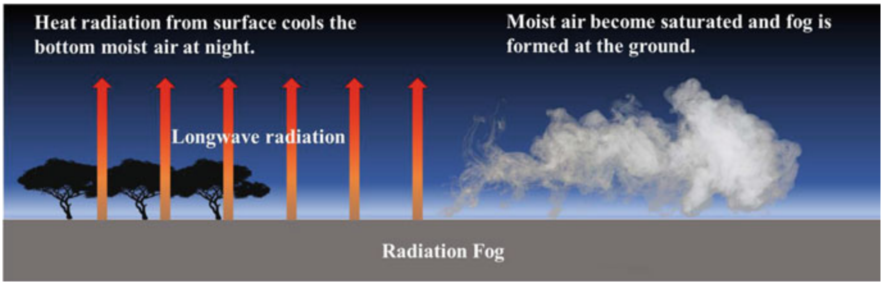

Fig. 2.2 The formation of radiation fog (modified from: Midwestern Regional Climate Center 2021)

(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).

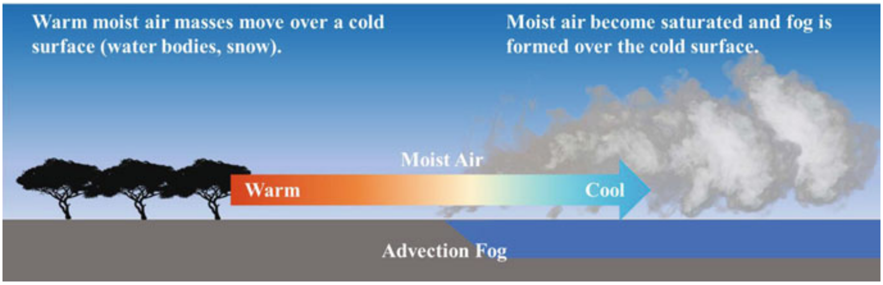

Fig. 2.3 The formation of advection fog (modified from: Midwestern Regional Climate Center 2021)

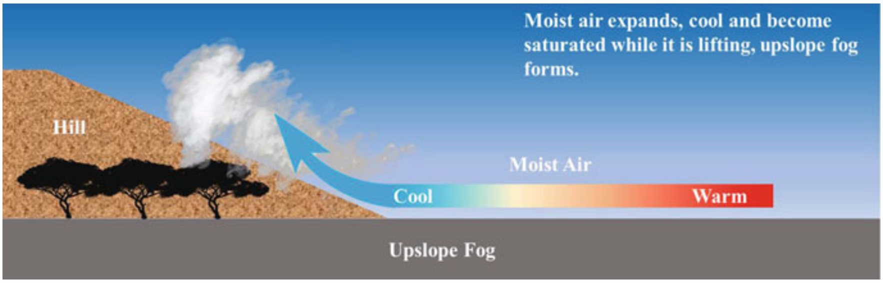

Fig. 2.4 The formation of upslope fog (modified from: Northern Vermont University n.d.)

"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

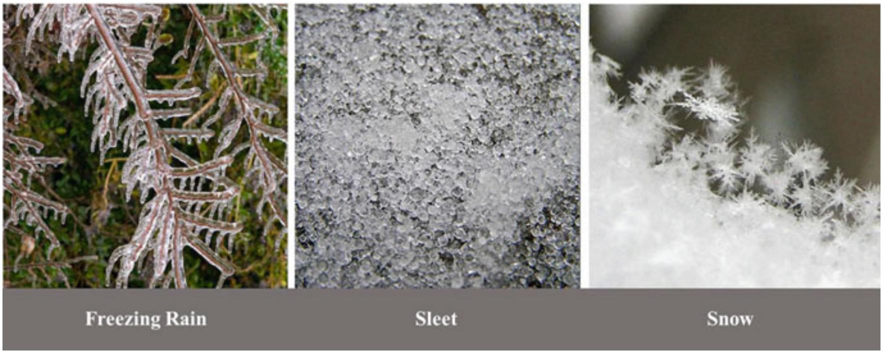

Fig. 2.5 Photo of freezing rain, sleet, and snow (NOAA 2015)

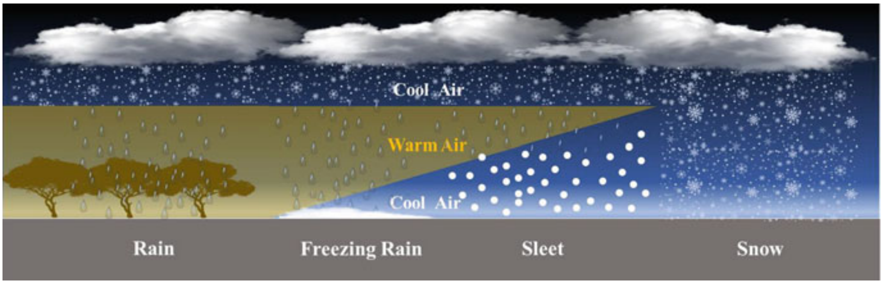

Fig. 2.6 Rain, freezing rain, sleet, and snow formation (modified from: NOAA 2013)

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

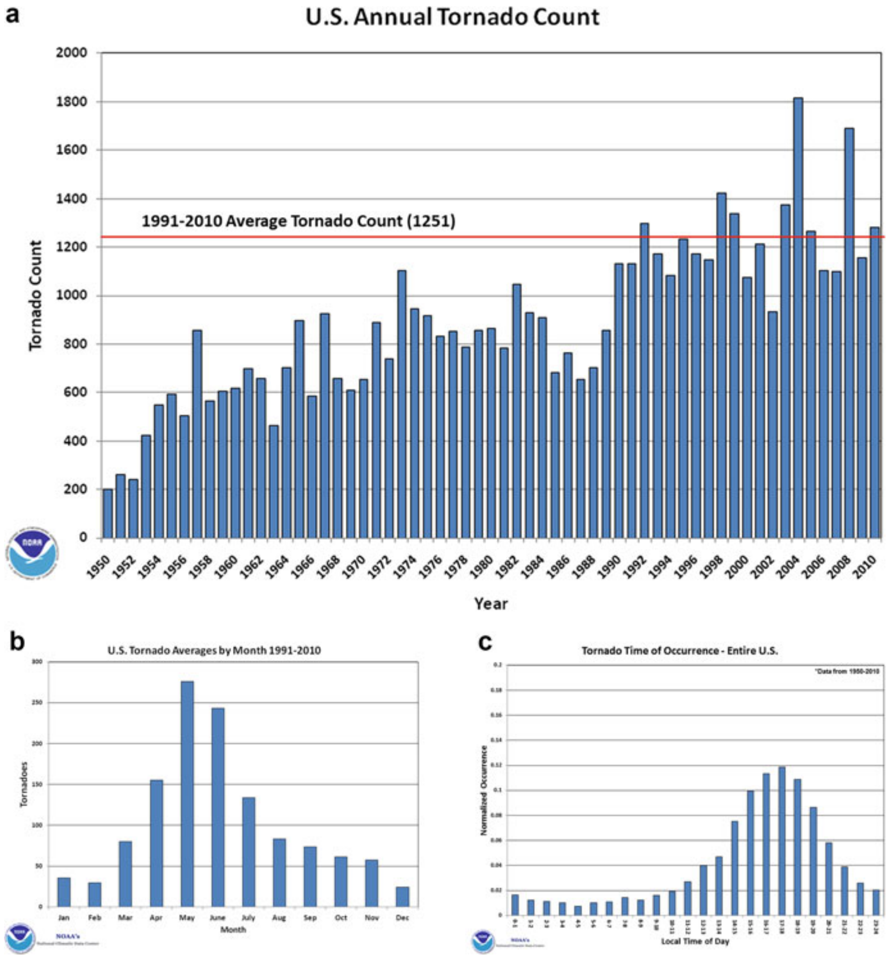

Fig. 2.8 Temporal distribution of Tornado count over the U.S. (**a**) from 1990 to 2019, (**b**) monthly average, and (**c**) daily average (NOAA 2019)

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)

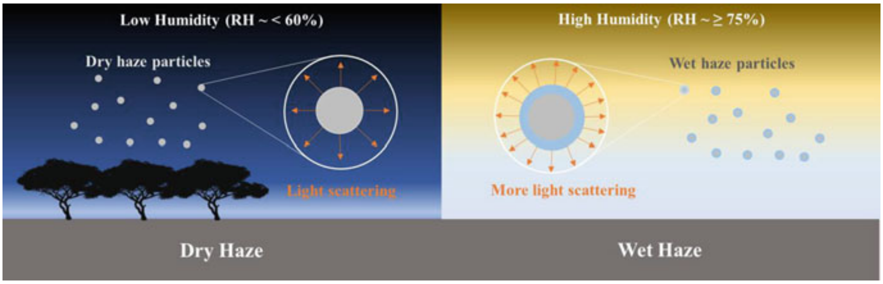

Fig. 2.10 The formation of dry haze with low relative humidity and wet haze with higher relative humidity (modified from: University of Arizona 2018b)

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

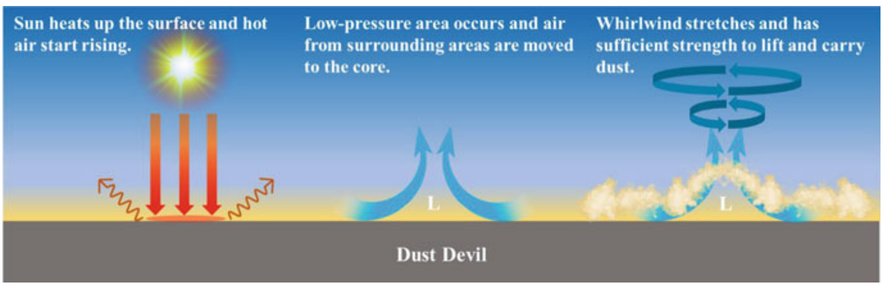

Fig. 2.11 The formation of dust devils (modified from: Gabbert 2019)

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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