# Climate change, tropospheric ozone and particulate matter, and health impacts *

## Mudanças climáticas, ozônio troposférico e partículas suspensas: impactos na saúde

Kristie Ebi [1]
Glenn McGregor [2]

**Abstract** *We review how climate change could affect future concentrations of tropospheric ozone and particulate matter (PM), and what changing concentrations could mean for population health, as well as studies projecting the impacts of climate change on air quality and the impacts of these changes on morbidity/mortality. Climate change could affect local to regional air quality through changes in chemical reaction rates, boundary layer heights that affect vertical mixing of pollutants, and changes in synoptic airflow patterns that govern pollutant transport. Sources of uncertainty are the degree of future climate change, future emissions of air pollutants and their precursors, and how population vulnerability may change in the future. Given the uncertainties, projections suggest that climate change will increase concentrations of tropospheric ozone, at least in high-income countries when precursor emissions are held constant, increasing morbidity/mortality. There are few projections for low- and middle-income countries. The evidence is less robust for PM, because few studies have been conducted. More research is needed to better understand the possible impacts of climate change on air pollution–related health impacts.*

**Key words** *Air pollution, Climate change, Health impacts, Ozone, Particulate matter*

**Resumo** *Examinamos como as mudanças climáticas podem afetar o futuro das concentrações de ozônio troposférico e de partículas suspensas (PS), e o que uma mudança nas concentrações significaria para a saúde da população. Analisaram-se estudos que projetam os impactos das mudanças climáticas na qualidade do ar e morbidade/mortalidade. A mudança climática pode afetar a qualidade do ar local e regional com mudanças nas taxas de reações químicas, altura das camadas limite que afetam a mistura vertical de poluentes e mudanças nos padrões sinóticos de circulação atmosférica que gerenciam o transporte de poluentes. Dentre as fontes de incerteza, a mudança climática futura, emissões de poluentes do ar e seus precursores e como a vulnerabilidade da população poderá ser modificada no futuro. Devido às incertezas, as projeções sugerem que as mudanças climáticas aumentarão as concentrações de ozônio troposférico pelo menos nos países de alta renda, onde as emissões precursoras de ozônio são constantes, resultando em maior morbidade/mortalidade. Para os países de baixa e média renda, há poucas projeções. A evidência é menor para PS, pois há poucos estudos. É preciso mais pesquisa para compreender os possíveis impactos da mudança climática nos impactos à saúde relacionados à poluição do ar.*

**Palavras-chave** *Poluição do ar, Mudanças climáticas, Impacto à saúde, Ozônio, Partículas em suspensão*

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[1] ESS, LLC, Alexandria, Virginia, USA. 5249 Tancreti Lane, Alexandria, VA 22034.
krisebi@ essllc.org.
[2] The University of Auckland, Auckland, New Zealand.

Extensive literature documents the adverse health impacts of exposure to elevated concentrations of air pollutants, particularly ozone, particulate matter with aerodynamic diameters < 10 (PM10) and < 2.5 µm (PM2.5), sulfur dioxide, nitrogen dioxide, carbon monoxide, and lead. Worldwide in the year 2000, 0.8 million deaths and 7.9 million disability-adjusted life-years lost from respiratory problems, lung disease, and cancer were attributed to urban air pollution[1]. Because the state of the atmosphere at various scales determines the development, transport, dispersion, and deposition of air pollutants, there is concern that climate change could affect the burden of illness and mortality associated with these gases and fine particles. Therefore, we review studies projecting the impacts of climate change on air quality and studies projecting the impacts of these changes on morbidity and mortality, with a focus on studies published since 2000. We limited our review to the past several years because of significant advances in climate modeling[2].

## Meteorology and air pollution

Air pollution concentrations are the result of interactions among local weather patterns, atmospheric circulation features, wind, topography, human activities (i.e., transport and coal-fired electricity generation), human responses to weather changes (i.e., the onset of cold or warm spells may increase heating and cooling needs and therefore energy needs), and other factors. Some locations, because of their general climate and topographic setting, are predisposed to poor air quality because the climate is conducive to chemical reactions leading to the transformation of emissions, and the topography restricts the dispersion of pollutants[3,4]. Some air pollutants demonstrate clear seasonal cycles[5-9]. Certain weather situations provide the requisite meteorologic conditions for pollution episodes. Air pollution episodes are often associated with stationary or slowly migrating anticyclonic or high-pressure systems that reduce pollution dispersion, diffusion, and deposition[10,11]. The three-dimensional wind field, its related turbulence, and vertical temperature are important[12,13]. Meteorologic conditions also influence the chemical and physical processes involved in the formation of secondary pollutants such as ozone[14,15]. Airflow along the flanks of anticyclonic systems can transport ozone precursors, creating the conditions for an ozone event[16-19]. Large-scale airflows not necessarily related to anticyclonic systems can interact with local topography, sea/lake and land breezes, or mountain and valley winds to increase pollutant concentrations[16,20-28]. Distant weather systems such as tropical cyclones and low-pressure systems lying over coastal regions can lead to high pollution levels[18,29,30]. Climate change could affect local to regional air quality directly through changes in chemical reaction rates, boundary layer heights (i.e., the layer of air near the ground that is affected by diurnal heat, moisture, and momentum transfer to/from the surface) that affect vertical mixing of pollutants, and changes in synoptic airflow patterns that govern pollutant transport. The synoptic scale corresponds to the typical size of mid-latitude high and low pressure systems (approximately a horizontal length of 1,000 km or 620 miles). Indirect effects could result from increasing or decreasing anthropogenic emissions via changes in human behavior or from altering the levels of biogenic emissions because of higher temperatures and land cover change. Higher temperatures can increase emissions of isoprene, a volatile hydrocarbon and ozoneprecursor emitted by many woody plant species. However, establishing the scale (local, regional, global) and direction of change (improvement or deterioration) of air quality is challenging[31-34]. More is known about the potential impacts of climate change on ground-level ozone than on other air pollutants.

## Ozone

Ground-level ozone is a known pulmonary irritant that affects the respiratory mucous membranes, other lung tissues, and respiratory function. Exposure to elevated concentrations of ozone is associated with increased hospital admissions for pneumonia, chronic obstructive pulmonary disease, asthma, allergic rhinitis, and other respiratory diseases, and with premature mortality[35-39]. Outdoor ozone concentrations and activity patterns are the primary determinants of ozone exposure[40]. Although a considerable amount is known about the health effects of ozone in Europe and North America, few studies have been conducted in other regions. Ground-level ozone is both naturally occurring and, as the primary constituent of urban smog, a secondary pollutant formed through photochemical reactions involving nitrogen oxides and volatile organic compounds in the presence of bright sunshine with high temperatures[41]. Land use changes over the past century affect ozone concentrations by altering vegetation patterns affecting biogenic volatile organic compound emissions that influence ozone production[2]. In addition, urbanization leading to heat islands can influence the local production and dispersion of ozone. In urban areas, gasoline-burning engines are major sources of volatile organic compounds, and nitrogen oxides are produced whenever fossil fuels are burned[41]. Temperature, wind, solar radiation, atmospheric moisture, venting, and mixing affect both emissions of ozone precursors and production of ozone[14,15,42]. Because ozone formation depends on sunlight, concentrations are typically highest during the summer months, although not all cities have shown seasonality in ozone concentrations[43]. Observations show that trends in tropospheric ozone in the past few decades vary in sign, with increased or decreased ozone, and in magnitude in many locations, with significant upward trends at low latitudes[2].

## Projected changes in tropospheric concentrations of ozone associated with climate change

There are two major sources of uncertainty when assessing the health impacts of future changes in tropospheric ozone concentrations: the extent of future changes in emissions of ozone precursors, and the degree to which future weather conditions could increase ozone concentrations. Future emissions are, of course, uncertain and depend on assumptions of population growth, economic development, regulatory actions, and energy use[44,45]. Increased regulation of anthropogenic emissions of volatile organic compounds and nitrogen oxides from gasoline-powered engines means that biomass burning, including fires, will likely increase in importance as sources of ozone precursors. Assuming no change in the emissions of ozone precursors, the extent to which climate change affects the frequency of future ozone episodes will depend on the occurrence of the required meteorologic conditions[46-52]. Where climate change is projected to result in an increased frequency of stable anticyclonic conditions with little boundary layer ventilation and associated high temperatures, cloud-free conditions, and large solar radiation inputs, exceedance of current air quality standards will likely occur[46,49,50,52]. Future air quality, especially at the local to regional level, will depend partially on concentrations of pollutants at the global scale. Concentrations of ozone have risen since preindustrial times because of increasing emissions of methane, carbon monoxide, and nitrogen oxides, and this trend is expected to continue over the next 50 years, based on projections of annual mean maximum concentrations[53]. However, as many major cities propose to reduce vehiclebased emissions of pollutants, it is expected that urban concentrations of ozone will rise less rapidly or be reduced[54,55]. For example, it has been estimated that for the United States a 50% reduction of methane emissions would nearly halve the incidence of high ozone events[56]. Decreases in stratospheric ozone may also result in greater increases in ground level ozone in polluted regions because of an increase in ultraviolet radiation reaching the ground; ultraviolet radiation is involved in the formation of ozone[57]. Changes in concentrations of ground-level ozone driven by scenarios of future emissions and/or weather patterns have been projected worldwide, with most projections for Europe and North America[36,48,50,51,58-71]; these studies, which range from global to local levels, are summarized in subsequent paragraphs. Although these studies are inconsistent in approaches taken and factors considered, most project increased tropospheric ozone concentrations, with high variability across regions. The Intergovernmental Panel on Climate Change concluded that climate change would modify a variety of chemicals and processes that control air quality, and the net effects are likely to vary from one region to another[2]. On a global scale, if 1990 is treated as the reference period, then moderately high annual mean maximum ozone concentrations of 60 parts per billion (ppb) were projected for central Europe, China, Brazil, South Africa, and eastern North America during summertime[58]. By 2030, under a high emission scenario [Standardized Reference Emission Scenarios (SRES); see Appendix 1, A2 scenario], the area experiencing a background of 60 ppb was projected to expand significantly, especially in Europe and North America. By 2060, most of the populated continental areas would experience ozone concentrations of at least 60 ppb. By 2100, much of the Northern Hemisphere was projected to have annual mean maximum ozone levels of 60 ppb, as were most of the populated areas of the Southern Hemisphere[58]. However, Liao ***et al.***[48] and Racherla and Adams[51], also using the SRES A2 scenario, projected that anthropogenic climate change could reduce the global ozone burden due to changes in atmospheric chemistry. Liao ***et al.***[48] also projected that surface ozone concentrations over or near populated and biomass-burning areas would increase. Ozone concentrations were projected for 10 world regions in 2030, using a coupled general circulation model with interactive chemistry (LMDz-INCA; http://aoc. ammainternational. org/researchProduct/aerosol chemistry/ lmdz/index.en.php?current= 20060930) driven by the SRES A2 scenario[71]. Modeled ozone concentrations for present conditions have been shown to reasonably agree with surface ozone measurements. The global average populationweighted 8-hr maximum ozone concentration was projected to increase by 9.4 parts per billion per volume (ppbv) compared with a simulation of the concentration in 2000, with the largest increases over South Asia (nearly 15 ppbv) and with large increases in the Middle East, Southeast Asia, Latin America, and East Asia. Forkel and Knoche[72] projected ozone concentrations in Germany under the IS92a ”business-as-usual” scenario for the 2030s compared with the 1990s. Both biogenic volatile organic compound emissions and soil nitrous oxide emissions were projected to increase as temperatures rise. Projected daily maximum ozone concentrations increased by between 2 and 6 ppb (6–10%) across the study region; the number of days in the 2030s when daily maximum ozone exceeded 90 ppb increased nearly 4-fold, from 99 to 384.

Murazaki and Hess[50], using the SRES A1 scenario and a global chemical transport model [MOZART-2; Model of OZone And Related chemical Tracers, version 2 (gctm.acd.ucar.edu/ Mozart)], projected that by the end of the twenty-first century anthropogenic climate change alone would decrease background ozone concentrations over the United States, while ozone produced internally would increase. Over the western United States, the two forces approximately equaled each other. The authors projected that over the eastern United States, up to 12 additional days annually would exceed 80 ppbv. Taha[70] estimated increases in ozone concentrations by the end of the century in two large cities in California based on model results that linked output from two general circulation models to future emissions of nitrous oxides, volatile organic compounds, biogenic hydrocarbons, and sulfates, and air pollution models used to evaluate air quality compliance in these regions. Two frequently used attainmentdemonstration modeling episodes were selected for the study, the 2010 projection of the 26–28 August “1987” episode for Los Angeles, and the 2005 projection of the 11–13 July ”1990" episode for Sacramento Valley. Ozone concentrations on the last day of each episode were modeled. Under assumptions of futureyear controlled emissions, the model suggested significant increases in ozone concentrations at the time of the base-case peak concentrations in the Los Angeles Basin (up to 26 ppb, an approximate 24% increase) and in the Sacramento Valley (up to 12 ppb, an approximate 10% increase). Aw and Kleeman[59] simulated an episode of high air pollution in Southern California in 1996 with observed meteorology and then with higher temperatures. Ozone concentrations increased up to 16% with higher temperatures (+ 5°K); there was less consistency in PM2.5 response, depending on whether increased secondary particle formation or more evaporative losses from nitrate particles were more important. Steiner ***et al***.[68] reported variations across California in the sensitivity of ozone to changing temperatures, absolute humidity, biogenic volatile organic compound emissions, and pollution boundary conditions on a fine scale (4 km grid resolution). In a coarse-scale analysis of pollution over the continental United States, Mickley ***et al***.[49] projected that, because of climate change alone (SRES A1b scenario), air pollution (as estimated by including combustible carbon monoxide and black carbon as tracers of anthropogenic pollution) could increase in the upper Midwest because of decreases between 2000 and 2052 in the frequency of Canadian frontal passages that clear away stagnating air pollution. Leung and Gustafson[67] used regional climate simulations for temperature, solar radiation, precipitation, and stagnation/ventilation, and projected worse air quality in Texas and better air quality in the Midwest in 2045–2055 compared with 1995–2005. Bell ***et al***.[36] showed greater sensitivity of ozone concentrations in the Mid-Atlantic to changes in biogenic than to changes in anthropogenic emissions. As part of the New York Climate and Health Project, Hogrefe and colleagues conducted local-scale analyses of air pollution impacts of future climate changes using integrated modeling[46,61-64] to examine the potential impacts of climate and land use changes on heat- and ozone-related health impacts in the New York City metropolitan area[36,73-75]. Hourly meteorologic data from the 1990s through the 2080s were simulated based on the SRES A2 and B2 scenarios. The global climate outputs were downscaled to a 36-km grid over the eastern United States using the MM5 (Penn State/National Center for Atmospheric Research Mesoscale Model 5; www.mmm. ucar.edu/mm5/) regional climate model. The MM5 results were then used as inputs to the CMAQ (Community Multiscale Air Quality) regional-scale air quality model. Five summers (June–August) in each of four decades (1990s, 2020s, 2050s, and 2080s) were simulated at the 36-km scale. Pollution precursor emissions over the eastern United States were based on U.S. EPA estimates at the county level for 1996. Compared with observations from ozone monitoring stations, initial projections were consistent with ozone spatial and temporal patterns over the eastern United States in the 1990s[46]. Average daily maximum 8-hr concentrations were projected to increase by 2.7, 4.2, and 5.0 ppb in the 2020s, 2050s, and 2080s, respectively, because of climate change[61]. The influence of climate on mean ozone values was similar in magnitude to the influence of rising global background by the 2050s, but climate had a larger impact on extreme values. When biogenic volatile organic emissions were allowed to increase in response to warming, an additional increase in ozone concentrations was projected that was similar in magnitude to that of climate alone[61]. Climate change shifted the distribution of ozone concentrations toward higher values, with larger relative increases in future decades.

## Particulate Matter

PM is well known to affect morbidity and mortality[76-79], so increasing concentrations would have significant negative health impacts. Using a coupled climate–air pollution, three-dimensional model, Jacobson[80] compared the health effects of preindustrial versus present-day atmospheric concentrations of carbon dioxide. The results suggest that increasing concentrations of CO2 increased tropospheric ozone and PM2.5, which increased mortality by about 1.1% per degree temperature increase over the baseline rate. Jacobson[80] estimated that about 40% of the increase was attributable to ozone and the rest to PM. The estimated mortality increase was higher in locations with poorer air quality. In comparison with ozone, assessments of the impact of climate change on other pollutants are few. These emphasize the role of local abatement strategies in determining the future concentrations of pollutants such as PM and sulfur dioxide and tend to project the probability of air quality standards being exceeded instead of absolute concentrations[81-84]. The results vary by region. The severity and duration of summertime regional air pollution (combustion carbon monoxide and black carbon) episodes were projected to increase in the northeastern and midwestern United States by 2045–2052 because of climate change–induced decreases in the frequency of surface cyclones[49]. A U.K. study projected that climate change would result in a large decrease in days with high particulate concentrations due to changes in meteorologic conditions[58]. However, in the New York Climate and Health Project, PM2.5 concentrations were projected to increase with climate change, with the effects differing by component species, with sulfates and primary PM increasing markedly and with organic and nitrated components decreasing, mainly because of movement of these volatile species from the particulate to the gaseous phase[64,65]. Because transboundary transport of pollutants plays a significant role in determining local to regional air quality[85-101], changing patterns of atmospheric circulation at the hemispheric to global level are likely to be equally important as regional patterns for future local air quality[102,103].

## Potential health effects

Table 1 summarizes projections of morbidity and mortality based on current exposure– mortality relationships applied to projected Climate change, air pollution, and health impacts ozone concentrations. An increase in ozone concentrations would affect the ability of regions to achieve air quality targets. There are few projections for cities in low- or middleincome countries, despite the heavier pollution burdens in these populations, presumably because of limited research funding.

The New York Climate and Health Project projected the potential health impacts of future ozone concentrations in the eastern United States[36,75]. Knowlton and colleagues computed absolute and percentage increases in ozone-related daily summer-season deaths in the New York City metropolitan region in the 2050s compared with the 1990s[74,75]. The availability of county-scale ozone projections made it possible to compare impacts in the urban core with those in outlying areas. Increases in ozone-related mortality due to climate change ranged from 0.4 to 7.0% across 31 counties. Bell ***et al***.[36] expanded the analysis to 50 eastern cities and examined both mortality and hospital admissions. Average ozone concentrations were projected to increase by 4.4 ppb (7.4%) in the 2050s; the range was 0.8–13.7%. In addition, ozone red-alert days could increase by 68%.

These changes were projected to result in

**Table 1.** Projected impacts of climate change on ozone-related health effects.

| Area | Health effect | Model | Climate scenario time slices | Temperature increase and baseline |
|---|---|---|---|---|
| New York metropolitan region United States | Ozone-related deaths by county | Concentration–response function from published epidemiologic literature. Gridded ozone concentrations from CMAQ. | GISS driven by SRES A2 downscaled using MM5. 2050s | 1.6–3.2°C in 2050s compared with 1990s |
| 50 cities, eastern United States | Ozone-related hospitalizations and deaths | Concentration–response function from published epidemiologic literature. Gridded ozone concentrations from CMAQ. | GISS driven by SRES A2 downscaled using MM5. 2050s | 1.6–3.2°C in 2050s compared with 1990s |
| Los Angeles and San Diego regions, California, United States | Ozone-related hospitalizations and deaths | Concentration–response function from published epidemiologic literature. Gridded ozone concentrations. | HadCM3 driven by SRES A2, downscaled using MM5, then a photochemical model (CAMx) in the 2050s and 2090s | 2.1– 2.7°C in 2050s, and 4.6 to 5.5°C in 2090s. |
| England and Wales, United Kingdom | Exceedance days (ozone, particulates, NOx) | Statistical, based on meteorologic factors for high pollutant days (temperature, wind, speed); projections of U.K. and northwest Europe urban traffic emissions ozone precursors. | UKCIP scenarios 2020s, 2050s, 2080s | 0.57–1.38°C in 2020s; .89 –2.44°C in 2050s; 1.13–3.47°C in 2080s compared with 1961–1990 baseline |
| 10 world regions | Premature mortality from acute ozone exposure | Ozone-mortality coefficient from a study of 95 cities in the United States. | Coupled general circulation model with interactive chemistry (LMDz-INCA) driven by SRES A2 for 2030. | Baseline simulated for 2000 |

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an 0.11 to 0.27% increase in nonaccidental mortality and an average 0.31% increase in cardiovascular disease mortality. Ozone concentrations for Los Angeles in 2050 were projected under the SRES A2 emission scenario[105]. Using several estimates of the ozone exposure–response relationship, Hwang ***et al***.[105] projected that mortality and hospital admissions would together increase up to approximately 3.7%, with most of the projected increases < 1%, depending on the city and the health outcome. As part of a U.K. assessment of the potential impacts of climate change, Anderson ***et al***.[58] used projected daily meteorologic parameters for each day through December 2099, driven by the Intergovernmental Panel on Climate Change IS92a (business as usual) scenario, for a single grid point representing the British Isles. A global three-dimensional

**Table 1.** continuation

| Population projections and other assumptions | Main results | Reference |
|---|---|---|
| Population and age structure held constant at year 2000. Assumes no change from U.S. EPA 1996 national emissions inventory and A2; consistent increases in NOx and VOCs by 2050s. | A2 climate only: 4.5% increase in ozone related-deaths. Ozone elevated in all counties. A2 climate and precursors: 4.4% increase in ozone related-deaths. (Ozone in not elevated in all areas due to NOx interactions.) | Knowlton ***et al***. |
| Population and age structure held constant at year 2000. Assumes no change from U.S. EPA 1996 national emissions inventory and A2; consistent increases in NOx and VOCs by 2050s. | Maximum ozone concentrations increase for all cities, with the largest increases in cities with currently higher concentrations; 68% increase in average number of days/summer exceeding the 8-hr regulatory standard, resulting in 0.11–0.27% increase in nonaccidental mortality and an average 0.31% increase in cardiovascular disease mortality. | Bell ***et al***. |
| Population and age structure held constant. Assumes no change from U.S. EPA 1997 national emissions inventory and A2-consistent increases in NOx and VOCs by 2050s and 2090s . | Average increase in ozone peaks of 2.0–3.2 ppb in the 2050s , and 3.1–4.8 ppb in the 2090s. Increases in maximum peak concentrations are 2-3-fold higher. Percent increase in daily mortality in the 2050s range from 0.08 to 0.46 depending on the exposure–response relationship. Increases in the 2090s are 0.12–0.69. Projected increases in hospital admissions are higher. | Hwang ***et al***. |
| Population and age structure held constant. | Over all time periods, large decreases in days with high particulates and SO2; small decrease in other pollutants except ozone, which increases. If a threshold is assumed, then ozone is projected to increase premature deaths by 10, 20, and 40% for the years 2020, 2050, and 2080, respectively. | Anderson ***et al***. |
| Population growth and emissions under SRES A2. One realization included recently enacted legislative to control ozone, and another assumed maximum feasible reduction of ozone precursors. | Large increase in ozone in 2030 under the A2 scenario; global population–weighted 8-hr ozone increased 9.4 ppbv. Along with population growth, this was associated with approximately 500,000 additional deaths. Using a of threshold of 25 ppbv, 191,000 deaths worldwide could be avoided using currently enacted legislation, and 458,000 deaths could be avoided using maximum feasible reduction technologies. | West ***et al***. |

Abbreviations: CMAQ, Community Multiscale Air Quality; GISS, Goddard Institute for Space Studies; HadCM3, one of the climate models from the Hadley Centre, United Kingdom; NOx, nitrogen oxides; UKCIP, United Kingdom Climate Impacts Programme; VOC, volatile organic compound. Modified from Confalonieri ***et al***.[104].

chemistry model was used to calculate the influence of the projected increases in emissions of methane, carbon monoxide, and nitrogen oxides from human activities on the global distribution of ozone through the year 2100. The impact of climate change on increases in the frequency and severity of the meteorologic conditions that lead to summertime ozone episodes was projected to be reduced by changes in European emissions of ozone precursor species. When the authors assumed thresholds for the health effects of ozone, the increase in health effects due to ozone was relatively small. If no threshold was assumed, then ozone was projected to increase premature deaths by 10, 20, and 40% for the years 2020, 2050, and 2080, respectively. Approximately 500,000 excess deaths were estimated for the year 2030 due to the impacts of changing ozone concentrations and population growth in 10 world regions under the SRES A2 scenario[71]. The daily acute mortality coefficient per parts per billion per volume ozone was taken from a study of 95 cities in the United States[35]. Assuming a low concentration threshold of 25 ppbv and taking into consideration recently enacted legislation to control zone precursors, an estimated 191,000 deaths would be avoided globally (0.2% of the projected total number of deaths in 2030). An estimated 458,000 deaths would be avoided (0.5% of the projected total number of deaths in 2030) if currently available emission control technologies were aggressively employed globally. Sensitivity analyses showed that the results were significantly affected by the threshold assumed and the daily acute ozone mortality coefficient used.

## Discussion

Poor air quality currently affects the health of millions of people. Climate change has the potential to increase harmful exposures to elevated concentrations of ozone and PM2.5 through changes in regional weather patterns. However, there is high uncertainty about future projections. Sources of uncertainty include not only future climate change but also future emissions of greenhouse gases, ozone precursors, and other pollutants, as well as how population vulnerability and activity patterns may differ in the future. Because of the high uncertainty of the extent and effectiveness of future emissions reductions, most studies that projected the impacts of climate change on air quality focused on future climate change alone and held precursor emissions constant over future decades. Therefore, the focus was on examining the sensitivity of ozone concentrations to alternative future climates rather than on attempting to project actual future ozone concentrations. On the basis of a limited number of modeling studies, climate change is likely to increase ozone concentrations in highincome countries when precursor emissions are held constant, leading to increased morbidity and mortality. There is less certainty of the possible impact of climate change on fine particulate concentrations. More stringent emissions controls for ozone, PM2.5, and other pollutants can be expected with the growing body of evidence of the adverse health impacts of these air pollutants. Therefore, the extent to which climate change affects air quality will depend partially on ongoing regulatory control of ozone and PM2.5. At the same time, population sensitivity may change because of medical advances and changes in risk factors. The main public health responses to the projected health impacts of climate change are mitigation and adaptation. Adaptation is not an effective risk management strategy for poor air quality, because physiologic mechanisms to decrease susceptibility to ozone and other air pollutants are limited. Therefore, if improved model experiments continue to project higher ozone concentrations under a changing climate, rapid reductions of emissions from fossil- fuel burning are needed to protect the health of current and future generations. Evidence suggests that reducing current tropospheric ozone concentrations reduces morbidity and mortality, with significant savings in medical care costs[106]. For relevant agencies and institutions to develop appropriate and timely responses, additional research is needed to reduce the uncertainties associated with projections of the health impacts of changing concentrations of ozone and PM due to climate change. Research is needed to better understand the impacts of future emissions pathways, climate change impacts on concentrations of fine particles and gases, how changing weather patterns could influence the frequency and severity of episodes of poor air quality, population sensitivity, and how these factors might interact. Increasing greenhouse gas emissions suggest that future air quality could decline without increased regulations and development and deployment of new technologies.

## Appendix 1: SRES

SRES were developed by the Intergovernmental Panel on Climate Change as alternative images of how the future might unfold[107]. Four different narrative storylines were developed to describe the relationships between the driving forces of greenhouse gas emissions and their evolution. Probabilities or likelihood were not assigned to the individual scenarios. There is no single most likely, or best guess, scenario. None of the scenarios represents an estimate of a central tendency for all driving forces or emissions. Each SRES storyline assumes a distinctly different direction for future development, such that the four storylines differ in increasingly irreversible ways. The storylines were created along two dimensions: global versus regional development patterns and whether economic or environmental concerns would be primary. It is important to note that the scenarios do not cover all possible future worlds. For example, there is no SRES world in which absolute incomes are constant or falling. The A2 and B2 storylines are frequently used in modeling health impacts. The A2 storyline describes a heterogeneous world with an underlying theme of selfreliance and preservation of local identities. Fertility patterns across regions vary slowly, resulting in continuously increasing global population. Economic development is primarily region oriented, and per capita economic growth and technological change are fragmented and slower compared with the other scenarios. The B2 storyline describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population (at a rate slower than that of A2), intermediate levels of economic development, and less rapid and more diverse technological change. The total cumulative CO2 emissions are categorized as very high in the A2 scenario [> 1,800 GtC (gigatons)] and medium-low in the B2 scenario (1,100–1,450 GtC) in 2100.

## References

1. WHO. ***World Health Report 2002: Reducing Risks, Promoting Healthy Life***. Geneva:World Health Organization; 2002.
2. Solomon S, Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, Chen Z, Chidthaisong A, Gregory JM, Hegerl GC, Heimann M, Hewitson B, Hoskins BJ, Joos BJ, Jouzel J, Kattsov V, Lohmann U, Matsuno T, Molina M, Nicholls N, Overpeck J, Raga G, Ramaswamy V, Ren J, Rusticucci M, Somerville R, Stocker TF, Whetton P, Wood RA, Wratt D. Technical summary. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller HL, editors. ***Climate Change 2007: The Physical Science Basis***. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK; New York, NY:Cambridge University Press; 2007. p. 19–91.
3. Kossmann M, Sturman A. The surface wind field during winter smog nights in Christchurch and coastal Canterbury, New Zealand. ***Int J Climatol*** 2004; 24:93–108.
4. Rappengluck B, Oyola P, Olaeta I, Fabian P. The evolution of photochemical smog in the metropolitan area of Santiago de Chile. ***J Appl Meteorol*** 1999; 39:275–290.
5. Alvarez E, de Pablo F, Tomás C, Rivas L. Spatial and temporal variability of ground-level ozone in Castilla-León (Spain). ***Int J Biometeorol*** 2000; 44:44–51.
6. Eiguren-Fernandez A, Miguel AH, Froines JR, Thurairatnam S, Avol EL. Seasonal and spatial variation of polycyclic aromatic hydrocarbons in vapor-phase and PM2.5 in Southern California urban and rural communities. ***Aerosol Sci Technol*** 2004; 38:447–455.
7. Hazenkamp-Von Arx ME, Gotschi T, Ackermann-Liebrich U, Bono R, Burney P, Cyrys J, Jarvis D, Lillienbergf L, Luczynskad C, Maldonado JA, Angeles J, Marco R, Mi Y, Modigk L, Bayer-Oglesbya L, Payol F, Soonm A, Sunyerh J, Villanin S, Weylero J, Künzli N. PM2.5 and NO2 assessment in 21 European study centres of ECRHS II: annual means and seasonal differences. ***Atmos Environ*** 2004; 38:1943–1953.
8. Kassomenos PA, Sindosi OA, Lolis CJ, Chaloulakou A. On the relation between seasonal synoptic circulation types and spatial air quality characteristics in Athens, Greece. ***J Air Waste Manag Assoc*** 2003; 53:309–324.
9. Nagendra S, Khare M. Diurnal and seasonal variations of carbon monoxide and nitrogen dioxide in Delhi City. ***Int J Environ Pollut*** 2003; 19:75–96.
10. Rao ST, Ku JY, Berman S, Zhang D, Mao H. Summertime characteristics of the atmospheric boundary layer and relationships to ozone levels over the eastern United States. ***Pure Appl Geophys*** 2003; 160:21–55.

11. Schichtel BA, Husar RB. Eastern North American transport climatology during high- and low-ozone days. ***Atmos Environ*** 2001; 35:1029–1038.
12. McGregor GR. Basic meteorology. In: Holgate S, Samet JM, Koren HS, Maynard RL, editors. ***Air Pollution and Health***. London: Academic Press;1999. p. 21–49.
13. Pal Arya S. Air pollution meteorology and dispersion. ***Bound Lay Meteorol*** 2000; 94:171–172.
14. Nilsson ED, Paatero J, Boy M. Effects of air masses and synoptic weather on aerosol formation in the continental boundary layer. Tellus Series B. ***Chem Phys Meteorol*** 2001; 53:462–478.
15. Nilsson ED, Rannik U, Kulmala M, Buzorius G, O'Dowd CD. Effects of continental boundary layer evolution, convection, turbulence and entrainment, on aerosol formation. Tellus Series B. ***Chem Phys Meteorol*** 2001; 53:441–461.
16. Lennartson GJ, Schwartz MD. A synoptic climatology of surface-level ozone in Eastern Wisconsin, USA. ***Clim Res*** 1999; 13:207–220.
17. Scott GM, Diab RD. Forecasting air pollution potential: a synoptic climatological approach. ***J Air Waste Manag Assoc*** 2000; 50:1831–1842.
18. Tanner PA, Law PT. Effects of synoptic weather systems upon the air quality in an Asian megacity. ***Water Air Soil Pollut*** 2002; 136:105–124.
19. Yarnal B, Comrie AC, Frakes B, Brown DP. Developments and prospects in synoptic climatology. ***Int J Climatol*** 2001; 21:1923–1950.
20. Cheng WL, Pai JL, Tsuang BJ, Chen CL. Synoptic patterns in relation to ozone concentrations in west-central Taiwan. ***Meteorol Atmos Phys*** 2001; 78:11–21.
21. Dayan U, Levy I. Relationship between synoptic-scale atmospheric circulation and ozone concentrations over Israel. ***J Geophys Res Atmos*** 2002; 107(D24):4813.
22. Grossi P, Philippe T, Martilli A, Clappier A. Effect of sea breeze on air pollution in the greater Athens area. Part II: Analysis of different emission scenarios. ***J Appl Meteorol*** 1999; 39:563–575.
23. Hess GD, Tory KJ, Puri K, Cope ME, Lee S, Manins PC, Young M. The Australian air quality forecasting system. Part II: case study of a Sydney 7-day photochemical smog event. ***J Appl Meteorol*** 2003; 43:663–679.
24. Kitada T, Regmi RP. Dynamics of air pollution transport in late wintertime over Kathmandu valley, Nepal, as revealed with numerical simulation. ***J Appl Meteorol*** 2003; 12:1770–1798.
25. Liu HP, Chan JCL. Boundary layer dynamics associated with a severe air-pollution episode in Hong Kong. ***Atmos Environ*** 2002; 36:2013–2025.
26. Ma YM, Lyons TJ. Recirculation of coastal urban air pollution under a synoptic scale thermal trough in Perth, Western Australia. ***Atmos Environ*** 2003; 37:443–454.
27. Pillai PS, Moorthy KK. Aerosol mass-size distributions at a tropical coastal environment: response to mesoscale and synoptic processes. ***Atmos Environ*** 2001; 35:4099–4112.
28. Triantafyllou AG. PM10 pollution episodes as a function of synoptic climatology in a mountainous industrial area. ***Environ Poll*** 2001; 112:491–500.
29. Gallardo L, Olivares G, Langner L, Aarhus B. Coastal lows and sulfur air pollution in Central Chile. ***Atmos Environ*** 2002; 36:3829–3841.
30. Wang T, Kwok JYH. Measurement and analysis of a multiday photochemical smog episode in the Pearl River delta of China. ***J Appl Meteorol*** 2002; 42:404–416.
31. Bernard SM, Samet JM, Grambsch A, Ebi KL, Romieu I. The potential impacts of climate variability and change on air pollution-related health effects in the United States. ***Environ Health Perspect*** 2001; 109:199–209.
32. Rainham DGC, Smoyer KE, Burnett RT. Spatial synoptic classification of air pollution and human mortality associations in Toronto, Canada: past relationships and policy implications. ***Am J Epidemiol*** 2001; 153(suppl S):1015.
33. Semazzi F. Air quality research: perspective from climate change modelling research. ***Environ Int*** 2003; 29:253–261.
34. Swart R, Amann M, Raes F, Tuinstra W. A good climate for clean air: linkages between climate change and air pollution. ***Clim Change*** 2004; 66:263–269.
35. Bell ML, McDermott A, Zeger SL, Samet JM, Dominici F. Ozone and mortality in 95 US urban communities, 1987 to 2000. ***JAMA*** 2004; 292:2372–2378.
36. Bell ML, Goldberg R, Hogrefe C, Kinney PL, Knowlton K, Lynn B, Rosenthal J, Rosenzweig C, Patz J. Climate change, ambient ozone, and health in 50 US cities. ***Clim Change*** 2007; 82:61–76.
37. Gryparis A, Forsberg B, Katsouyanni K, Analitis A, Touloumi G, Schwartz J, Samoli E, Medina S, Anderson HR, Niciu EM, Wichmann HE, Kriz B, Kosnik M, Skorkovsky J, Vonk JM, Dörtbudak Z. Acute effects of ozone on mortality from the "air pollution and health: a European approach" project. ***Am J Respir Crit Care Med*** 2004; 170:1080–1087.
38. Ito K, De Leon SF, Lippmann M. Associations between ozone and daily mortality: analysis and meta-analysis. ***Epidemiology*** 2005; 16:446–457.
39. Mudway IS, Kelly FJ. Ozone and the lung: a sensitive issue. ***Mol Aspects Med*** 2000; 21:1–48.
40. Suh HH, Bahadori T, Vallarino J, Spengler JD. Criteria air pollutants and toxic air pollutants. ***Environ Health Perspect*** 2000; 108(suppl 4):625–633.
41. U.S. EPA. Review of the National Ambient Air Quality Standards for Ozone: Policy Assessment of Scientific and Technical Information. OAOPS Staff Paper. EPA-452/R-07- 007. Research Triangle Park, NC: U.S. Environmental Protection Agency; 2007. [accessed 1 May 2008]. Available from: http://www.epa.gov/ ttnnaaqs/standards/ozone/data/2007_07_ozone_staff_ paper.pdf
42. Mott JA, Mannino DM, Alverson CJ, Kiyu A, Hashim J, Lee T, Falter K, Redd SC. Cardiorespiratory hospitalizations associated with smoke exposure during the 1997 Southeast Asian forest fires. ***Int J Hyg Environ Health*** 2005; 208:75–85.
43. Bates DV. Ambient ozone and mortality. ***Epidemiology*** 2005; 16(4):427–429.
44. Syri S, Karvosenoja N, Lehtila A, Laurila T, Lindfors V, Tuovinen JP. Modeling the impacts of the Finnish Climate Strategy on air pollution. ***Atmos Environ*** 2002; 36:3059–3069.

45. Webster MD, Babiker M, Mayer M, Reilly JM, Harnisch J, Hyman R, Sarofim MC, Wang C. Uncertainty in emissions projections for climate models. ***Atmos Environ*** 2002; 36:3659–3670.
46. Hogrefe C, Biswas J, Lynn B, Civerolo K, Ku J-Y, Rosenthal J, Rosenzweig C, Goldberg R, Kinney PL. Simulating regional-scale ozone climatology over the Eastern United States: model evaluation results. ***Atmos Environ*** 2004; 38:2627–2638.
47. Jones JM, Davies TD. The influence of climate on air and precipitation chemistry over Europe and downscaling applications to future acidic deposition. ***Clim Res*** 2000; 14(1):7–24.
48. Liao H, Chen WT, Seinfeld JH. Role of climate change in global predictions of future tropospheric ozone and aerosols. ***J Geophys Res Atmos*** 2006; 111:D12304.
49. Mickley LJ, Jacob DJ, Field BD, Rind D. Effects of future climate change on regional air pollution episodes in the United States. ***Geophys Res Lett*** 2004; 31:L24103.
50. Murazaki K, Hess P. How does climate change contribute to surface ozone change over the United States? ***J Geophys Res*** 2006; 111:D05301.
51. Racherla PN, Adams PJ. Sensitivity of global tropospheric ozone and fine particulate matter concentrations to climate change. ***J Geophys Res Atmos*** 2006; 111:D24103.
52. Sousounis PJ, Scott CPJ, Wilson ML. Possible climate change impacts on ozone in the Great Lakes region: some implications for respiratory illness. ***J Great Lakes Res*** 2002; 28:626–642.
53. Prather M, Gauss M, Berntsen T, Isaksen I, Sundet J, Bey I, Brasseur G, Dentener F, Derwent R, Stevenson D, Grenfell L, Horowitz L, Jacob D, Mickley L, Lawrence M, von Kuhlmann R, Muller J-F, Pitari G, Rogers H, Johnson M. Pyle J, Law K, van Weele m, Wild O. Fresh air in the 21st century? ***Geophys Res Lett*** 2003; 30(2):1100.
54. Cifuentes L, Borja-Aburto VH, Gouveia N, Thurston G, Davis DL. Assessing the health benefits of urban air pollution reductions associated with climate change mitigation (2000–2020): Santiago, São Paulo, Mexico City, and New York City. ***Environ Health Perspect*** 2001; 109:419–425.
55. Metcalfe SM, Whyatt JD, Derwent RG, O'Donoghue M. The regional distribution of ozone across the British Isles and its response to control strategies. ***Atmos Environ*** 2002; 36:4045–4055.
56. Fiore AM, Jacob DJ, Field DB, Streets DG, Fernandes SD, Jang C. Linking ozone pollution and climate change: the case for controlling methane. ***Geophys Res Lett*** 2002; 29 (19):919.
57. Solomon KR, Tang XY, Wilson SR, Zanis P, Bais AF. Changes in tropospheric composition and air quality due to stratospheric ozone depletion. ***Photochem Photobiol Sci*** 2003; 2:62–67.
58. Anderson HR, Derwent RG, Stedman J. Air pollution and climate change. In: UK Department of Health. ***Health Effects of Climate Change in the UK***. London: UK Department of Health; 2001. p. 193–217.
59. Aw J, Kleeman MJ. Evaluating the first-order effect of inter-annual temperature variability on urban air pollution. ***J Geophys Res*** 2003; 108:7/1–7/18.
60. Derwent RG, Collins WJ, Johnson CE, Stevenson DS. Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects. ***Clim Change*** 2001; 49:463–487.
61. Hogrefe C, Civerolo K, Ku J-Y, Lynn B, Rosenthal J, Knowlton K, Solecki B, Cox J, Small C, Gaffin S, Goldberg R, Rosenzweig C, Kinney PL. ***Modeling the Air Quality Impacts of Climate and Land Use Change in the New York City Metropolitan Area***. Models-3 Users' Workshop; 18–20 October 2004; Research Triangle Park, NC. [accessed 15 Sept 2008]. Available: http://wwwcmascenterorg/html/2004_workshop/abstracts/ Climate%20Multiscale/Hogrefe_abstractpdf
62. Hogrefe C, Lynn B, Civerolo K, Ku J-Y, Rosenthal J, Rosenzweig C, Goldberg R, Gaffin S, Knowlton K, Kinney PL. Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions. ***J Geophys Res*** 2004; 109:D22301
63. Hogrefe C, Leung R, Mickley L, Hunt S, Winner D. Considering climate change in air quality management. ***Environmental Manager*** 2005; October:19–23.
64. Hogrefe C, Lynn B, Rosenzweig C, Goldberg R, Civerolo K, Ku JY, Rosenthal J, Knowlton K, Kinney PL. ***Utilizing CMAQ Process Analysis to Understand the Impacts of Climate Change on Ozone and Particulate Matter***. Models-3 Users' Workshop, 26–28 September 2005. Chapel Hill, NC. [accessed 15 Sept 2008]. Available from: http://www.cmascenter.org/conference/2005/abstracts/3_2.pdf
65. Hogrefe C, Civerolo K, Ku J-Y, Lynn B, Rosenthal J, Solecki B, Small C, Gaffin S, Knowlton K, Goldberg R, Rosenzweig C, Kinney PL. Air quality in future decades — determining the relative impacts of changes in climate, anthropogenic and biogenic emissions, global atmospheric composition, and regional land use. In: ***Proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modeling and Its Application***; 2004 25–29 October; Banff, Canada. New York: Springer; 2006. p. 217–226.
66. Johnson CE, Stevenson DS, Collins WJ, Derwent RG. Role of climate feedback on methane and ozone studied with a coupled ocean-atmosphere-chemistry model. ***Geophys Res Lett*** 2001; 28:1723–1726.
67. Leung RL Gustafson WI Jr. Potential regional climate change and implications to US air quality. ***Geophys Res Lett*** 2005; 32(16).
68. Steiner AL, Tonse S, Cohen RC, Goldstein AH, Harley RA. Influence of future climate and emissions on regional air quality in California. ***J Geophys Res Atmos*** 2006; 111:D18303.
69. Stevenson DS, Johnson CE, Collins WJ, Derwent RG, Edwards JM. Future estimates of tropospheric ozone radiative forcing and methane turnoveræthe impact of climate change. ***Geophys Res Lett*** 2000; 27:2073–2076.
70. Taha H. ***Potential Impacts of Climate Change on Tropospheric Ozone in California: A Preliminary Episodic Modeling Assessment of the Los Angeles Basin and the Sacramento Valley***. Berkeley, CA: Lawrence Berkeley National Laboratories; 2001.
71. West JJ, Szopa S, Hauglustaine DA. Human mortality effects of future concentrations of tropospheric ozone. ***CR Geoscience*** 2007; 339:775–783.

72. Forkel R, Knoche R. Regional Climate Change and Its Impact on Photooxidant Concentrations in Southern Germany: Simulations with a Coupled Regional Climatechemistry Model. ***J Geophys Res*** 2006; 111:D12302.
73. Civerolo, K, Hogrefe C, Lynn B, Rosenthal J, Ku J-Y, Solecki W, Cox J, Small C. Estimating the effects of increased urbanization on future surface meteorology and ozone concentrations in the New York City metropolitan region. ***Atmos Environ*** 2007; 41(9): 803–1818.
74. Kinney P, Rosenthal J, Rosenzweig C, Hogrefe C, Solecki W, Knowlton K, Small C, Lynn B, Civerolo K, Ku J, Goldberg R, Oliveri C. Assessing the potential public health impacts of changing climate and land use: NY Climate and Health Project. In: Ruth M, Donaghy K, Kirshen P, editors. ***Regional Climate Change and Variability: Impacts and Responses.*** New Horizons in Regional Science Series. Cheltenham, UK: Edward Elgar; 2006. p. 161–189.
75. Knowlton K, Rosenthal JE, Hogrefe C, Lynn B, Gaffin S, Goldberg R, Rosenzweig C, Civerolo K, Ku J, Kinney PL. Assessing ozone-related health impacts under a changing climate. ***Environ Health Perspect*** 2004; 112:1557–1563.
76. Dominici F, Peng RD, Bell ML, Pham L, McDermott A, Zeger SL, Samet JM. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. ***JAMA*** 2006; 295(10): 1127–1134.
77. Ibald-Mulli A, Wichmann HE, Kreyling W, Peters A. Epidemiological evidence on health effects of ultrafine particles. ***J Aerosol Med*** 2002; 15:189–201.
78. Kappos AD, Bruckmann P, Eikmann T, Englert N, Heinrich U, Hoppe P, Koch E, Krause GHM, Kreyling WG, Rauchfuss K, Rombout P, Schulz-Klemp V, Thiel WR, Wichmann H-E. Health effects of particles in ambient air. ***Int J Hyg Environ Health*** 2004; 207:399–407.
79. Pope CA III, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. ***JAMA*** 2002; 287:1132–1141.
80. Jacobson MZ. On the causal link between carbon dioxide and air pollution mortality. ***Geophys Res Lett*** 2008; 35:L03809.
81. Guttikunda SK, Carmichael GR, Calori G, Eck C, Woo J-H. The contribution of megacities to regional sulfur pollution in Asia. ***Atmos Environ*** 2003; 37:11–22.
82. Hicks BB. Planning for air quality concerns of the future. ***Pure Appl Geophys*** 2003; 160(1–2):57–74.
83. Jensen SS, Berkowicz R, Winther M, Palmgren F, Zlatev Z. Future air quality in Danish cities due to new emission and fuel quality directives of the European Union. ***Int J Vehicle Design*** 2001; 27:195–208.
84. Slanina S, Zhang YH. Aerosols: connection between regional climatic change and air quality (IUPAC Technical Report). ***Pure Applied Chem*** 2004; 76:1241–1253.
85. Ansmann A, Bosenberg J, Chaikovsky A, Comeron A, Eckhardt S, Eixmann R, Freudenthaler V, Ginoux P, Komguem L, Linne H, Lopez Marquez MA, Matthias V, Mattis I, Mitev V, Müller D, Music S, Nickovic S, Pelon J, Sauvage L, Sobolewsky P, Srivastava MK, Stohl A, Torres O, Vaughan G, Wandinger U, Wiegner M. Long-Range Transport Of Saharan Dust To Northern Europe: The 11-16 October 2001 outbreak observed with EARLINET. ***J Geophys Res Atmos*** 2003; 108(D24):4783.
86. Bergin MS, West JJ, Keating TJ, Russell AG. Regional atmospheric pollution and transboundary air quality management. ***Annu Rev Environ Resources*** 2005; 30:1–37.
87. Buchanan CM, Beverland IJ, Heal MR. The influence of weather-type and long-range transport on airborne particle concentrations in Edinburgh, UK. ***Atmos Environ*** 2002; 36:5343–5354.
88. Chan CY, Chan LY, Lam KS, Li YS, Harris JM, Oltmans SJ. Effects of Asian air pollution transport and photochemistry on carbon monoxide variability and ozone production in subtropical coastal south China. ***J Geophys Res Atmos*** 2002; 107(D24):4746.
89. Claiborn, CS, Finn D, Larson TV, Koenig JQ. Windblown dust contributes to high PM25 concentrations. ***J Air Waste Manag Assoc*** 2000; 50:1440–1445.
90. Martin BD, Fuelberg HE, Blake NJ, Crawford JH, Logan LA, Blake DR, Sachseet GW. Long-range transport of Asian outflow to the equatorial Pacific. ***J Geophys Res Atmos*** 2002; 108(D2):8322.
91. He Z, Kim YJ, Ogunjobi KO, Hong CS. Characteristics of PM2.5 species and long-range transport of air masses at Taean background station, South Korea. ***Atmos Environ*** 2003; 37:219–230.
92. Helmis CG, Moussiopoulos N, Flocas HA, Sahm P, Assimakopoulos VD, Naneris C, Maheras P. Estimation of transboundary air pollution on the basis of synoptic-scale weather types. ***Int J Climatol*** 2003; 23:405–416.
93. Holloway T, Fiore A, MG Hastings MG. Intercontinental transport of air pollution: will emerging science lead to a new hemispheric treaty? ***Environ Sci Technol*** 2003; 37:4535–4542.
94. Jaffe D, McKendry I, Anderson T, Price H. Six 'new' episodes of trans-Pacific transport of air pollutants. ***Atmos Environ*** 2003; 37:391–404.
95. Jaffe D, Bertschi I, Jaegle L, Novelli P, Reid JS, Tanimoto H, Vingarzan R, Westphal DL. Long-range transport of Siberian biomass burning emissions and impact on surface ozone in western North America. ***Geophys Res Lett*** 2004; 31:L16106.
96. Kato S, Kajiia Y, Itokazuc R, Hirokawad J, Kodae S, Kinjof Y. Transport of atmospheric carbon monoxide, ozone, and hydrocarbons from Chinese coast to Okinawa island in the Western Pacific during winter. ***Atmos Environ*** 2004; 38:2975–2981.
97. Kellogg CA, Griffin DW. Aerobiology and the global transport of desert dust trends. ***Ecol Evol*** 2006; 21(11):638–644.
98. Liang Q, Jaegle L, Jaffe DA, Weiss-Penzias P, Heckman A, Snow JA. Long-range transport of Asian pollution to the northeast Pacific: seasonal variations and transport pathways of carbon monoxide**.** ***J Geophys Res Atmos*** 2004; 109(D23):D23S07.

99. Moore KG, Clarke AD, Kapustin VN, Howell SG. Long-range transport of continental plumes over the Pacific Basin: aerosol physiochemistry and optical properties during PEM-Tropics A and B. ***J Geophys Res Atmos*** 2003; 108(D2):8236.

100. Ryall DB, Derwent RG, Manning AJ, Redington AL, Corden J, Millington W, Simmonds PG, O'Doherty S, Carslaw N, Fullere GW. The origin of high particulate concentrations over the United Kingdom, March 2000. ***Atmos Environ*** 2002; 36:1363–1378.

101. Tu FH, Thornton DC, Brandy AR, Carmichael GR, Tang YH, Thornhill KL, Sachse GW, Blake DR. Long-range transport of sulfur dioxide in the central Pacific. ***J Geophys Res Atmos*** 2004; 109(D15): D15S08.

102. Langmann B, Bauer SE, Bey I. The influence of the global photochemical composition of the troposphere on European summer smog. Part I: Application of a global to mesoscale model chain. ***J Geophys Res Atmos*** 2003; 108(D4):4146.

103. Takemura T, Nakajima T, Nozawa T, Aoki K. Simulation of future aerosol distribution, radiative forcing, and longrange transport in East Asia. ***J Meteorol Soc Japan*** 2001; 79:1139–1155.

104. Confalonieri U, Menne B, Akhtar R, Ebi KL, Hauengue M, Kovats RS, Revich B, Woodward A. Human health. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hansson CE, editors. ***Climate Change 2007: Impacts, Adaptation and Vulnerability***. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press; 2007.

105. Hwang R, Burer MJ, Bell M. ***Smog in the Forecast: Global Warming, Ozone Pollution and Health in California***. San Francisco: National Resources Defense Council; 2004.

106. Ostro BD, Tran T, Levy JI. The health benefits of reduced tropospheric ozone in California. ***J Air Waste Manag Assoc*** 2006; 56:1007–1021.

107. Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner HH, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, Van Rooijen S, Victor N, Dadi Z. ***Special Report on Emissions Scenarios***. Cambridge, U.K.: Cambridge University Press; 2000.

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