Chapter 2
Air Quality in Changing Climate: Implications for Health Impacts

Sourangsu Chowdhury and Sagnik Dey

Abstract Poor air quality is a leading risk factor for global disease. Two major pollutants – fine particulate matter ($PM_{2.5}$) and surface ozone – are also linked to climate change. A unified framework to quantify the morbidity and mortality burden from air pollution exposure was developed in Global Burden of Disease Study. 1500 and 2200 premature deaths from ozone and ambient PM2.5 exposure can be attributed to past climate change (from pre-industrial era to present day). For the future, air pollution exposure can be quantified by four Representative Concentration Pathways (RCPs) emission scenarios in a modelling framework. In addition to the role of climate change in modulating air quality in future, the changes in socio-economic and demographic condition of the future population are also expected to determine the burden due to air pollution. These may be quantified using the demographic and socioeconomic drivers used in formulating the Shared Socio-economic Pathways (SSP) scenarios. Combining the SSP and RCP scenarios in a scenario matrix framework would lead to the estimate of premature mortality burden for the future within an uncertainty range that can drive the policymakers to exercise adequate mitigation measures, which are expected to facilitate a healthier and climate secure society in future.

Keywords PM2.5 exposure • Ozone exposure • Changing climate • Premature mortality burden • RCP scenarios • SSP scenarios

Air Quality, Exposure and Health Impacts

Chronic exposure to $PM_{2.5}$ and ozone leads to cardiovascular and cardiopulmonary diseases and lung cancer and eventually premature death of millions of people worldwide (Cesaroni et al. 2014; Krewski et al. 2009; Pope et al. 2002; Chen et al. 2008). Some studies have depicted evidence of premature mortality due to diseases like neurological disorders and diabetes from exposure to ambient $PM_{2.5}$ (Gouveia

---

S. Chowdhury (✉) • S. Dey
Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, Hauz Khas,
New Delhi, India
e-mail: sourangsu@cas.iitd.ac.in; sagnik@cas.iitd.ac.in

R. Akhtar, C. Palagiano (eds.), *Climate Change and Air Pollution*,
Springer Climate, DOI 10.1007/978-3-319-61346-8_2

and Fletcher 2000; Bell et al. 2004). Though the problem is fast growing in the developing world (West et al. 2016), health impacts of air pollution have been documented in the developed countries even at very low air pollution exposure (Shi et al. 2015). $PM_{2.5}$ is emitted from various natural and anthropogenic sources and its spatio-temporal variation is modulated by meteorology and topography. Global burden of disease (GBD) effort (Lim et al. 2012; Murray 2015) establishes a unified framework to quantify the morbidity and mortality burden of air pollution globally. Studies showing evidence of mortality and morbidity due to diseases like chronic obstructive pulmonary diseases (COPD), ischemic heart diseases (IHD), stroke, lung cancer, diabetes and acute lower respiratory infection from $PM_{2.5}$ exposure are mostly limited to the developed countries. To address this issue, an integrated exposure-response (IER) function (Burnett et al. 2014) was developed for risk estimation by incorporating exposure spanning across ambient air pollution, household air pollution, passive smoking and active smoking (Burnett et al. 2014). This risk function enabled comparative assessment of the burden of diseases from air pollution across the world (Arnold 2014).

Exposure to ozone primarily affects the lungs causing short-term changes in lung function and escalates respiratory syndromes (Bell et al. 2004, 2005). Chronic long-term exposure to ozone may result in permanent impairment of the lungs, damage of the tissues lining the airways and development of pulmonary fibrosis (Lin et al. 2008; Jerrett et al. 2009; Li et al. 2016). Tropospheric ozone exposure not only results in impairment of human health but also damages vegetation with substantial reduction in crop yield and crop quality (Morgan et al. 2006; Avnery et al. 2011). In India wheat production is impacted the most due to exposure to ozone with an estimated loss of 3.5 ± 0.8 million tons followed by rice and other cereals (Ghude et al. 2014). On national scale, the yield loss due to ozone exposure is about 9.2% of the cereals required every year under the provisions of the recently implemented National Food Security Bill (2013) by the Government of India. Climate change can further exacerbate the current situation as it has been projected that ozone exposure will increase in the future (Horowitz 2006). This may lead to food shortage, which in turn can cause malnourishment impacting the health indirectly. A study by Jerrett et al. (2009) followed up 448,850 subjects as a part of the American Cancer Society Cancer Prevention Study II for 18 years and found that the relative risk (which may be defined as the ratio of probability of an event occurring in an exposed group to the probability of an event occurring in comparison with nonexposed group) of death from exposure to ground-level ozone due to respiratory causes with a 10 ppb increase in ozone concentration was 1.040 (95% CI 1.010–1.067). A global study (Anenberg et al. 2010) estimated that about 0.7 ± 0.3 million premature death/year can be attributed globally to ozone exposure. Another estimate (Silva et al. 2013) used ACCIMIP model simulations to determine exposure to ozone, the mortality attributed to exposure to ozone for past climate change (1850 to present day) was estimated to be around 1500 (−20,000 – 27,000) deaths/year. An India-based study (Ghude et al. 2016) has used a chemical transport model to estimate the exposure, and the resulting premature death due to chronic obstructive pulmonary diseases was estimated to be ~12,000 using the 2011 census data for the exposed population. Premature mortality (Mort) is generally estimated as a function of exposed population (*Pop*), relative risk (RR) and the background mortality (BM) rate (Anenberg et al. 2010; Murray 2015; Chowdhury and Dey 2016; Silva et al. 2016) and can be expressed as in Eq. 2.1. RR can be estimated as a function of exposure to pollutants (Pope et al. 2002; Burnett et al. 2014).

$$\mathrm{Mort} = \mathrm{Pop} \times \mathrm{BM} \quad \times \frac{\mathrm{RR} - 1}{\mathrm{RR}} \tag{2.1}$$

Climate Change and Air Pollution

Since the Industrial Revolution, human activities have released huge amounts of carbon dioxide and other greenhouse gases (GHG) into the atmosphere, primarily from fossil fuel burning, to meet the energy demand of the growing population and industrial needs. Other activities like agricultural waste and solid fuel burning also contribute to climate-warming pollutants. Black carbon aerosol that is mostly emitted from incomplete combustion of fossil fuel, biofuel and biomass warms the atmosphere, which in turn influences the global and regional wind patterns, humidity and precipitation. Black carbon is also a major component of ambient $PM_{2.5.}$ Therefore, reducing black carbon has co-benefits to limit climate change and avert premature mortality burden. Changing meteorology under warming climate is expected to play an important role in modulating $PM_{2.5}$ by controlling its dispersion and life cycle due to changes in boundary layer depth, wind circulation pattern, precipitation frequency, relative humidity and temperature. Globally the climate is expected to become more stagnant in the future with weaker global circulation and decreasing frequency of mid-latitude cyclones (Daniel and Winner 2009). With increasing stagnation, the pollutants are expected to get piled near the surface thereby increasing the relative exposure. Increased humidity in the future can tend to influence local air quality at individual scale by diminishing ambient bio-aerosols (pollens, grains, spores and other aero-allergens) as they tend to clump together and become less respirable. Changes in precipitation pattern may also affect the aerosol scavenging. Wind speed and precipitation are projected to increase over India (Christensen et al. 2007; Menon et al. 2013) in the future under the warming climate. Although not much information is available about the projected mixing layer depth over India, it is expected that increasing temperature and wind speed will contribute towards expanding the mixing layer depth. It is implied that these projected meteorological factors in the future will contribute to escalated washout and ventilation. Thus we may expect that meteorology will partially help in reducing $PM_{2.5}$ exposure irrespective of the projected exposure strength in future.

Ozone is a secondary air pollutant formed in the atmosphere by photochemical processes in the presence of precursors like oxides of nitrogen (NO_x) and volatile organic compounds (VOC) which are mostly emitted by mobile vehicular sources (cars, trucks, etc.), industrial sources and natural sources like lightening, forest and grassland fires. In urban areas, power plants, industries, chemical solvents and vehicular emissions are the primary sources of the ozone precursors. In presence of sunlight, these precursors undergo chemical transformation to form ozone. The chemistry of ozone formation is temperature dependent and occurs in multiple number of steps. Methane (emitted primarily due to fossil fuel use, biomass burning, livestock farming, landfills and waste) which is one of the major components responsible for global warming is also one of the major components of VOC, but in urban settings, the non-methane volatile organic compounds (NMVOC) emitted generally outpace methane as the major component of VOC responsible for ozone formation. West et al. (2006) shows that reducing global anthropogenic methane emissions by 20% will avert around 30,000 premature deaths in 2030, and the cost-effectiveness of methane reduction is expected to be around $420,000 per avoided mortality (West et al. 2006). Thus it can be argued that mitigating methane emission can help to improve air quality globally bringing multiple benefits for air quality, climate, public health, agriculture and energy. With temperature projected to increase globally in the future (Daniel and Winner 2009), the ozone concentration is expected to escalate (Kinney 2008).

From Pre-industrial Era to Present Day

Since the pre-industrial era, human activities led to degradation of air quality across the globe. Measurements at various sites across the northern hemisphere indicate that surface ozone has increased by about fourfolds from 1860s to 2000s (Marenco et al. 1998). The change of surface concentration and exposure to $PM_{2.5}$ and ozone from the pre-industrial period to present can be attributed to multiple factors (Fang et al. 2013) – (a) changes in direct emissions of their constituents and precursors, (b) climate change induced changes in surface emissions, (c) the influence of increasing CH_4 concentration on tropospheric chemistry and (d) changes and transition in demographical features. Fang et al. 2013 have reported that global population-weighted $PM_{2.5}$ and O_3 have increased by about 8 ± 0.16 μg/m^3 and 30 ± 0.16 ppb, respectively, from the period 1860 to 2000 utilizing the Geophysical Fluid Dynamics Laboratory Atmospheric Model, version 3. Another study by Silva et al. (2013) used Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) group of models to conclude that global population-weighted $PM_{2.5}$ and ozone exposure increased by about 7.3 μg/m^3 and 26.5 ppb, respectively. Global mean concentrations of $PM_{2.5}$ and ozone in 1850 were estimated to be 11.4 μg/m^3 and 28 ppb, respectively, while the corresponding values in 2000 changed to 18.6 μg/m^3 and 54.5 ppb, respectively. Over the Indian landmass, mean concentrations of $PM_{2.5}$ and ozone increased from 14.3 μg/m^3 and 33.2 ppb, respectively, in 1850 to 22 μg/m^3 and 61.9 ppb, respectively, in 2000. The exposure over India and South Asia is generally underestimated by the global

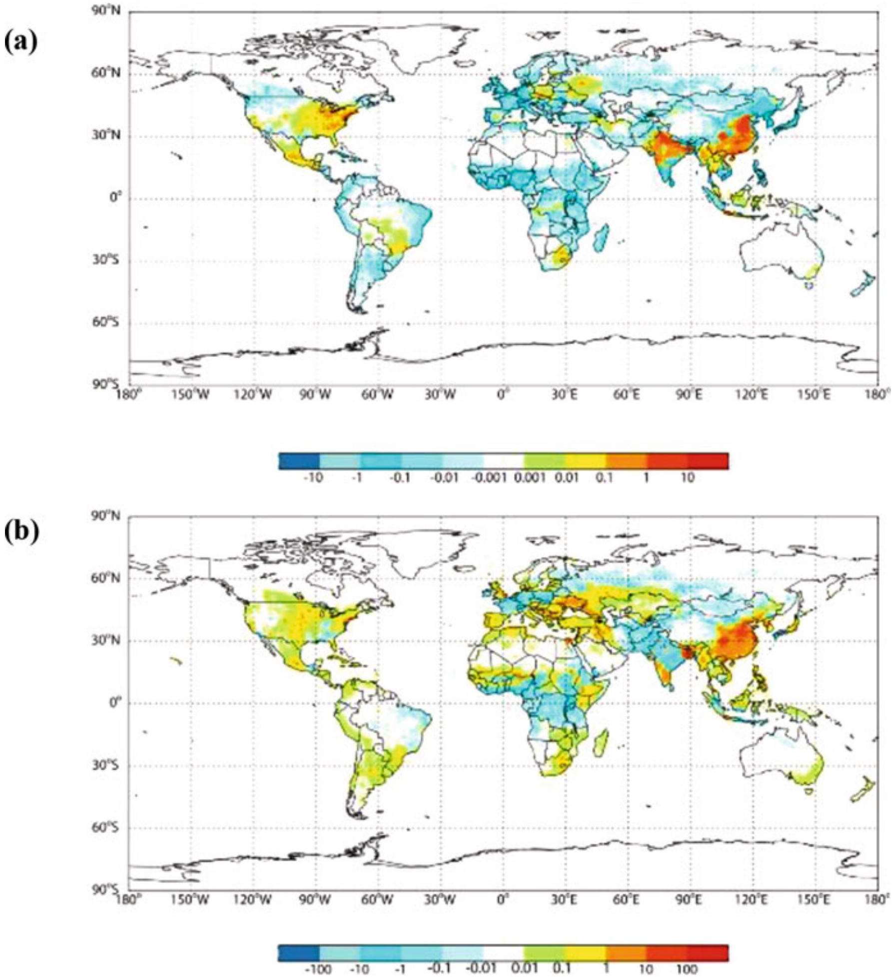

Fig. 2.1 Premature mortality attributed to past climate change in death/year (1000 km^2)$^{-1}$ for (**a**) ozone exposure (respiratory mortality) and (**b**) $PM_{2.5}$ exposure (cardiopulmonary diseases and lung cancer mortality (Adopted from Silva et al. 2013)

models (Pan et al. 2015). Figure 2.1 depicts the premature mortality that can be attributed to past climate change (1850–2000) due to $PM_{2.5}$ (a) and ozone (b) exposure, respectively. Past climate change (from pre-industrial era to present day) was estimated to cause ~1500 and 2200 premature deaths per year from ozone and $PM_{2.5}$ exposure, respectively.

Future Projections

Future air quality will be influenced by changes in emission and meteorology in warming climate. Changes in anthropogenic emissions are expected to dominate in the near future (Kirtman et al. 2013) and depend on various socio-economic factors such as demographic transition, economic growth, energy demand, technological choices, land use changes and implementation of policies regarding climate and air quality. Following a meeting on 8th September, 2008, a global initiative was taken for climate modelling under the fifth phase of the Coupled Climate Model Intercomparison Project (CMIP5) to enhance the earlier activities by incorporating 20 climate modelling groups from around the world (Taylor et al. 2012). These model simulations were targeted to focus on major gaps in understanding past and future climate changes described by Moss et al. (2010). The RCPs (summarized in Table 2.1) unlike the Special Report on Emission Scenarios (SRES) used for the earlier CMIP3 simulations include policy interventions and are built based on a range of projections of future socio-economic factors. These scenarios assume that certain policy actions will be taken to achieve certain emission targets. The labels of the four RCPs (RCP2.6, RCP4.5, RCP6 and RCP8.5) indicate a rough estimate of the radiative forcing at the end of the twenty-first century. Apart from the CMIP5 models, various chemical transport models (CTMs) like GEOS-Chem, WRF Chem and CMAQ models can also be utilized to estimate the concentration of the criterion pollutants. The CMIP5 and CTM model simulations for the projected concentration of various $PM_{2.5}$ components (viz. dust, black carbon, primary organic aerosols, secondary organic aerosols, sea salt and sulphate), VOC and NO_x in the future require data on emissions from RCP scenarios. The projected emissions of VOC and black carbon (among other constituents) over Asia are depicted in Fig. 2.2. One study (Silva et al. 2016) projected that global population-weighted ozone concentration in 2030 will change from present-day concentration by −2.5 to 15.2 ppb in

Table 2.1 Details about RCP scenarios

Scenario	Radiative forcing	Concentration (ppm)	Pathway	Model providing RCP
RCP8.5	>8.5 W/m^2 in 2100	>1370 CO_2 equiv. in 2100	Rising	MESSAGE
RCP6.0	~6 W/m^2 at stabilization after 2100	~850 CO_2 equiv. (at stabilization after 2100)	Stabilization without overshoot	AIM
RCP4.5	~4.5 W/m^2 at stabilization after 2100	~650 CO_2 equiv. (at stabilization after 2100)	Stabilization without overshoot	GCAM
RCP2.6	Peak at 3 W/m^2 before 2100 and the declines	Peak at ~490 CO_2 equiv. before 2100 and then declines	Peak and decline	IMAGE

The table is adopted from Moss et al. (2010)

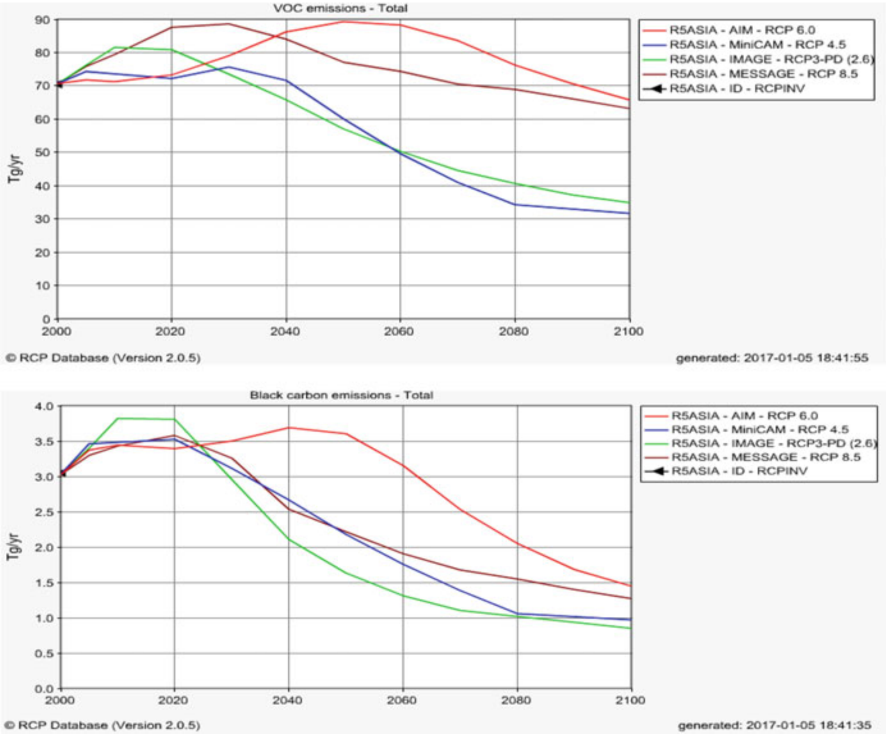

Fig. 2.2 Shows the emission of VOC (**a**) and black carbon (**b**) in future over Asia as projected by the RCP scenarios. These emissions go into the CMIP5 model simulations to determine the concentration of the pollutants in future decades. The figures are generated from the RCP scenario database hosted by IIASA

2030 across all the RCP scenarios using data from 14 ACCMIP models, while the change is projected to range from −11.7 to 13.6 ppb in 2100. They project an overall decrease of global population-weighted $PM_{2.5}$ exposure by 2100 ranging from −0.4 to −5.7 $\mu g/m^3$ across six ACCMIP models for all the RCP scenarios.

Projected Exposure to Ground-Level Ozone and Ambient $PM_{2.5}$

Very few studies have attempted to estimate the future exposure to ozone and $PM_{2.5}$. A recently published study (Madaniyazi et al. 2015) recognized the urgency to project premature mortality due to exposure to air pollutants in developing countries to facilitate implementation of policies. They also suggested that multi-model ensembles should be used to project the exposure to the air pollutants and

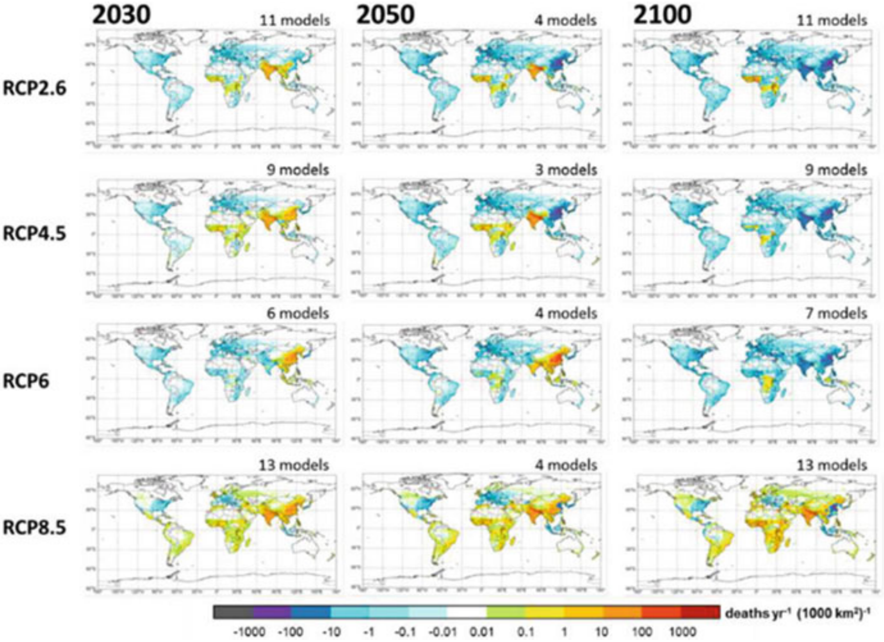

Fig. 2.3 Future ozone respiratory mortality for all RCP scenarios in 2030, 2050 and 2100, showing the multi-model average in each grid cell, for future air pollutant concentrations relative to 2000 concentrations (Adopted from Silva et al. 2016)

related excess premature mortality to better quantify the related uncertainty. Another study (Selin et al. 2009) used GEOS-Chem model to simulate future $PM_{2.5}$ exposure. Global ozone exposure is expected to increase by 6.1 ppb at the end of 2050, whereas the increase is expected to be about 24.4 ppb over India. They estimated that around 812,000 excess premature deaths per year can be attributed to exposure to ozone in 2050 as compared to 2000 due to changes in emission and climate. Recently, Silva et al. (2016) used an ensemble of ACCMIP models and projected global mortality burden due to ozone exposure to increase markedly from 382,000 (121,000–728,000) in 2000 to between 1.09 and 2.36 million deaths/year across all four RCPs in 2100. Figure 2.3 shows the projected premature mortality for three future decades. This study also identifies that change in premature ozone-related respiratory mortality/year in India in 2100 with respect to 2000 is projected to range from −230,000 to 292,000 across all the RCP scenarios.

The most unsettled issue regarding projection of aerosol concentration and $PM_{2.5}$ in future is whether $PM_{2.5}$ is expected to decrease or increase in future. Allen et al. (2016) projected that aerosol concentration is expected to increase in future, whereas Silva et al. (2016) projected that $PM_{2.5}$ exposure is expected to decrease relative to present-day exposure by the end of the century. Tagaris et al. (2009) used CMAQ modelling system to estimate 4000 premature mortality/year from $PM_{2.5}$ exposure in the USA due to climate change by the end of 2050. Tainio

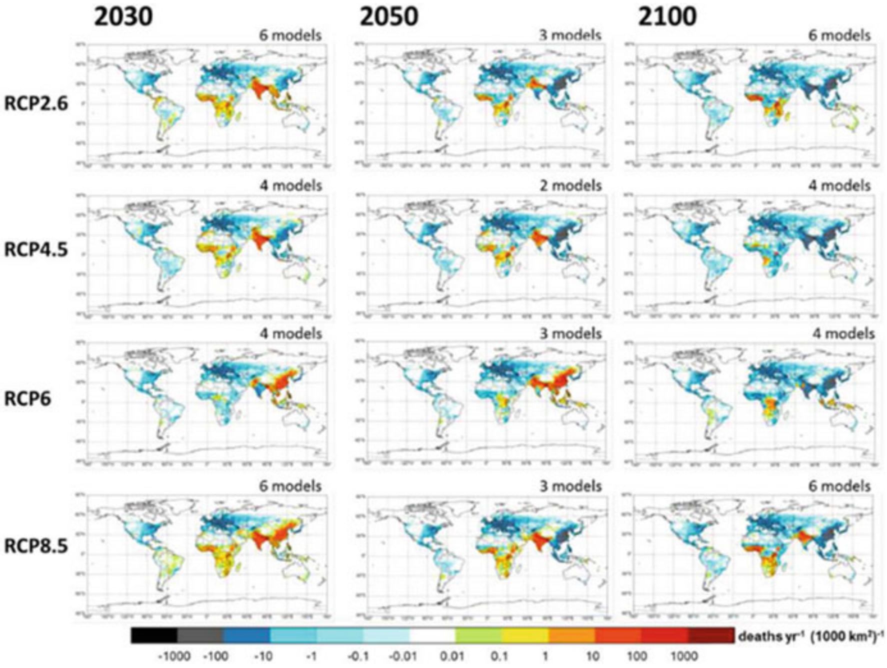

Fig. 2.4 Future mortality due to exposure to $PM_{2.5}$ for all RCP scenarios in 2030, 2050 and 2100, showing the multi-model average in each grid cell, for future air pollutant concentrations relative to 2000 concentrations (Adopted from Silva et al. 2016)

et al. (2013) used coupled RegCM and CAMx CTM to project a decrease in $PM_{2.5}$ exposure in future over Poland. Nawahda and Yamashita, (2012) projected $PM_{2.5}$ exposure to increase in future over East Asia using CMAQ modelling system which can be attributed to about 1,035,000 premature mortality by the end of 2020. Silva et al. (2016) projected that discounted exposure to $PM_{2.5}$ by the end of the century is expected to avert 1,310,000–1,930,000 premature mortality/year with respect to the estimated premature mortality using 2000 $PM_{2.5}$ exposure. Figure 2.4 depicts the projected premature mortality for three future decades (2030, 2050 and 2100).

Co-benefits of Reducing Air Pollutants

It is well established that human activities affect climate change, and as a consequence they are affected by climate change impacts (Smith et al. 2014). The focus to mitigate the concentration of warming climate-altering pollutants also holds the potential to benefit human health significantly. These co-benefits include health gains from strategies directed primarily at mitigation of climate change from policies implicated for health benefits (Haines et al. 2007; Smith and Balakrishnan 2009). In a nutshell, co-benefits are positive impacts on human health that arise from interventions to reduce the emission of climate-altering air pollutants. Co-benefits can be achieved in many ways (Smith et al. (2014) and references therein). For example, the reduction of co-pollutants from household solid fuel combustion will result in reduced exposure to air pollutants that are associated with diseases like chronic and acute respiratory illnesses, lung cancer, low birth weights and still births and tuberculosis. On the other hand, controlling household combustion of solid fuels will reduce emission of black carbon, $CH_{4,}$ CO and other climate-altering air pollutants. Reduction in CH_4 and CO emission will also restrict the formation of tropospheric ozone. Cutting down the emission of health damaging co-pollutant from industries will reduce outdoor exposure to ambient air pollution and hence has the potential to avert large premature mortality. The benefits for climate include reduction in emission of climate-altering air pollutants like black carbon, CO and CH_4. Increased energy efficiency will reduce fuel demands and hence reduce emissions of climate-altering air pollutants. Health benefits of increased urban green space include reduced temperature and heat island effect, physiological benefits and better self-perceived health status. It also helps in partially reducing atmospheric CO_2 via carbon sequestration in plant tissues and soil. Increased urban greeneries will also facilitate deposition of climate-altering air pollutants emitted from various vehicular and industrial sources.

Few studies quantify the health and climate benefits of reducing climate-altering air pollutants. A study in India found that the benefits of hypothetically reducing solid fuel combustion in households by introducing clean cook stoves would help to avert about 2 million premature death and 55 million DALYs over the period of 10 years and reduction of 0.5–1 billion tons of CO_2 equivalent (Wilkinson et al. 2009). A study (Markandya et al. 2009) assessed the changes in emission of $PM_{2.5}$ and subsequent effects on human health that could result from climate change mitigation aimed to halve the GHG emission by 2050 from the electricity generation sector of India, China and European Union. In all these three regions, changes in modes of production of electricity to reduce CO_2 emission were associated with reduction in $PM_{2.5}$-related premature mortality.

Socio-economic Projection for Vulnerability Assessment

Certain group of population is more vulnerable and susceptible to air pollution than the others, like children, people with pre-existing heart and lung diseases, people with diabetes, outdoor workers and aged people (Balbus and Malina 2009; Makri and Stilianakis 2008). Socio-economic factors also influence the susceptibility towards air pollution exposure in terms of disproportionate exposure, coping capacities and access to health care (Makri and Stilianakis 2008). The most vulnerable population are the homeless with six times more odds to be morbid or die due to lungs or respiratory infections, asthma and cardiovascular and pulmonary diseases.

To assess the relationships between socio-economic development in response to climate change, the Integrated Assessment Modelling (IAM) and the Impacts, Adaptation and Vulnerability (IAV) group launched a set of scenarios that describe the future in terms of social and economic mitigation and adaptation challenges known as the Shared Socio-economic Pathways (SSP) (O'Neill et al. 2012; Ebi et al. 2014). This set of scenarios provides projections by age, sex and six levels of education for all the countries. The five SSP scenarios are a green growth strategy (SSP1), a middle of the road development pattern (SSP2), a fragmentation between the regions (SSP3), an increase in inequality across and within regions (SSP4) and a fossil fuel-based economic development (SSP5). To encompass a wide range of possible development pathways, the SSP are defined in terms of socio-economic challenges to mitigation and to adaptation (Fig. 2.5a). Figure 2.6 shows the

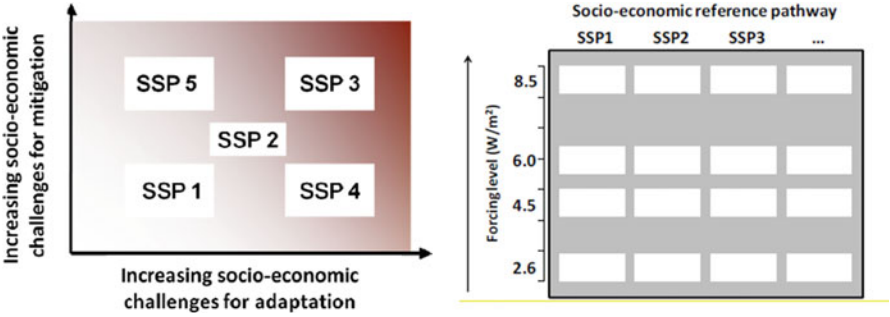

Fig. 2.5 (*Left*) The scenario space spanned by the SSP scenarios and (*right*) the scenario matrix architecture (Both figures are adapted from IPCC 2010)

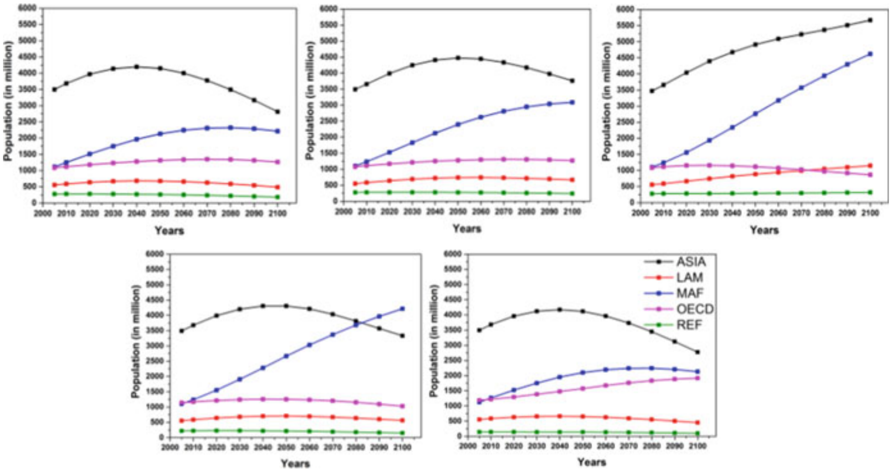

Fig. 2.6 Projected population used in developing the 5 SSPs'(numbered chronologically from a to b) for five world regions, namely, Asia, Latin American (LAM) countries, Middle East and Africa (MAF), OECD (OECD group of countries) and reforming economies (REF)

projected population used as a driver for developing each of the five SSP scenarios for five broad world regions, namely, Asia, Latin American (LAM) countries, Middle East and Africa (MAF), OECD (OECD group of countries) and reforming economies (REF).

SSP1 (Vuuren et al. 2016) considers the world to make definite progress towards sustainability, achieve development goals by cutting off resource intensity and dependency on fossil fuels. In SSP2 (Fricko et al. 2016) trends typical to recent decades are projected to continue, with some progress towards achieving development goals, historic reductions in resource and energy and slowly decreasing fossil fuel dependency. In SSP3 (Fujimori et al. 2016) scenario, the pathway assumed is opposite to sustainability which describes a world with stalled demographic transition. The SSP4 (Calvin et al. 2016) scenario predicts a very unequal world both within and across the countries, and the SSP5 scenario (Kriegler et al. 2016) envisions a world that stresses conventional development oriented towards economic growth.

Scenario Matrix Architecture: A Way Forward for Estimating Future Burden Due to Air Pollution

Premature mortality burden from air pollution depends on concentration of pollutant, exposed population and background mortality rate. The air pollutant concentration in the future can be projected by climate models following RCP emission scenarios, while the socio-economic factors like population and background mortality rate can be quantified following SSP scenarios. Therefore, the burden of disease in the future is expected to be quantified by RCP-SSP scenario matrix (4×5). This scenario matrix architecture (Fig. 2.5b) can be used in different ways for scientific and policy analyses. For example, analysts can compare consequences under the same climate scenario (RCP driven) across all socio-economic scenarios (“what is the effect of future socio-economic conditions on the impacts of a given climate change”). An assessment of the effect of future socio-economic conditions on the effectiveness and costs of a suite of mitigation and adaptation measures to combat climate change would allow comparing the differences between the SSP scenarios across a single RCP scenario (IPCC 2010; O’Neill et al. 2012). For example, population distribution from a particular SSP scenario can be combined with the exposure to $PM_{2.5}$ or ozone under different climate change scenarios to estimate the premature mortality burden that can be expected for a particular population if the world follows different climate change pathways in future.

Concluding Remarks

Despite continuous efforts to restrict various sources of pollutants by the government, air pollution remains as one of the major environmental hazards in India (Dey and Di Girolamo 2011). GBD study shows large premature mortality from air pollution exposure in India. However, burden estimates at regional level needs to be adjusted for the local condition. Our recent study (Chowdhury and Dey 2016) estimated about 800,000 premature adult deaths per year by adjusting for the heterogeneity in background mortality rate as a function of socio-economic development represented in terms of gross domestic product. Following example will clarify the importance of local adjustment. Delhi has the highest ambient $PM_{2.5}$ exposure in India, but at the same time, its GDP is also one of the highest in the country. If the baseline mortality of Delhi is not adjusted and instead a single India-specific value is considered, the premature mortality burden of Delhi is overestimated. Similarly, the burden would have been underestimated in regions that are less developed and have higher background mortality than all-India average. Therefore, identification of vulnerable regions based on premature mortality burden and prioritization of mitigation measures in these regions should be facilitated by such analysis.

The exposure to $PM_{2.5}$ and ozone has been increasing over India in the last decade (Saraf and Beig 2004; Dey and Di Girolamo 2011; Dey et al. 2012) resulting in increasing number of the population being pitched at risk of dying prematurely. What intrigues the policymakers is whether exposure to air pollution will continue to increase in the future. To project future premature mortality from air pollution exposure for India or any other country, the scenario matrix framework will be useful, because it will enable to isolate the relative roles of meteorological, demographic and epidemiological changes on the projected burden. Such strategic knowledge will provide the government adequate information to formulate policy to mitigate air pollution and develop climate change resilient society.

Acknowledgement Financial support from the Department of Science and Technology, Government of India, through a research grant (DST/CCP/NET-2/PR-36/2012(G)) under the first phase of the network program of “climate change and human health” is acknowledged.

References

Allen RJ, Landuyt W, Rumbold ST (2016) An increase in aerosol burden and radiative effects in a warmer world. Nat Clim Change 6:269–274. doi:10.1038/NCLIMATE2827

Anenberg SC, Horowitz LW, Tong DQ, West JJ (2010) An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. Environ Health Perspect 118:1189–1195. doi:10.1289/ehp.0901220

Arnold C (2014) Newslscience selections disease burdens associated with PM 2.5 exposure how a new model provided global estimates. Environ Health Perspect 13:981277

Avnery S, Mauzerall DL, Liu J, Horowitz LW (2011) Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage “and” Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under. Atmos Environ 45:2297–2309. doi:10.1016/j.atmosenv.2012.12.045

Balbus John M, Malina Catherine M (2009) Identifying vulnerable subpopulations for climate change health effects in the United States. J Occup Environ Med 51:33–37. doi:10.1097/JOM.0b013e318193e12e

Bell ML, Samet JM, Dominici F (2004) Time-series studies of particulate matter. Annu Rev Public Health 25:247–280. doi:10.1146/annurev.publhealth.25.102802.124329

Bell ML, Dominici F, Samet JM (2005) A meta-analysis of time-series studies of ozone and mortality with comparison to the National Morbidity, mortality, and air pollution study. Epidemiology 16:436–445. doi:10.1001/jama.292.19.2372.Ozone

Burnett RT, Arden Pope C, Ezzati M et al (2014) An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ Health Perspect 122:397–403. doi:10.1289/ehp.1307049

Calvin K, Bond-lamberty B, Clarke L et al (2016) The SSP4: A world of deepening inequality. Glob Environ Chang. doi:10.1016/j.gloenvcha.2016.06.010

Chen H, Goldberg MS, Villeneuve PJ (2008) A systematic review of the relation between long-term exposure to ambient air pollution and chronic diseases. Rev Environ Health 23:243–297. doi:10.1515/reveh.2008.23.4.24

Chowdhury S, Dey S (2016) Cause-specific premature death from ambient PM2.5 exposure in India: estimate adjusted for baseline mortality. Environ Int 91:283–290. doi:10.1016/j.envint.2016.03.004

Christensen JH, Hewitson B, Busuioc A, et al (2007) Regional climate projections. In: Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

Daniel JJ, Winner DA (2009) Effect of climate change on air quality. Atmos Environ 43:51–63. 10.1016/j.atmosenv.2008.09.051

Dey S, Di Girolamo L (2011) A decade of change in aerosol properties over the Indian subcontinent. Geophys Res Lett 38:1–5. doi:10.1029/2011GL048153

Dey S, Di Girolamo L, van Donkelaar A et al (2012) Variability of outdoor fine particulate (PM2.5) concentration in the Indian subcontinent: a remote sensing approach. Remote Sens Environ 127:153–161. doi:10.1016/j.rse.2012.08.021

Ebi KL, Hallegatte S, Kram T, et al (2014) A new scenario framework for climate change research: background, process, and future directions. pp 363–372. doi:10.1007/s10584-013-0912-3

Fang Y, Naik V, Horowitz LW, Mauzerall DL (2013) Air pollution and associated human mortality: the role of air pollutant emissions, climate change and methane concentration increases from the preindustrial period to present. Atmos Chem Phys 13:1377–1394. doi:10.5194/acp-13-1377-2013

Fricko O, Havlik P, Rogelj J et al (2016) The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. Glob Environ Chang. doi:10.1016/j.gloenvcha.2016.06.004

Fujimori S, Hasegawa T, Masui T et al (2016) SSP3: AIM implementation of shared socioeconomic pathways. Glob Environ Chang. doi:10.1016/j.gloenvcha.2016.06.009

Ghude SD, Jena C, Chate DM et al (2014) Reductions in India's crop yield due to ozone. Geophys Res Lett 41:5685–5691. doi:10.1002/2014GL060930

Ghude SD, Chate DM, Jena C et al (2016) Premature mortality in India due to PM 2.5 and ozone exposure. Geophys Res Lett 43:4650–4658. doi:10.1002/2016GL068949

Gouveia N, Fletcher T (2000) Time series analysis of air pollution and mortality: effects by cause, age and socioeconomic status. J Epidemiol Community Health 54:750–755. doi:10.1136/jech.54.10.750

Haines A, Smith KR, Anderson D et al (2007) Policies for accelerating access to clean energy, improving health, advancing development, and mitigating climate change. Lancet 370:1264–1281. doi:10.1016/S0140-6736(07)61257-4

Horowitz LW (2006) Past, present and future concentrations of tropospheric ozone and aerosols: methodology, ozone evaluation, and sensitivity to aerosol wet removal. J Geophys Res Atmos. doi:10.1029/2005JD006937

IPCC (2010) IPCC workshop on socio-economic scenarios. IPCC Work Socio-Economic Scenar Victor’s Residenz-Hotel, Berlin, Ger 1-3 November 2010, pp 1–61

Jerrett M, Burnett RT, Pope CA, et al (2009) Long-term ozone exposure and mortality. N Engl J Med 360:1085–1095. doi:10.1056/NEJMoa0803894

Kinney PL (2008) Climate change, air quality, and human health. Am J Prev Med 35:459–467. doi:10.1016/j.amepre.2008.08.025

Kirtman B, Power SB, Adedoyin J, et al (2013) Near-term climate change: projections and predictability

Kriegler E, Bauer N, Popp A, et al (2016) Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. doi:10.1016/j.gloenvcha.2016.05.015

Li C, Balluz LS, Vaidyanathan A et al (2016) Long-term exposure to ozone and life expectancy in the United States, 2002 to 2008. Medicine (Baltimore) 95:e2474. doi:10.1097/MD.0000000000002474

Lim SS, Vos T, Flaxman AD, et al (2012) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the global burden of disease study 2010. Lancet 380:2224–2260. doi:10.1016/S0140-6736(12)61766-8

Lin S, Liu X, Le LH, Hwang SA (2008) Chronic exposure to ambient ozone and asthma hospital admissions among children. Environ Health Perspect 116:1725–1730. doi:10.1289/ehp.11184

Madaniyazi L, Guo Y, Yu W, Tong S (2015) Projecting future air pollution-related mortality under a changing climate: progress, uncertainties and research needs. Environ Int 75:21–32. doi: 10.1016/j.envint.2014.10.018

Makri A, Stilianakis NI (2008) Vulnerability to air pollution health effects. Int J Hyg Environ Health 211:326–336. doi:10.1016/j.ijheh.2007.06.005

Marenco A, Gouget H, Nedelec P et al (1998) Evidence of a long-term increase in tropospheric ozone from Pic du Midi data series: consequences: positive radiative forcing. J Geophys Res Atmos 99:16617–16632

Markandya A, Armstrong BG, Hales S et al (2009) Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. Lancet 374:2006–2015. doi:10.1016/S0140-6736(09)61715-3

Menon A, Lvermann A, Schewe J, Lehmann JFK (2013) Consistent increase in Indian monsoon rainfall and its variability Geoscientific across CMIP-5 models. Dynam Earth Syst:287–300. doi:10.5194/esd-4-287-2013

Morgan PB, Mies TA, Bollero GA et al (2006) Season-long elevation of ozone concentration to projected 2050 levels under fully open-air conditions substantially decreases the growth and production of soybean. New Phytol 170:333–343. doi:10.1111/j.1469-8137.2006.01679.x

Moss RHRH, Edmonds JAJA, Hibbard KAKA et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756. doi:10.1038/nature08823

Murray C (2015) Global, regional and national comparative risk assessment of 76 behavioural, environmental, occupational and metabolic risks or clusters of risks in 188 countries 1990–2013: a systematic analysis for the GBD Background. Lancet 6736:1–27. doi:10.1016/S0140-6736(15)00128-2

Nawahda A, Yamashita K (2012) Evaluation of premature mortality caused by exposure to PM 2.5 and ozone in East Asia:2000, 2005, 2020, pp 3445–3459. doi:10.1007/s11270-012-1123-7

O’Neill BC, Carter TR, Ebi KL, et al (2012) Workshop on the nature and use of new socioeconomic pathways for climate change research core writing team acknowledgments. Meet Rep Work Nat Use New Socioecon Pathways Clim Chang Res:1–37

Pan X, Chin M, Gautam R et al (2015) A multi-model evaluation of aerosols over South Asia: common problems and possible causes. Atmos Chem Phys 15:5903–5928. doi:10.5194/acp-15-5903-2015

Pope A, Burnett RT, Thun MJ, et al (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution

Saraf N, Beig G (2004) Long-term trends in tropospheric ozone over the Indian tropical region. Geophys Res Lett 31:1–5. doi:10.1029/2003GL018516

Selin NE, Wu S, Nam KM et al (2009) Global health and economic impacts of future ozone pollution. Environ Res Lett 4:44014. doi:10.1088/1748-9326/4/4/044014

Shi L, Zanobetti A, Kloog I, et al (2015) Low-concentration PM and mortality: estimating acute and chronic effects in a population-based study. Environ Health Perspect:46–52. doi:10.1289/ehp.1409111

Silva RA, West JJ, Zhang Y et al (2013) Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change. Environ Res Lett 8:34005. doi:10.1088/1748-9326/8/3/034005

Silva RA, West JJ, Lamarque JF et al (2016) The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. Atmos Chem Phys 16:9847–9862. doi:10.5194/acp-16-9847-2016

Smith KR, Balakrishnan K (2009) Mitigating climate, meeting MDGs, and moderating chronic disease: the health co-benefits landscape. “Commonwealth Health Ministers” Update

Smith KR, Woodward A, Al E (2014) Human health: impacts, adaptation, and co-benefits. In: Field CB, Barros VR, Dokken DJ (eds) Climate change: 2014 impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change, pp 709–756

Tagaris E, Liao K, Delucia AJ, Deck L (2009) Potential impact of climate change on air pollution-related human health effects. Environ Sci Technol:4979–4988

Tainio M, Juda-rezler K, Reizer M, et al (2013) Future climate and adverse health effects caused by fine particulate matter air pollution: case study for Poland, pp 705–715. doi:10.1007/s10113-012-0366-6

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498. doi:10.1175/BAMS-D-11-00094.1

Van Vuuren DP, Stehfest E, Gernaat DEHJ, et al (2016) Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob Environ Chang:1–14. doi:10.1016/j.gloenvcha.2016.05.008

West JJ, Cohen A, Dentener F et al (2016) What we breathe impacts our health: improving understanding of the link between air pollution and health. Environ Sci Technol 50:4895–4904. doi:10.1021/acs.est.5b03827

West JJ, Fiore AM, Horowitz LW, Mauzerall DL (2006) Global health benefits of mitigating ozone pollution with methane emission controls. Proc Natl Acad Sci U S A 103:3988–3993. doi:10.1073/pnas.0600201103

Wilkinson P, Smith KR, Davies M et al (2009) Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. Lancet 374:1917–1929. doi:10.1016/S0140-6736(09)61713

Sourangsu Chowdhury received his MSc degree in atmospheric sciences from the University of Calcutta in 2012. He is a doctoral candidate at the Centre for Atmospheric Sciences, IIT Delhi. His primary research interest is to quantify the impact of particulate matter on human health with a focus on India.

Sagnik Dey is an associate professor at the Centre for Atmospheric Sciences, IIT Delhi. His research interest is to understand air quality, climate change and human health connection. He is a science team member of the NASA MAIA mission. He has published more than 60 peer-reviewed articles with an h-index of 22.