Technical Challenges of Multipollutant Air Quality Management
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11. Global Change and Air Quality

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Abstract

World population growth, industrialization, energy demand, and environmental goals are presently driving rapid global change in emissions with complex consequences for climate, air quality, and ecosystems. As North America strives to reduce its pollutant emissions to meet air quality standards, rising global emissions may increase background pollutant concentrations and offset some of the gains. Climate change can have important impacts on air quality, and in turn, air pollutants are recognized to be major climate forcing agents. Policies to mitigate climate change could have important implications for air quality and vice versa. It is becoming increasingly important to view air quality from a global perspective and to integrate air quality and climate stabilization goals in the design of environmental policy. This chapter presents a review and analysis of these issues with the air quality perspective focused on tropospheric ozone, particulate matter, and mercury.

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rising emissions in the developing world may increase background pollutant concentrations and offset some of the gains. Climate change can have important impacts on air quality, and in turn air pollutants are recognized to be major climate forcing agents. Policies to mitigate climate change could have important implications for air quality and vice versa. It is becoming increasingly important to view air quality from a global perspective and to integrate air quality and climate stabilization goals in the design of environmental policy. This chapter presents a review and analysis of these issues with the air quality perspective focused on tropospheric ozone, particulate matter (PM), and mercury.

11.1 Intercontinental Pollution

Intercontinental transport of pollution between Asia, North America, and Europe takes place via the prevailing westerly winds. Asian dust events in the western United States provide a vivid image of this intercontinental transport (Fig. 11.1). Satellite observations of dust transport across the Pacific show that sources in Asia can affect U.S. surface sites in less than a week (Husar et al. *2001*), although the average transport time is 2–3 weeks (Liu and Mauzerall *2005*). Circumpolar transport of pollution around the globe at northern mid-latitudes takes place on a time scale of a month, and meridional mixing of the northern hemisphere requires about three months. Global-scale mixing of the troposphere takes place on a time scale of a year. These time scales can be used to determine the appropriate spatial scope of air quality policy depending on the atmospheric lifetime of the pollutant considered. Pollutants with lifetimes of a few days or less do not generally warrant an intercontinental perspective, while pollutants with lifetimes longer than a month are best addressed from that perspective.

Fig. 11.1 Visibility impairment at Glen Canyon, Arizona, during an Asian dust event on April 16, 2001 (*right photo*) as compared to a clear day (*left photo*). (Source: U.S. EPA (http://www.epa.gov/visibility/program.html). See Fairlie et al. (*2007*) for a discussion of the April 2001 dust events including evidence that the dust was of Asian origin)

Mercury has long been recognized by the scientific community as a global pollutant for which regulation can best be accomplished by a global emissions treaty (Selin *2005*). Mercury is mostly emitted in elemental form Hg(0), which is oxidized in the atmosphere to Hg(II) and subsequently deposited. The atmospheric residence time of Hg(0) is on the order of a year (Selin et al. *2007*), sufficiently long to allow transport on a global scale. Although local emissions may affect near-source "hot spots" (Dvonch et al. *2005*; Keeler et al. *2006*), global model simulations indicate that only 20–30% of U.S. mercury deposition originates from North American sources, and that anthropogenic Asian sources contribute a comparable fraction (Seigneur et al. *2004*; Travnikov *2005*; Selin and Jacob *2008*;

Selin et al. *2008*). Asian emissions of mercury have been rapidly increasing over the past two decades (Wu et al. *2006*) while North American emissions have been decreasing (Fig. 11.2).

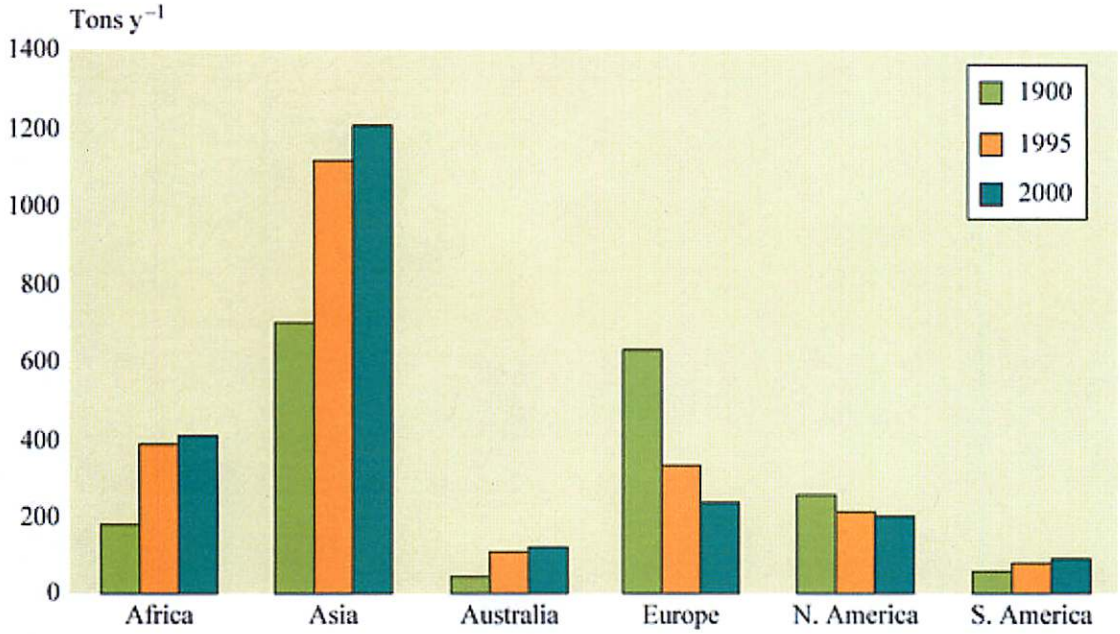

Fig. 11.2 Global trend of mercury anthropogenic emissions by continent, 1990–2000. (Data from Pacyna et al. *2006*)

Intercontinental influence on surface ozone can also be significant. Ozone has a lifetime of days in the continental boundary layer but several weeks in the free troposphere. It is produced in the free troposphere from anthropogenic precursors vented from the source continents, most importantly methane and NO_x (Fiore et al. *2002*). Methane has an atmospheric lifetime of 10 years and thus produces ozone on a global scale. Observations at northern mid-latitudes have shown a rising ozone background over the past century (Marenco et al. *1994*), and observations in North America show a continuing rise in background ozone in the past few decades (Lin et al. *2000*; Jaffe et al. *2003*; Jaffe and Ray *2007*). These increases can only be partly explained by anthropogenic emissions of NO_x and methane (Wang and Jacob *1998*; Fusco and Logan *2003*; Lamarque et al. *2005*) and could reflect additional factors such as lightning (Mickley et al. *2001*), fires (Jaffe et al. *2004*) and atmospheric dynamics (Ordonez et al. *2007*).

EPA (*2003*) defines a policy-relevant background (PRB) as the ozone concentration that would be present in U.S. surface air in the absence of North American anthropogenic emissions, and thus not amenable to regulation under current policy frameworks. The PRB has been used by EPA as a baseline to quantify the incremental health impacts of North American pollution sources. The present-day PRB is in the range 20–40 ppbv (Fiore et al. *2003*), which represents a significant increment toward ozone air quality standards (Fig. 11.3). At least half of this PRB is anthropogenic (Mickley et al. *2001*; Shindell and Favulegi *2002*; Fiore et al. *2003*; Lamarque et al. *2005*), with a growing contribution from Asia. Asian NO_x emissions have doubled over the past decade and presently enhance surface ozone concentrations in the United States by 3–7 ppbv according to global models (Zhang et al. *2008a*). A recent study conducted by the U.S. National Academy of Sciences concludes that the association between short-term changes in ozone concentrations and mortality is generally linear throughout most of

the concentration range, although uncertainties make it difficult to determine whether there is a threshold for the association at the lower end of the range. The NRC concludes that if there is a threshold, it is likely to be below the current NAAQS (NRC *2008*). Thus, enhancements in ozone concentrations resulting from international transport are implicated in increases in premature mortality rates.

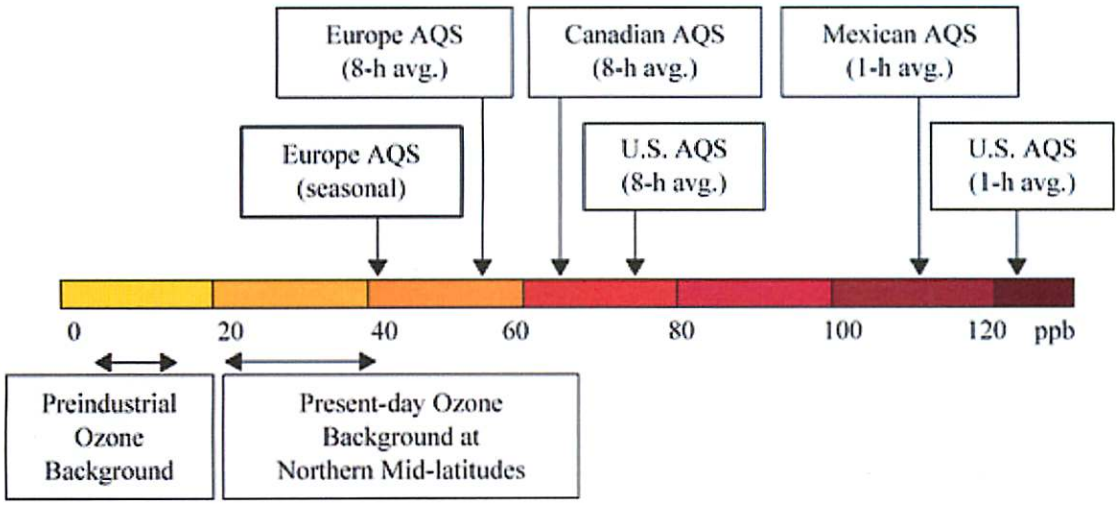

Fig. 11.3 Ozone Air Quality Standards (AQS) and background surface ozone concentrations. The U.S. 8-h AQS was reduced to 75 ppb in 2008. The U.S. EPA is presently (January 2010) considering reducing its 8-h AQS from 75 ppb to a value in the range 60–70 ppb. EPA is also proposing a secondary seasonal standard in a range between 7 and 15 ppm-h (weighted, cumulative exposure to ozone during daylight hours over a three-month growing season) to reduce ozone damage to vegetation

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Intercontinental influence on PM is limited by scavenging during transport (Tarrason and Iversen *1998*; Park et al. *2004*). A major exception is the Arctic in winter–spring, where boundary layer transport of European pollution under dry stratified conditions leads to the phenomenon known as "Arctic haze" (Barrie *1986*). Observations and models for the western United States indicate surface air concentrations of Asian sulfate of the order of 0.1 mg m^{-3} on an annual mean basis (Heald et al. *2006*; Park et al. *2006*; Liu and Mauzerall *2007*; Liu et al. *2008*), while van Donkelaar et al. (*2008*) report 0.13–0.17 mg m^{-3} for western Canada in spring. These intercontinental pollution enhancements are of little concern for air quality standards, though they could affect visibility standards under the Regional Haze Rule (Park et al. *2006*).

In addition to ozone and PM, recent air quality policy has focused on a large number of hazardous air pollutants (HAPs) that can be harmful to human health. The U.S. EPA lists 187 HAPs with atmospheric lifetimes ranging from minutes to years, which determine their potential for intercontinental transport. Most have sufficiently short lifetimes (less than a day) that intercontinental transport is not an issue.

11.2 Effects of Climate Change on Air Quality

Air quality is highly sensitive to weather, and it follows that a change in climate (i.e., in the long-term statistics of weather) may have important air quality implications. Jacob and Winner (*2009*) give a

recent review. Major heat waves in the eastern United States in 1988 and in Europe in 2003 were associated with intense pollution episodes (Lin et al. *2001*; Guerova and Jones *2007*). Such heat waves are likely to become more frequent in the future climate (Christensen et al. *2007*). Interest in the effect of climate change on U.S. air quality has grown in recent years, including in particular through the EPA Global Change Research Program. In Mexico, there are particular concerns about the effects of drought-related forest fires on air quality and whether or not the frequency of severe droughts might be enhanced by climate change. The effect of forest fires on urban air quality in Mexico can be substantial. For example, in the spring of 2005 metropolitan Guadalajara experienced one of the most severe air quality episodes in its history due to a fire in the La Primavera forest (INE-SEMARNAT *2006a*).

11.2.1 Twenty-First Century Climate Change

Increasing greenhouse gas concentrations over the twenty-first century are expected to drive significant climate change. Current projections draw mainly from four socioeconomic scenarios constructed by the Special Report on Emission Scenarios (SRES) of the IPCC (SRES *2001*): A1 (rapid economic growth and efficient introduction of new technologies), A2 (very heterogeneous world with sluggish economic growth), B1 (convergent world with rapid introduction of clean and efficient technologies), and B2 (focus on sustainability, intermediate economic development). The A1 scenario further distinguishes three sub-scenarios (A1FI, fossil intensive; A1T, predominantly non-fossil; and A1B, balanced across energy sources) by technological emphasis. SRES (*2001*) reports emission projections for greenhouse and other gases developed by a number of economic models for the different scenarios. The IPCC (*2001*) reports the multi-model means, and these are the standard greenhouse emission scenarios used in global climate models. The IPCC also includes consistent future scenarios for aerosol and ozone precursor emissions, but these are generally not used in future-climate projections because of the difficulty of converting them into future perturbations to concentrations and radiative budgets. These issues are discussed in Sect. 11.4.

The global climate models (GCMs) used in projections of twenty-first century climate change simulate the climate of the Earth by solving the primitive equations for atmospheric dynamics and physics on a global scale, generally including some coupling with ocean and land dynamics. The IPCC (Christensen et al. *2007*; Meehl et al. *2007*) reports climate change projections for the twenty-first century from a large ensemble of GCMs applied to the SRES scenarios. The projected 1990–2050 increases in global mean surface temperatures range from 0.8 to 2.7°C for the different GCMs and scenarios. Associated with this projected global temperature increase is a global increase in humidity, due to enhanced evaporation from the oceans, and consequently an increase in global precipitation though with large regional variations. For North America, the ensemble of models projects higher-than-average surface warming, an increase in heat waves, and a wetter climate in the north vs. drier in the south (Fig. 11.4). The results in Fig. 11.4 are for the IPCC A1B scenario in 2090 but similar patterns of change are found for other scenarios and shorter time horizons (Christensen et al. *2007*).

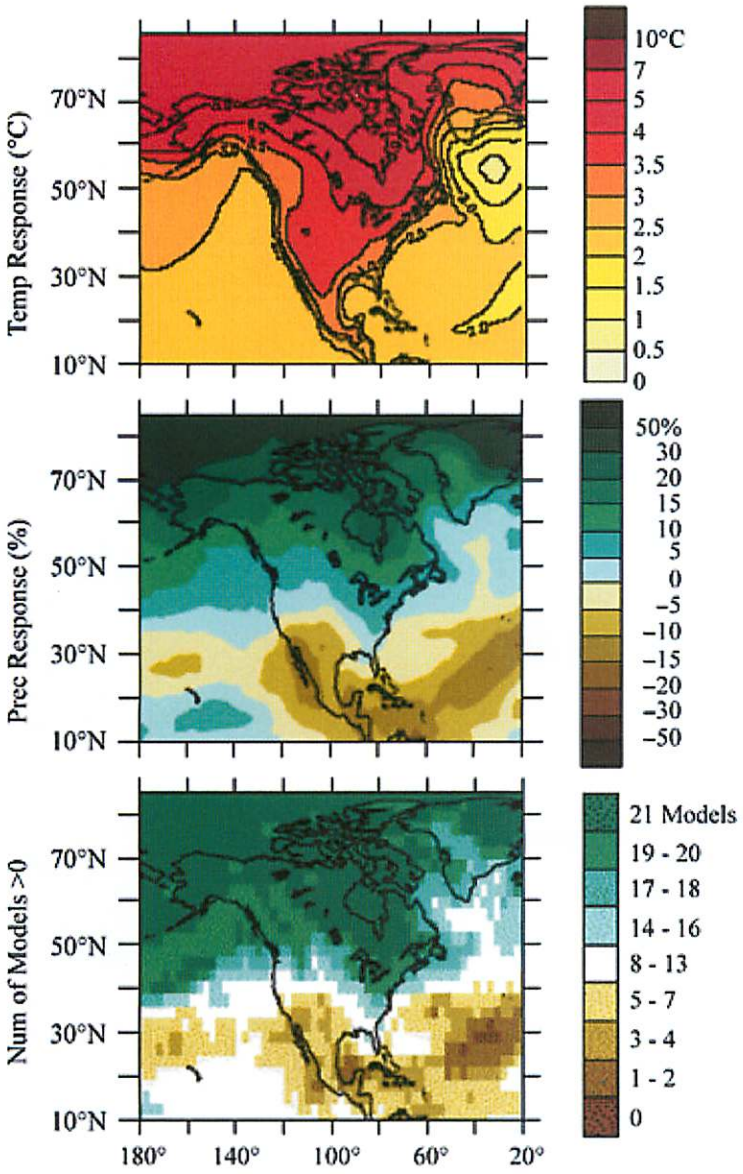

Fig. 11.4 Projected 1990–2090 changes in annual mean surface temperature (*top*) and precipitation (*middle*) for North America (A1B scenario). Values are averages from 21 GCMs contributing to the IPCC (Christensen et al. 2007). The bottom panel shows the number of models projecting a precipitation increase: a value of 21 indicates consensus for an increase, and zero indicates consensus for a decrease. A mid-range value (8–13) indicates lack of consensus regarding the sign of the precipitation change. Model results for other scenarios and shorter time horizons show similar patterns of change. (Christensen et al. 2007)

11.2.2 Effects of Climate Change on Ventilation

Air pollution episodes are associated in general with suppressed horizontal and vertical mixing, i.e., stagnant conditions and shallow mixing depths. A major factor determining regional stagnation in the East is the frequency of mid-latitude cyclones tracking across southern Canada. The cold fronts associated with these cyclones sweep the polluted air ahead of the front, replacing it with cleaner polar air (Cooper et al. 2001; Li et al. 2005). GCM simulations by Mickley et al. (2004a), Murazaki and Hess (2006), and Wu et al. (2008a) indicate a higher frequency of summer pollution episodes in the central

and eastern United States in the future climate due to reduced frequency and northward shift of mid-latitude cyclones. Such a trend in cyclone activity is a robust feature of GCMs at least in winter (Lambert and Fyfe *2006*), and can be explained by weakening of the meridional thermal gradient due to strong Arctic warming. Observations for the past several decades show indeed a significant decrease in mid-latitude cyclone frequency (McCabe et al. *2001*).

Climate change may either increase or decrease mixing depths, depending in particular on the change in soil moisture. GCM simulations for the twenty-first century climate find inconsistent results (Jacob and Winner *2009*). According to Jazcilevich et al. (*2000*, *2003a*, *b*, *2005*), rapid urbanization and its associated land-use changes have had a large effect on mixing depths and urban-scale circulations affecting air quality in Mexico City.

Uncertainty in GCM projections of future climate change generally increases as the spatial scale of interest decreases and as coupling to the hydrological cycle becomes involved. There is a strong need to assess GCM skill in simulating present-day climatological statistics relevant to air quality including mixing depths, stagnation events, and precipitation frequency. Eventually, the multi-model ensemble approach used by the IPCC to assess robustness in projections of future regional climate change (Christensen et al. *2007*) should be extended to meteorological variables of interest for air quality. Dynamical downscaling of GCM fields using regional climate models could significantly improve the simulation of air quality (Gustafson and Leung *2007*).

11.2.3 Effects on Ozone

Surface ozone is strongly correlated with temperature during pollution episodes (Jacob and Winner *2009*). This relationship is driven in part by the joint association of high ozone and temperature with stagnation episodes, in part by the temperature dependence of emission of biogenic isoprene (a major ozone precursor), and in part by the temperature dependence of the chemistry for ozone formation (Jacob et al. *1993*; Sillman and Samson *1995*). A few studies have used observed correlations of high-ozone events (>80 ppbv) with meteorological variables, together with regionally downscaled GCM projections of these meteorological variables, to infer the effect of twenty-first century climate change on air quality if emissions were to remain constant. A major assumption is that the observed present-day correlations, based on short-term variability of meteorological variables, are relevant to the longer-term effect of climate change. Cheng et al. (*2007*) correlates ozone levels at four Canadian cities with different synoptic weather types, and use projected changes in the frequency of these weather types (in particular more frequent stagnation) to infer an increase in the frequency of high-ozone events by 50% in the 2050s and 80% in the 2080s. Lin et al. (*2007*) apply the relationship of Fig. 11.5 for the northeastern United States to infer a 10–30% increase in the frequency of high-ozone events by the 2020s and a doubling by 2050. Wise (*2009*) projects a quadrupling in the frequency of high-ozone events in Tucson, Arizona by the end of the twenty-first century.

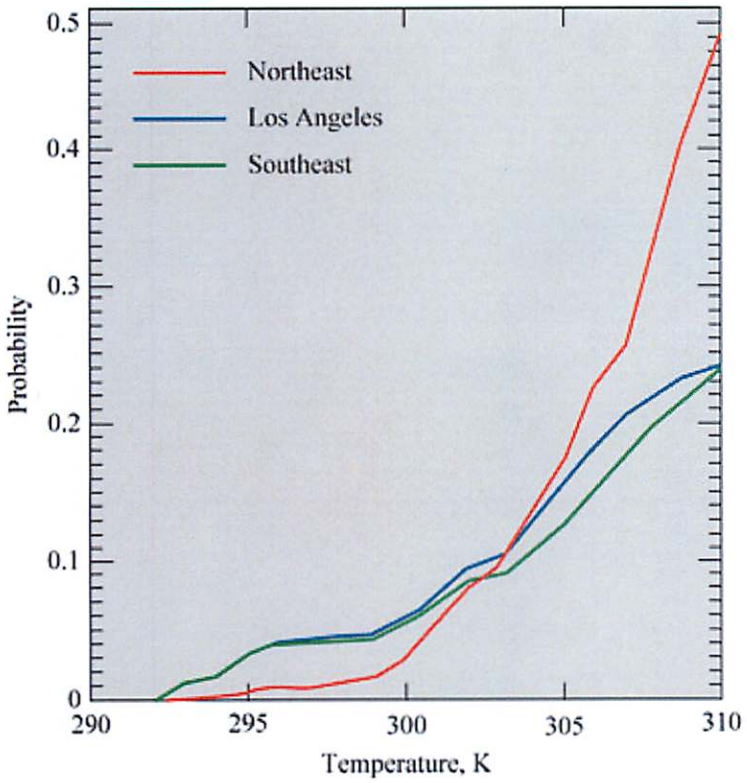

Fig. 11.5 Probability that the daily maximum 8-h average ozone will exceed 84 ppb for a given daily maximum temperature, based on 1980–1998 data. Values are shown for the Northeast, the Los Angeles Basin, and the Southeast. (From Lin et al. *2001*)

A number of recent studies have presented a more fundamental approach to the problem by using future-climate GCM simulations, sometimes nested with regional meteorological models (e.g., Leung and Gustafson *2005*), to drive global and regional chemical transport models (CTMs), keeping anthropogenic emissions at present levels (Hogrefe et al. *2004*; Murazaki and Hess *2006*; Racherla and Adams *2006*; Tagaris et al. *2007*; Tao et al. *2007*; Wu et al. *2008a*; Lin et al. *2008*; Zhang et al. *2008b*). Other studies have perturbed individual meteorological variables in CTM simulations for the present climate and diagnosed the ozone response (Steiner et al. *2006*; Dawson et al. *2007a*).

A general result across all models is that twenty-first century warming is projected to increase surface ozone in polluted regions of the United States and that temperature is the principal driving factor. Increases in the summertime maximum 8-hour daily average (MDA8) surface ozone are typically 1–10 ppbv depending on the model, the region, and the time horizon considered (Jacob and Winner *2009*; EPA *2009*). Decreases are mostly confined to clean and coastal areas where ozone is largely determined by its background, which declines in the future climate because of increasing water vapor stimulating ozone chemical loss (Wu et al. *2008b*; Lin et al. *2008*). Significant increases of ozone in the northeastern United States are found in all models, but beyond this there are large regional differences between models (Jacob and Winner *2009*). For example, Racherla and Adams (*2006*) and Tao et al. (*2007*) find a maximum effect in the Southeast, where Wu et al. (*2008a*) find little effect. This difference appears to reflect at least in part different assumptions regarding the fate of isoprene nitrates (Wu et al. *2008a*; Horowitz et al. *2007*).

A prevailing finding among models is that the ozone increase from climate change is largest under

conditions where present-day ozone is already high. Bell et al. (2007) (using model results from Hogrefe et al. 2004) find a strong correlation between present-day ozone and the magnitude of ozone increase for 50 cities in the eastern United States, and attribute it to the higher ozone production potential in areas with high anthropogenic emissions. Jacobson (2008) finds greatest sensitivity in Los Angeles and attributes it to increased chemical sensitivity of ozone to temperature when ozone is high.

Although current emission control strategies will likely remain effective in the future climate (Liao et al. 2007), stronger emission controls may be required to meet a given air quality objective (Wu et al. 2008a). This 'climate change penalty' is illustrated in Fig. 11.6 with simulated probability distributions of summertime ozone in the Midwest for 2050 vs. 2000 conditions. We see that the same ozone air quality that would be achieved with a 40% decrease of anthropogenic NO_x emissions for the present-day climate would require a 50% decrease in the 2050 climate. Wu et al. (2008a) find that as U.S. NO_x emissions decrease, the climate penalty also decreases and can even become a climate benefit, thus amplifying the effectiveness of emission controls.

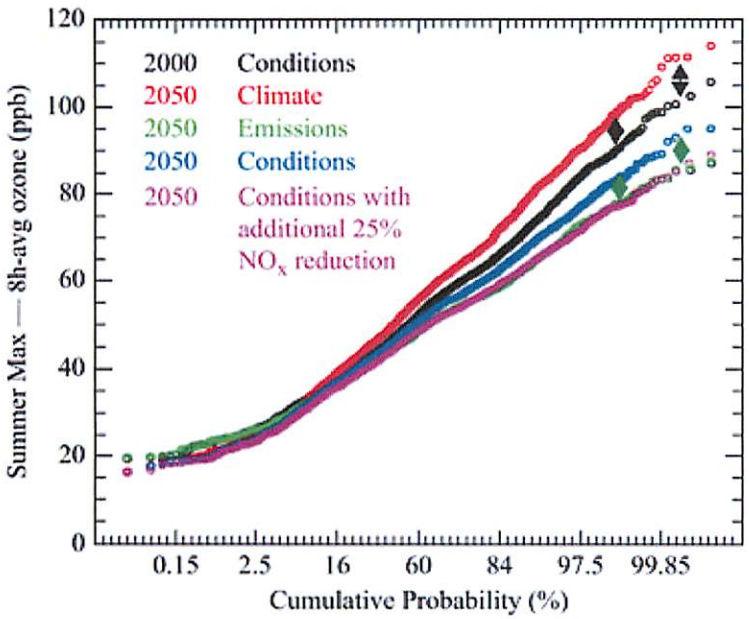

Fig. 11.6 Simulated effect of 2000–2050 global change in emissions and climate (A1 scenario) on surface ozone in the Midwest, illustrating the climate change penalty (Wu et al. 2008a). The figure shows cumulative probability distributions of summer daily maximum 8 h-average surface ozone for (1) 2000 climate and anthropogenic emissions (*black*), (2) 2050 climate and 2000 anthropogenic emissions (*red*), (3) 2000 climate and 2050 anthropogenic emissions (*green*), (4) 2050 climate and anthropogenic emissions (*blue*), and (5) 2050 climate and anthropogenic emissions but with 25% additional domestic NO_x emission reductions (U.S. anthropogenic NO_x emissions reduced by 50% instead of 40% compared to 2000 levels) (*pink*, closely overlaps the *green*). The *black* and *green arrows* measure the climate change penalty for ozone air quality with 2000 and 2050 anthropogenic emissions respectively

11.2.4 Effects on PM

Unlike for ozone, no strong and consistent correlation is observed between PM concentrations and meteorological variables that would provide guidance on the expected effects of climate change. This is likely because PM includes a number of components with different and complex sensitivities to the

meteorological environment. For example, increasing temperature would cause nitrate to decrease but sulfate to increase (Aw and Kleeman *2003*; Dawson et al. *2007b*; Tagaris et al. *2007*). The effect on secondary organic aerosol (SOA) involves compensating factors between increased biogenic VOC emissions and increased volatility (Liao et al. *2007*). PM should correlate with precipitation (Dawson et al. *2007b*), reflecting removal by wet scavenging, but finding this correlation in the observations is elusive (Woods et al. *2007*), possibly because precipitation is in general associated with air mass changes. The few CTM studies in the literature reviewed by Jacob and Winner (*2009*) indicate ±0.1–1 mg m^{-3} changes in surface $PM_{2.5}$ concentrations in the United States as a result of 2000–2050 climate change, although the patterns of these changes are inconsistent among the various studies.

Climate-driven changes in natural emissions from dust and forest fires could be the most important factors driving changes in PM concentrations. Wildfires in North America have increased over the past decade, reflecting both the legacy of fire suppression in the twentieth century and the effect of climate change (Westerling et al. *2006*). Spracklen et al. (*2009*) project a 50% increase in fire emissions in North America in the 2050 climate solely due to climate change, resulting in a 10% increase in annual mean $PM_{2.5}$ in the western United States.

11.2.5 Effects on Hazardous Air Pollutants

Many HAPs are produced or consumed in the atmosphere by reaction with the hydroxyl radical (OH). Concentrations of OH are generally expected to increase in the future climate due to increase in water vapor (Johnson et al. *1999*), but the effect as found in different models is only on the order of 10% over the course of the twenty-first century (Wu et al. *2008b*). It is likely that climate-driven changes in pollutant ventilation (Sect. 11.2.2) will affect HAP concentrations more than changes in chemistry.

11.2.6 Effects on Atmospheric Deposition and Mercury

The only study so far to have examined the effect of climate change on atmospheric deposition in North America is the regional climate simulation of Zhang et al. (*2008b*). They find varying spatial patterns of increases and decreases, reflecting calculated changes in precipitation patterns and regional circulations, as found also in a model study for Europe by Langner et al. (*2005*). Predicting these regional-scale changes is subject to large uncertainty, as pointed out above. Regardless of changes in the deposition patterns, the total amount deposited is determined to first-order by the amount emitted (what goes up must come down). In the case of acid and nitrogen deposition, the relevant emissions are mainly anthropogenic, and changes in these emissions (Sect. 11.4) would be the main drivers of changes in deposition.

The effect of climate change on mercury cycling through the atmosphere has received little attention so far. A potentially important issue is the volatility of mercury accumulated in land and ocean reservoirs (Jacob and Winner *2009*). Volatilization of soil mercury as a result of climate change could be of considerable importance, as the amount of mercury stocked in soil (1.2×10^6 Mg) dwarfs that in the atmosphere (6×10^3 Mg) and in the ocean (4×10^4 Mg) (Selin et al. *2008*). Soil mercury is mainly bound to organic matter, and future warming at boreal latitudes could release large amounts of this organic matter to the atmosphere as CO_2 either through increased respiration or through increased fires. The soil mercury bound to this carbon could volatilize to the atmosphere, eventually re-depositing to ecosystems in a mobile and more toxic form.

11.3 Effects of Air Pollutants on Climate Change

Tropospheric ozone and PM are recognized by the IPCC as important agents of climate change (Forster et al. *2007*); thus, it follows that air quality policy could have significant climate consequences (Levy et al. *2008a*, *b*). Decreases of ozone and BC PM can mitigate warming, while decreases of sulfate, nitrate, and OC PM can exacerbate warming. The list of climate-relevant air pollutants should also include methane, which is the second most important anthropogenic greenhouse gas and also affects air quality by increasing the tropospheric ozone background (West and Fiore *2005*).

11.3.1 Radiative Forcing

The global energy budget of the Earth is determined by a balance at the top of the atmosphere between incoming solar radiation (peaking in the visible), reflected solar radiation, and outgoing terrestrial radiation (peaking in the infrared). Climate is in equilibrium when the absorbed solar radiation (incoming minus reflected) equals the outgoing terrestrial radiation. A change in atmospheric composition can perturb this balance. The radiative forcing associated with this change is defined as the resulting energy flux imbalance at the top of the atmosphere, as computed by a radiative transfer model with all other factors (including temperature) kept at their original equilibrium values. Eventually the climate responds to the forcing by moving to a new energy-flux equilibrium, with associated changes in temperature and other variables.

Radiative forcing has been the standard metric used by the IPCC since 1990 to quantify the contributions of different agents to climate change. It is much easier to calculate than the climate response, and it is more certain because it avoids the complexity of climate feedbacks represented in different manners in different GCMs. The change in global equilibrium surface temperature (T_o) from a given radiative forcing varies by a factor of four between state-of-science GCMs (NRC *2005*), but a consistent finding across GCMs is that the response of T_o is proportional to the magnitude of the forcing and largely insensitive to the nature of the forcing agent (Boer and Yu *2003*; NRC *2005*). This makes radiative forcing a valuable metric to compare the importance of different climate change agents and to develop policies for mitigating climate change.

Radiative forcing is defined as positive if it results in a gain of energy for the Earth system, negative if it results in a loss. Positive forcing causes warming, negative forcing causes cooling. Greenhouse gases including ozone and methane absorb infrared radiation emitted from the Earth's surface and re-emit it at a lower temperature, thus decreasing the outgoing radiation flux and producing a positive forcing. Ozone also absorbs solar radiation in the near-UV and this makes an additional small positive forcing. PM interacts with solar radiation, scattering it back to space (negative forcing) or absorbing it (positive forcing). The absorbing component of PM radiative forcing is mainly BC, and the scattering component is mostly sulfate.

Figure 11.7 from the IPCC (Forster et al. *2007*) shows the present-day global radiative forcings from different anthropogenic emissions relative to pre-industrial radiative equilibrium (1750 climate). Figure 11.7 departs from the usual presentation of radiative forcings in that it is based on anthropogenic emissions rather than changes in concentrations. The emission-based perspective (Shindell et al. *2005*) is more useful for analyzing the impacts of air quality policy. In particular, the radiative forcing from tropospheric ozone is not identified *per se* but rather as the radiative forcings from the emissions of its precursors, which affect not only ozone but other climate agents as well.

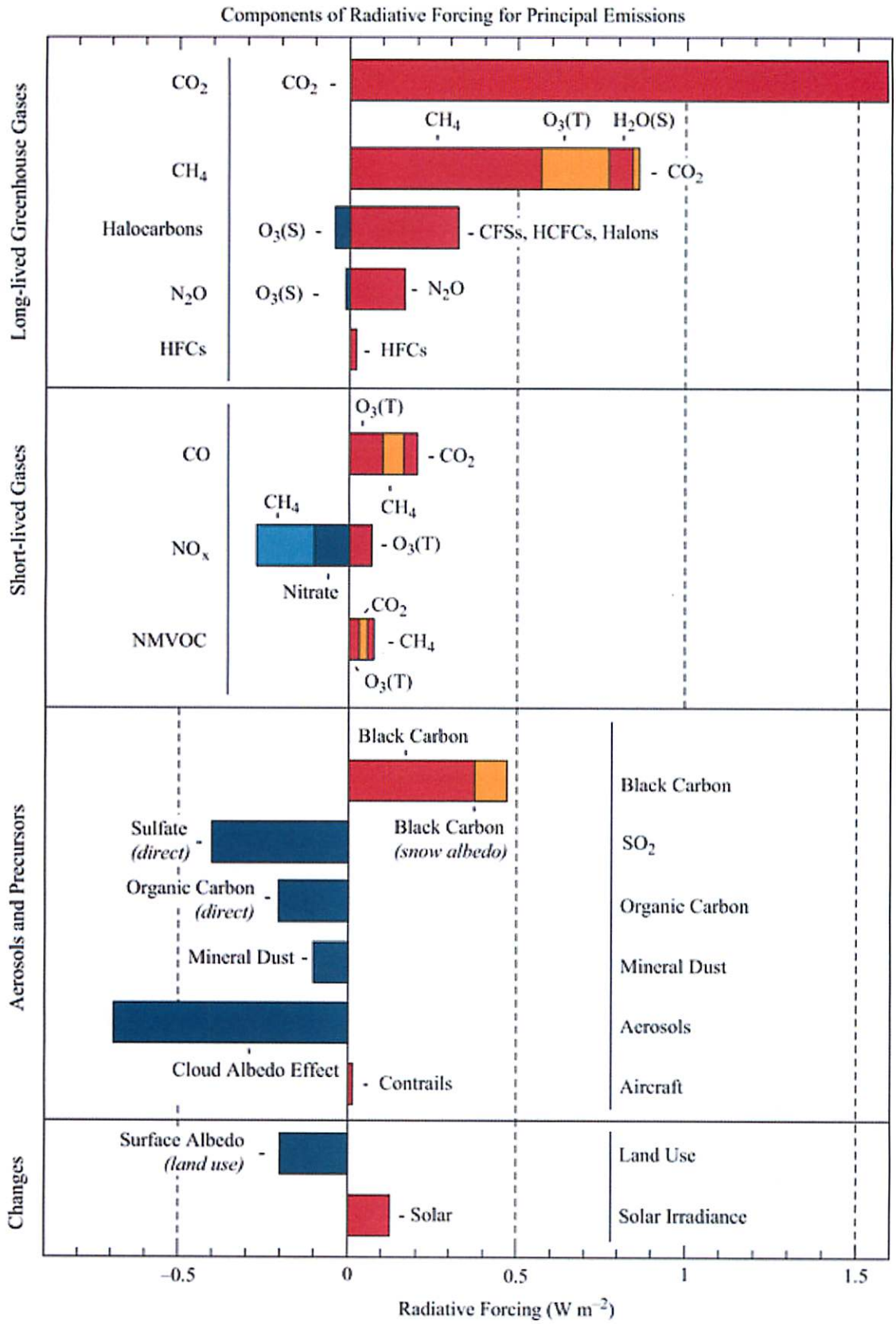

Fig. 11.7 Global radiative forcings due to emission changes between 1750 and 2000, from IPCC (Forster et al. 2007). In the figure, NMVOC refers to (non-methane) volatile organic compounds

We see from Fig. 11.7 that the largest positive radiative forcing is from CO_2 emissions (+1.56 W m^{-2}). Second is from methane emissions (+0.66 W m^{-2}), representing the sum of effects of methane emissions on the concentrations of methane, ozone, stratospheric water vapor, and CO_2. Third is from BC emissions (+0.46 W m^{-2}), including the effects on both atmospheric concentrations and snow albedo. Anthropogenic emissions of CO and non-methane volatile organic compounds (VOCs) also have significant positive radiative forcings (+0.20 and +0.09 W m^{-2} respectively), even though they are not significant greenhouse gases themselves, because of their effects on OH concentrations (and hence on the lifetime of methane), tropospheric ozone, and CO_2. Adding up the effects of these four emissions relevant to air quality (methane, BC, CO, VOCs) yields a total radiative forcing of +1.41 W m^{-2}, comparable to that from CO_2. Clearly, air quality policy can play a role in mitigating or enhancing climate change over the near term.

Emissions of NO_x appear to have compensating effects on climate (Fuglesvedt et al. *1999*; Wild et al. *2001*; West et al. *2007*). They provide a source of tropospheric ozone (positive forcing) but also of nitrate aerosols (negative forcing), and in addition increase the concentration of OH and hence the loss of methane (negative forcing). The net overall effect in Fig. 11.7 is a small negative forcing (−0.11 W m^{-2}), but the sign is within the range of uncertainty on the individual terms and Forster et al. (*2007*) decline to give a best estimate.

Anthropogenic emissions of scattering PM have large negative radiative forcings. These include a direct effect from aerosol scattering of solar radiation and an indirect effect from perturbation to cloud properties, the latter being highly uncertain (NRC *2005*). Figure 11.7 gives best estimates for direct forcings of −0.40 W m^{-2} from SO_2 emissions, −0.20 W m^{-2} from OC emissions, and −0.10 W m^{-2} from anthropogenic dust emissions (desertification, agricultural erosion). The sources of OC are not well known, and could include a major contribution from SOA production by anthropogenic VOC emissions not included in Fig. 11.7 (Volkamer et al. *2005*; Donahue et al. *2006*; Fu et al. *2008*). If so, the net radiative forcing from anthropogenic VOCs could possibly be negative rather than positive. The current best estimate of the indirect aerosol forcing given in Fig. 11.7 (−0.9 W m^{-2}) is larger than the direct forcing. Adding up the PM-related negative radiative forcings in Fig. 11.7 yields a total of −1.6 W m^{-2}, indicating that PM may have masked much of the greenhouse warming over the past century. Regulatory actions to reduce emissions of SO_2 will reduce sulfate aerosol concentrations and hence also reduce negative radiative forcing. Air quality policies aimed at PM reductions could thus impede efforts to curb anthropogenic climate change (Ming et al. *2005*).

The radiative forcing estimates reported by the IPCC are global averages. Ozone and PM have short lifetimes and hence their radiative forcings show far more spatial variability than those of long-lived greenhouse gases such as CO_2 and methane. For ozone, the spatial gradient in forcing is mainly between the northern and southern hemispheres (Mickley et al. *2004b*). For PM, the forcing is concentrated over the polluted continents, and in urban areas of the United States it can reach values of −30 W m^{-2} (Jin et al. *2005*). Deposition of BC to snow further contributes a positive regional radiative forcing (Hansen and Nazarenko *2004*; Qian et al. *2009*). Such regional structure in radiative forcing cannot be simply translated into a surface temperature change because of horizontal transport of heat (Boer and Yu *2003*; Levy et al. *2008a*). GCM simulations of climate response are necessary for quantitative interpretation and we discuss those next.

11.3.2 Climate Response for North America

Recent model results using the IPCC A1B scenario to examine the effect of changing concentrations of ozone, BC, OC, and sulfate on future climate find that by the year 2100 the projected decrease in sulfate aerosol (driven by a 65% reduction in global sulfur dioxide emissions) and the projected increase in BC aerosol (driven by a 100% increase in its global emissions) contribute a significant portion of the simulated A1B surface air warming relative to the year 2000: 0.4°C globally, 0.6°C (Northern Hemisphere), 1.5–3°C (wintertime Arctic), and 1.5–2°C (~40% of the total) in the summertime United States (Levy et al. *2008a*, *b*).

Mickley et al. (*2004b*) find that the predicted surface warming from anthropogenic tropospheric ozone is twice as large in the northern as in the southern hemisphere, reflecting the northern dominance of the forcing. They and Shindell et al. (*2006*) find disproportionately strong warming in continental interiors of northern mid-latitudes in summer, when ozone is highest, in contrast to forcing by CO_2 for which the strongest warming is in winter. Shindell et al. (*2006*) further point out that the Arctic, where warming has been strongest over the past decades, is particularly sensitive to ozone radiative forcing.

Direct radiative forcing by PM is more localized over source regions than that of ozone, although Levy et al. (*2008a*) find that the climate response is not necessarily enhanced over the region of forcing but is mostly spread over the global scale. The sharp distinction in temperature effects between PM types is of concern because sulfate in North America has been decreasing faster than BC PM, and this is apparent in some long-term observed trends of radiative forcing (Liepert and Tegen *2002*).

Besides this direct radiative forcing effect, PM affects the formation and microphysics of clouds and thus can modify precipitation locally, as has been observed for orographic precipitation (Jirak and Cotton *2006*; Rosenfeld and Givati *2006*). A climatological data analysis for coastal areas of the western North Atlantic by Ceverny and Balling (*1998*) shows precipitation to be highest on Saturdays and minimum early in the week, which the authors attribute to precipitation enhancement by anthropogenic PM accumulating over the course of the working week. Forster and Solomon (*2003*) similarly find a weekly variation in the diurnal temperature range over the United States which they attribute to the effect of anthropogenic PM on clouds. The sign of the effect varies with location, suggesting that PM could enhance cloud formation in some areas and suppress it in others. Bell et al. (*2008*) find a midweek maximum in summer afternoon rain intensity and storm height in the U.S. Southeast that they attribute to the weekly cycle of PM concentrations.

PM may elicit further climatic responses. A regional model study by Qian et al. (*2009*) indicates that BC deposition to the snowpack of the western United States has significant consequences on wintertime snowpack accumulation and spring runoff. Jacobson and Kaufman (*2006*) find a reduction in wind speed over California correlated with anthropogenic PM, which they interpret with a GCM as driven by increased atmospheric stability from PM radiative forcing. PM-driven changes in precipitation and atmospheric stability would in turn affect PM concentrations, representing a possible regional feedback between climate change and air quality.

Regional climate effects of air-quality related emissions can be especially significant in megacities such as Mexico City. Emissions in Mexico City differ substantially from cities in Canada and the United States, with a much higher contribution of carbonaceous PM (Molina and Molina *2002*). Magaña (*2007*) estimates that average temperatures in Mexico City have risen 4–5°C over the past 100 years, which presumably reflects in part the urban heat island effect (Jáuregui and Luyando *1998*), in part global climate change, but also the effect of BC emissions. In 2006, two field campaigns (MILAGRO and MAX-Mex, http://www.eol.ucar.edu/projects/milagro/) were conducted in the Mexico City region to

characterize emissions from Mexico City and examine their effects on regional and global climate. As results from these campaigns are analyzed, the contributions of local emissions to urban climate change in Mexico City should become clearer.

11.4 Projections of Future Anthropogenic Emissions

The Special Report on Emission Scenarios (SRES) of the IPCC in 2000 included consistent 2000–2100 projections of global methane, CO, NO_x, SO_2 and VOC anthropogenic emissions along with CO_2 for the different socioeconomic scenarios described in Sect. 11.2.1 (Nakicenovic et al. *2000*). They do not include consideration of how climate change may affect emissions. Figure 11.8 shows the projections for NO_x, methane and SO_2. All scenarios project a steady global increase of NO_x emissions over the 2000–2050 period, ranging from 20 (B1) to 200% (A1F), and mostly driven by China and India. NO_x emissions in the United States are projected to decrease over that period in all scenarios except A2. Methane emissions are projected to increase in all scenarios. In the A1F and A2 scenarios these emissions increase by as much as a factor of two by 2050 due to increases in livestock, landfill, and fossil fuel sources. CTM simulations based on the different SRES scenarios indicate that the global rises in NO_x and methane emissions will increase the surface background ozone in the northern hemisphere by 2–7 ppbv by 2030 (Prather et al. *2003*; Unger et al. *2006*), independent of any climate change.

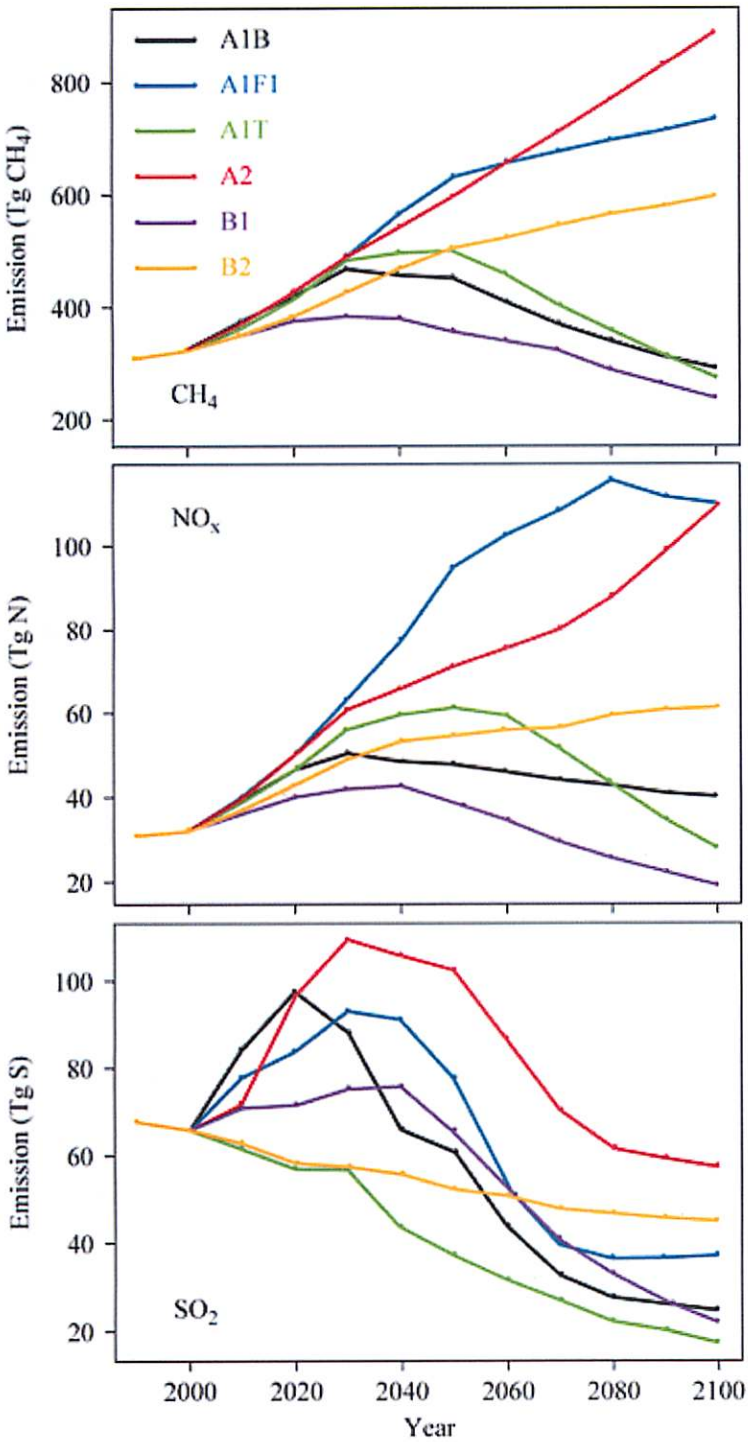

Fig. 11.8 Global 2000–2100 trends of methane, NO_x, and SO_2, for different IPCC SRES scenarios (Source: Nakicenovic et al. *2000*)

Dentener et al. (*2005*) suggest that the SRES projections for NO_x may be too pessimistic because they do not sufficiently account for recent and pending air pollution control legislation in the developing world. The authors present two alternate scenarios, a relatively optimistic one assuming full enforcement of current legislation (CLE), and an extremely optimistic one assuming maximum feasible reduction

(MFR) of emissions based on implementation of all currently available technology without regard to cost. The CLE scenario shows a modest 13% increase in global NO_x emissions by 2030 relative to 2000. The MFR scenario shows a decline to 35% of present-day emissions by 2030. Reductions in fossil fuel use to meet climate stabilization targets would also decrease the NO_x emissions relative to the SRES projections (Smith and Wigley *2006*).

Such optimism must however be tempered by observations of recent trends. Measurements of tropospheric NO_2 from space have shown a doubling of NO_x emissions from China over the 2000–2006 time period (Zhang et al. *2008a*), much faster than projected by any of the SRES emission scenarios. In the United States, NO_x emissions from power plants have decreased in response to recent regulations (Frost et al. *2006*), but there is some evidence from atmospheric observations that the NO_x source from motor vehicles has increased (Parrish *2006*; Boersma et al. *2008*), contrary to emission trends reported by EPA. Data for 1984–2004 from the National Atmospheric Deposition Program show a large increasing trend in ammonium deposition (Lehmann et al. *2007*), suggesting an increase in nitrogen cycling from agriculture. Such an increase would affect soil and livestock NO_x emissions, already thought to be underestimated in current inventories (Martin et al. *2003*; Bertram et al. *2005*; McElroy and Wang *2005*).

For methane, the CLE scenario gives results similar to SRES. However, observations over the past decade show a leveling of methane concentrations (Forster et al. *2007*). It is thus possible that the SRES scenarios for methane are too pessimistic, though it is also possible that the present plateau is only a temporary reprieve (Wuebbles and Hayhoe *2002*). Positive feedback of climate change on methane emission from wetlands and thawing permafrost could be a major driver for increasing methane in the future (Gedney et al. *2004*)

Global SO_2 emissions are projected to increase over the next few decades (except in the B2 scenario) but then to level off and start decreasing between 2020 and 2040 reaching emissions below present levels after 2050 (Smith et al. *2005*). The short-term increase in projected emissions is driven mainly by China and India, and the eventual decrease reflects implementation of coal washing, scrubbers, and a transition away from coal. More recent evidence suggests that SO_2 emissions from China may decrease sooner than indicated in the scenario as SO_2 scrubbers are now being installed on new power plants. As SO_2 emissions decrease, sulfate concentrations will decrease essentially simultaneously, hence removing the negative radiative forcing of sulfate from the atmosphere. Recent estimates of black carbon (BC) and organic carbon (OC) emissions for the years 2030 and 2050 also project decreases in global emissions relative to 1996 (Streets *2007*). However, the magnitude of emission reductions varies greatly depending on which IPCC SRES storyline is followed (A1B, A2, B1, and B2) in the development of the projections and which region of the world is considered with emissions from South America potentially even increasing (Streets *2007*). The relative rate of change of aerosol concentrations in the atmosphere will have a large impact on radiative forcing. As shown in Fig. 11.9, the combination of increasing BC and decreasing sulfate along with increases in OC and ozone is projected to result in a 1–2°C net increase in summer temperatures over most of North America in 2100 (Levy et al. *2008a*, *b*).

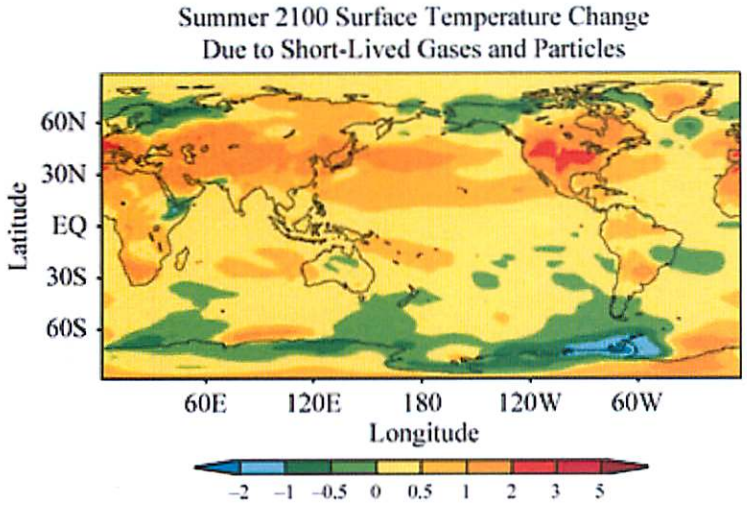

Fig. 11.9 Surface temperature change in °C due to short-lived gases and particles during northern hemisphere summer for 2100–2091 *vs.* 2010–2001 in the GFDL model. (Levy et al. *2008b*)

Streets et al. (*2009*) projected future mercury emissions out to 2050 on the basis of the IPCC (*2001*) scenarios. They find a global change in emission relative to present ranging from −4 to +96% depending on the scenario. The trend is mainly driven by increased coal use in the developing world, principally China and India which already dominate the global mercury emission inventory (Selin *2005*). The fraction of total mercury emitted in elemental form is expected to decrease from 65% today to 50–55% by 2050, which would tend to reduce global-scale transport. This decrease is due to reductions in industrial (non-coal) emissions, which have a low Hg(II)/Hg(0) ratio relative to coal combustion (Pacyna et al. *2006*).

11.5 Time Scales and Implications for Accountability

The rate of change in anthropogenic emissions affecting ozone, PM, and mercury has accelerated over the past decade. This reflects on the one hand vigorous emission controls in North America and Europe to meet increasingly stringent air quality objectives, and on the other hand rapid growth of emissions in China (and to a lesser extent India) from industrialization. This shift is clearly apparent from satellite observations (Fig. 11.10). It has important implications for both climate change and intercontinental pollution. Meeting ozone and mercury air quality standards in North America in the future is likely to be increasingly on external pollution sources outside North America, making the development of international policies and agreements increasingly important.

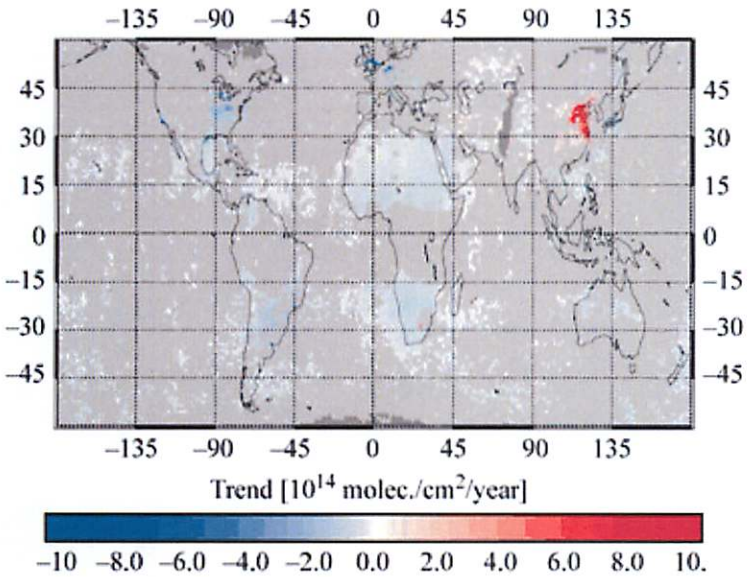

Fig. 11.10 1996–2005 trends in tropospheric NO_2 columns as observed by the GOME and SCIAMACHY satellite instruments. (van der A et al. *2008*)

In the case of mercury, rapid change in global emissions (Fig. 11.2) is likely to obfuscate benefits from North American emission controls, except at sites immediately downwind of major point sources where high mercury deposition is of local origin (Keeler et al. *2006*). In the case of ozone, intercontinental pollution influence acts mainly to increase background ozone concentrations with peak ozone concentrations largely a result of regional emissions of ozone precursors.

Effects of climate change on air quality are expected to develop over a time scale of decades, corresponding to the time scales for climate change (Lin et al. *2007*). Direct observation of these effects will be difficult because of the confounding effect from regional changes in emissions. However, it should be possible to monitor long-term trends in air pollution meteorology, in particular the frequency of stagnation episodes. Leibensperger et al. (*2008*) report a decrease in the frequency of mid-latitudes cyclones ventilating the northeastern United States over the 1980–2006 time period, consistent with expected trends from greenhouse warming. Combining this information with the strong observed interannual correlation between cyclone frequency and ozone pollution episodes, they conclude that the 80 ppbv standard for ozone at that time period would largely have been met in the region by now were it not for climate change.

International policies for reducing hemispheric-scale pollution can be monitored and evaluated by satellite observations of atmospheric composition, which represent a major new development in the observation system for global atmospheric chemistry over the past decade. Inverse model analyses applied to satellite observations of NO_2, formaldehyde, methane, and CO have been used to improve national and global emission estimates for NO_x (Martin et al. *2003*), VOCs (Shim et al. *2005*), methane (Bergamaschi et al. *2007*), and CO (Stavrakou and Müller *2006*). They have been used to monitor decadal trends in NO_x emissions from the United States (Frost et al. *2006*) and worldwide (van der A et al. *2008*), and to detect changes in emissions on a weekly or event time scale (Beirle et al. *2003*; Wang et al. *2007*). Adjoint approaches to inverse modeling allow satellite data to constrain emissions at the scale of individual cities (Kopacz et al. *2009*). Satellite observations of ozone and PM have also been used to test models of intercontinental transport (Heald et al. *2006*; Zhang et al. *2006*). As discussed in

Chap. 10, the present observing system, if sustained in the future, should make it possible to monitor and diagnose the effects of changes in certain global pollutant emissions on background air quality on a decadal time scale. It would also allow for comparison of projected with actual emissions, adding an additional element of accountability.

11.6 Climate Mitigation, Air Quality Management, and Technological Change

In the long run, the most consequential effects of climate change on air quality may arise from the technological changes that will be required to minimize anthropogenic influences on the Earth's climate. Achieving the objectives of the United Nations Framework Convention on Climate Change (http://unfccc.int/resource/docs/convkp/conveng.pdf)—"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"—requires capping the atmospheric concentrations of long-lived greenhouse gases at some yet-to-be-determined value. Achieving this goal means that at some point in the future the net emissions of these gases must decline until a desired steady-state capping concentration is reached. The emission trajectories required depend on the capping concentration. The lower the concentration, the more rapidly emissions must be reduced. In addition, reductions in BC (a particulate with adverse health effects, a short lifetime and a high radiative forcing) would provide a rapid reduction in positive radiative forcing and could decrease the rate of global warming in the short-term (Kopp and Mauzerall *2010*). How an emission trajectory may be achieved depends on many factors such as global population growth, levels of and diversity in global economic development, the goods and services demanded by these economies, the energy needed to deliver these goods and services, the current and future technologies available to supply this energy, the performance of these technologies (and how they change with time), when future technologies may become available, and the cost and availability of fuel sources.

This dependency is illustrated in Fig. 11.11 (Clarke et al. *2007*), which shows emission trajectory scenarios for CO_2 generated by three integrated assessment models: the Integrated Global Systems Model (IGSM) (Sokolov et al. *2005*; Paltsev et al. *2005*), the Model for Evaluating the Regional and Global Effects (MERGE) of greenhouse gas reduction policies (Manne and Richels *2005*), and the MiniCAM model (Brenkert et al. *2003*; Kim et al. *2006*). Each of the models combines, in an integrated framework, components that simulate the socioeconomic systems and physical processes that determine the effects of human activities on the physical environment and vice versa. They differ, however, in how these systems are represented and simulated. Figure 11.11 depicts simulated global emissions of CO_2 in the twenty-first century for five different scenarios: a reference "business as usual" case (similar to the A1 scenario described in Sect. 11.2.1) and four stabilization scenarios that would cap the atmospheric concentrations of CO_2 at approximately 450 ppm (Level 1), 550 ppm (Level 2), 650 ppm (Level 3), and 750 ppm (Level 4). Each modeling group was given flexibility regarding their assumptions of population growth, economic development, and the other factors that affect future CO_2 emissions. The emission trajectories simulated by the models show significant differences, but all share common features: (1) the lower the desired capping concentration the more quickly emissions must begin to deviate from the reference scenario, (2) for capping targets of 550 ppm and above, several decades may elapse before significant reductions in global CO_2 emissions growth must occur, and (3) nearly all capping scenarios require that net CO_2 emissions reach an allowable maximum sometime within the twenty-first century.

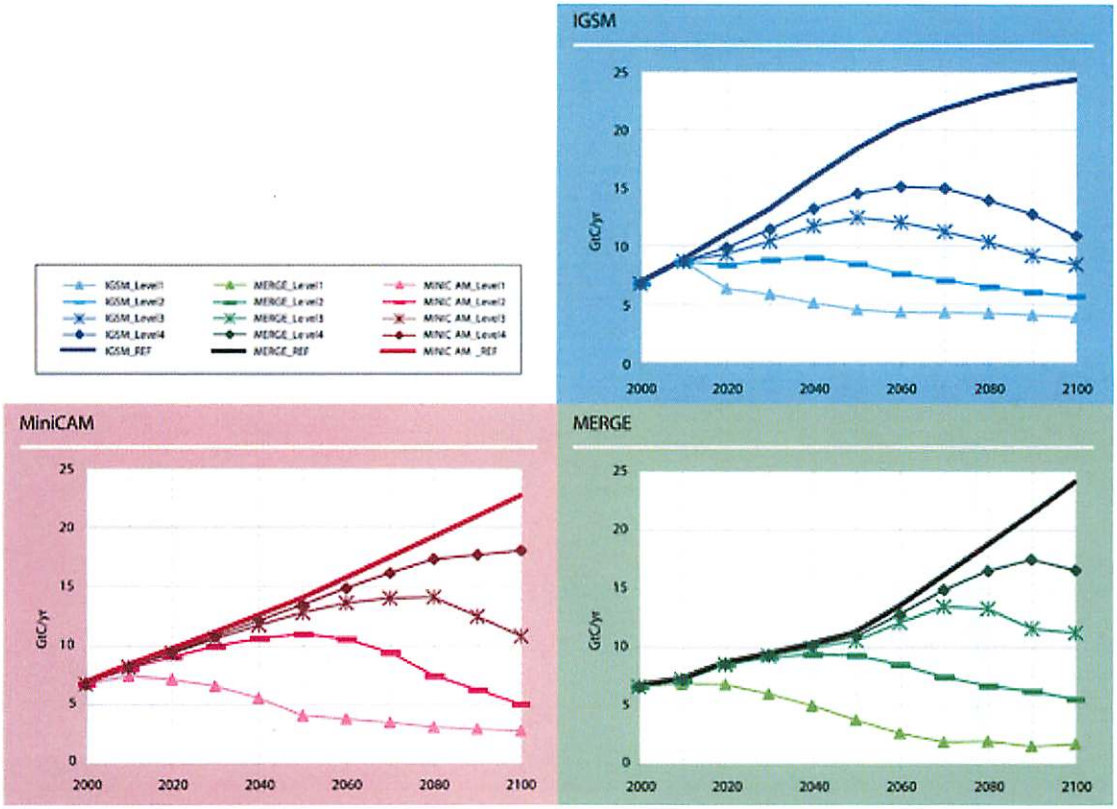

Fig. 11.11 Projected global CO_2 emissions for various GHG mitigation scenarios. Results are from three separate integrated assessment models. The *dark solid lines* depict futures in which no special actions are taken to mitigate anthropogenic climate change (i.e., business as usual). The other *curves* represent four GHG stabilization scenarios that would cap the atmospheric concentrations of CO_2 at approximately 450 ppm (*Level 1*), 550 ppm (*Level 2*), 650 ppm (*Level 3*), and 750 ppm (*Level 4*). (Results are from Clarke et al. *2007*)

The differences among the three models are more obvious in Fig. 11.12a, 11.12b (Clarke et al. *2007*). The figure depicts how global "market share" for various energy sources (see Fig. 11.12a for definitions) evolves in time and changes with the magnitude of the CO_2 concentration target—assuming perfect flexibility in the global deployment of energy technology or conservation measures. All of the models show that the lower the desired capping concentration, the more rapidly and fundamentally the energy supply system must change in order to meet the target. However, each model paints a significantly different picture of how this evolution might be achieved. These differences result from different assumptions about how the economy responds to environmental costs of greenhouse gas emissions, changes in the energy intensity of the global economy, the cost and availability of fuel sources and energy technologies, and the possibility of social or policy constraints on fuel sources or technologies (e.g., nuclear power). Differences among the models indicate how uncertainty about the evolution of the energy system (and the myriad emissions associated with this system) increases with time. The actual uncertainty is even greater than indicated here because we cannot know the political and socioeconomic conditions, social attitudes, or available technologies decades into the future.

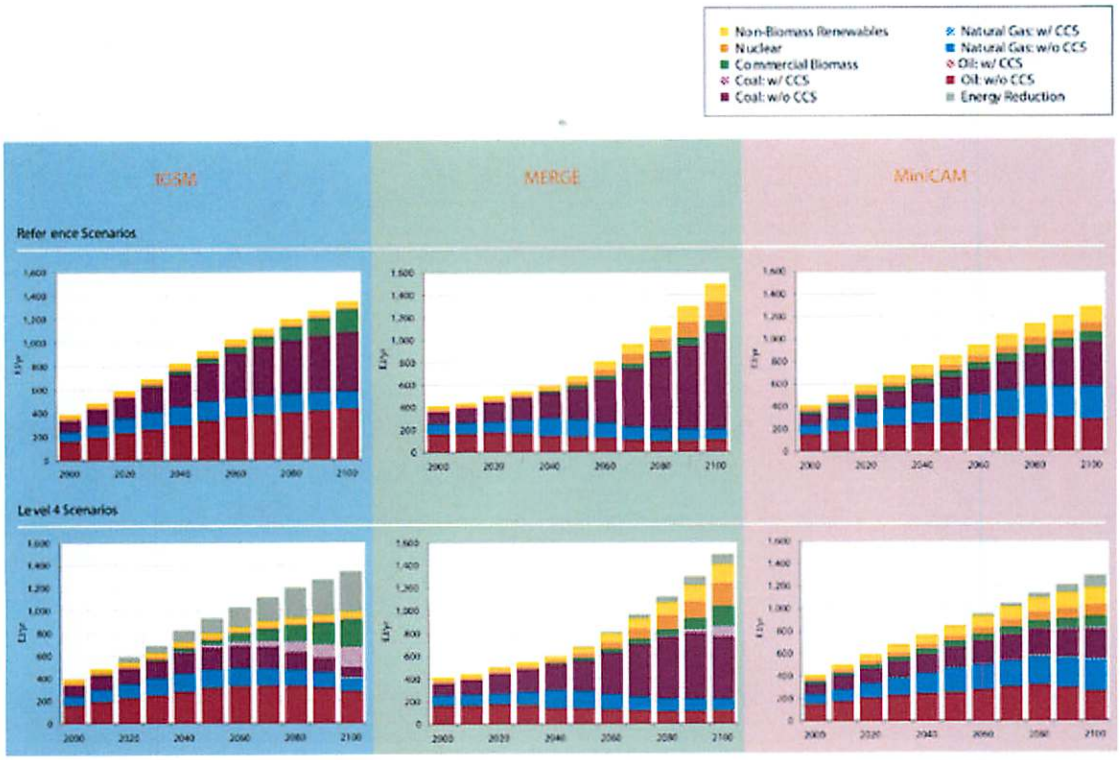

Fig. 11.12a Projected global primary energy consumption (exajoules/year) by energy source for the reference and Level 4 GHG stabilization scenarios. These scenarios are the same as described in Fig. 11.11. Energy sources considered by the models are indicated in the figure legend. Fossil fuel sources are modeled with and without Carbon Capture and Sequestration (CCS). Note that if cost effective CCS technologies are available, fossil fuels may supply significant fractions of global energy consumption even under aggressive GHG reduction scenarios (see Fig. 11.13a, 11.13b also). (Clarke et al. *2007*)

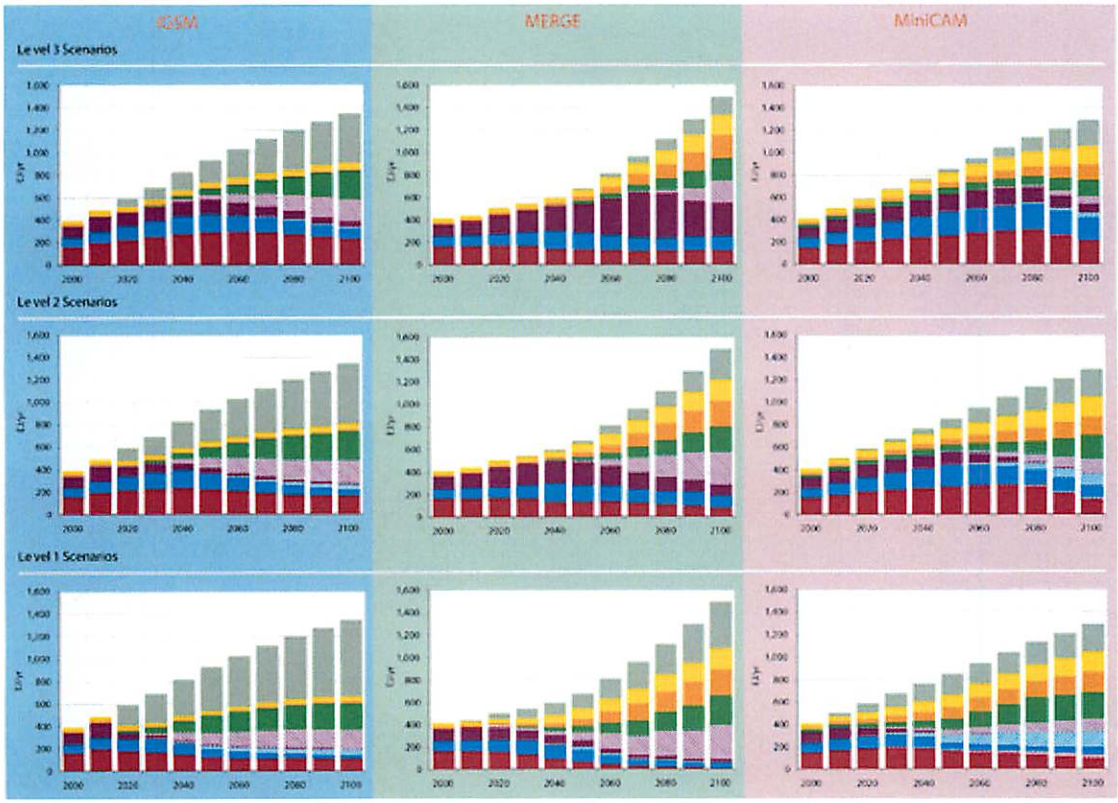

Fig. 11.12b Projected global primary energy consumption (exajoules/year) by energy source for Level 1, 2, and 3 GHG stabilization scenarios. The scenarios and suite of technologies are the same as described in Fig. 11.11 and 11.12a, respectively

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The model simulations provide one important insight regarding the future: considering the cost and availability of fossil fuels (especially coal), it is difficult to envision a future energy system that does not include a major contribution from fossil fuel sources, especially in rapidly developing countries. Thus, meeting the emission reduction demands of most target CO_2 concentrations implies the availability of practical and effective technologies for capturing and sequestering the CO_2 emissions from fossil fuels. Without them, meeting the most commonly discussed greenhouse gas reduction targets will be difficult. However, implementing carbon capture and sequestration (CCS) at the scale envisioned by these simulations will be a monumental technical and logistical challenge. To give an idea of the global magnitude of a future CCS industry, the three models project that stabilizing atmospheric CO_2 concentrations at about 550 ppm will require a total cumulative capture and sequestration of 140–200 Gt C by the year 2100 (Clarke et al. *2007*), or approximately 20 times current annual global emissions (Fig. 11.11).

When performed at a national and energy-sector level scale, simulations such as these provide insight into how climate mitigation policies could affect future air quality. Figure 11.13a, 11.13b (Clarke et al. *2007*) depicts how the energy sources for U.S. electricity production might evolve over the twenty-first century as a function of the various greenhouse gas reduction scenarios discussed previously. The figure shows that the mix of generation technologies will have to change dramatically, especially after 2050, in order to meet the more stringent greenhouse gas concentration targets. This change will clearly affect air-quality related emissions. However, these simulations also show that on a 10–20 year timescale, the mix of energy sources and generating technologies (and, presumably, the associated emission sources)

should be fairly stable. This stability reflects the inherent inertia of the energy system. In fact, the rate of technological change may be overestimated in these simulations. In the models, changes in the energy system are driven purely by economic considerations, assuming perfect flexibility. Change in the real world could be either considerably more difficult, or significantly easier depending on political will.

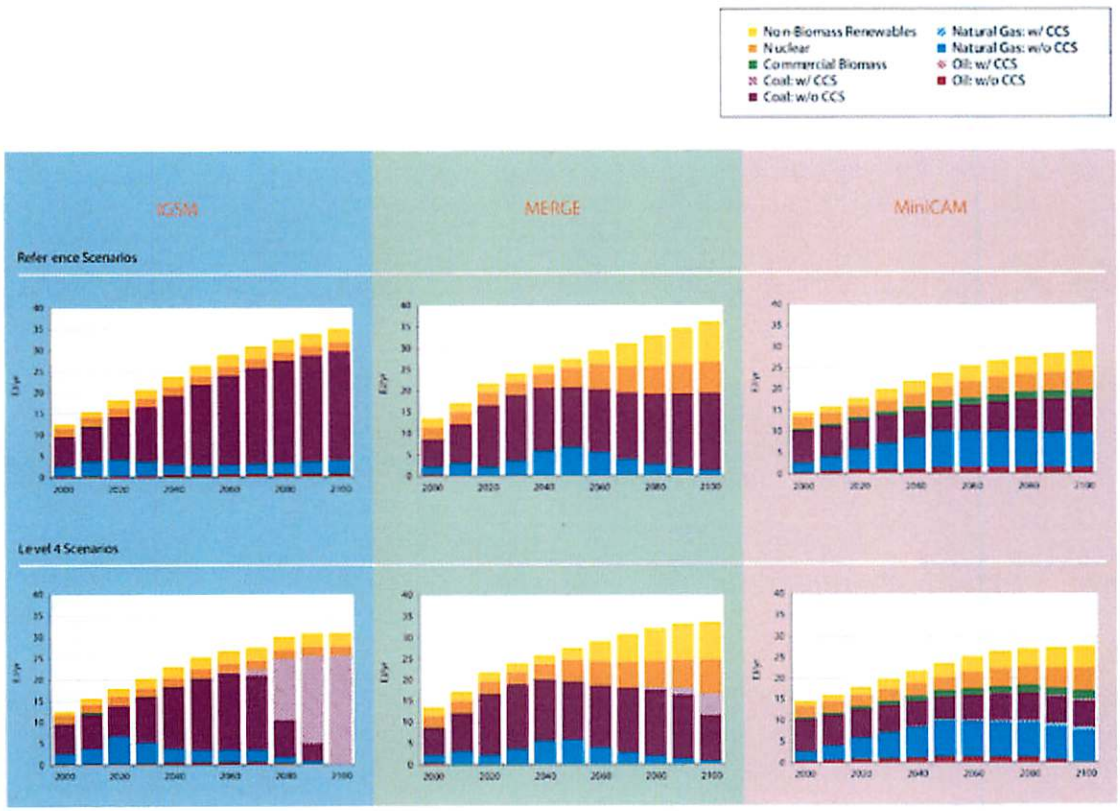

Fig. 11.13a U.S. electricity production by energy source for the reference and Level 4 GHG stabilization scenarios. The figure indicates how uncertainty concerning future fuel sources and energy technologies increases with time. Also, the lower the target GHG stabilization target (see Fig. 11.13b), the greater the projected changes in fuel-sources and energy-technologies. Figures 11.12a, 11.12b and 11.13a, 11.13b suggest that future technology and fuel-source change within a given national energy sector (here, U.S. electricity production) could be much greater than global averages. (Clarke et al. *2007*)

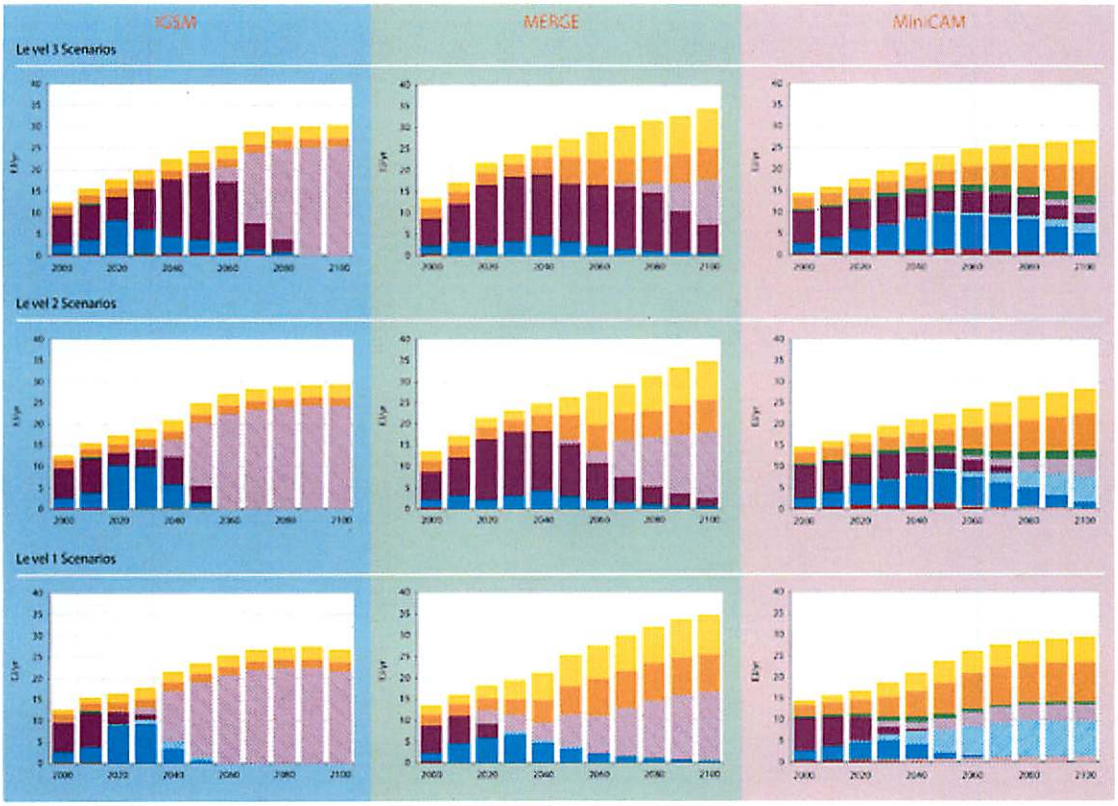

Fig. 11.13b U.S. electricity production by energy source for Level 1, 2, and 3 GHG stabilization scenarios

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The timescale issue also applies to other energy sectors. For example, for transportation, fuel sources and technologies that have been proposed for reducing greenhouse gas emissions include biofuels (e.g., ethanol and biodiesel), hydrogen, conventional and plug-in hybrids, electric vehicles, various mass transit options, and fuel cells. The air-quality related emissions from each of these options will be different. However, it will be some time before any of them can achieve significant market penetration, which provides opportunity to assess their implications for future air quality. The tools for conducting these assessments exist today. They include the air quality models described in Chap. 10 of this book and integrated assessment models such as those discussed in this section and the next. Using these tools, we can assess not only the potential effects of greenhouse gas emission reduction policies and options on air quality, but also the implications of air quality management decisions on climate change and climate change policy. This application is discussed further in the next section.

Researchers in Mexico have also investigated future greenhouse gas emission scenarios as part of Mexico's Third National Communication to the United Nations Framework Convention on Climate Change (INE-SEMARNAT *2006b*). Greenhouse gas emissions from the Mexican energy sector were estimated for years 2008, 2012 and 2030. The estimates showed a great deal of sensitivity to GDP growth assumptions; nevertheless, the analysis indicated that near-term greenhouse gas emissions could be reduced by 17% compared to the base scenario if a number of familiar measures were adopted, such as increased utilization of renewable energy sources, implementation of stricter fuel economy standards in private gasoline-run and diesel-run vehicles, and improved energy efficiency.

11.7 Integrated Assessment Studies of the Co-benefits of Air Pollution and Greenhouse Gas Mitigation Strategies

Integrated assessment studies can be very helpful in examining mitigation strategies that could benefit both air quality and climate. Several recent integrated assessment studies have examined the co-benefits to air quality, human health and welfare, and climate change of controlling methane emissions. Fiore et al. (*2002*, *2008*) show that reductions in methane emissions should lead to global reductions in surface ozone concentrations. The benefits of these reductions to agriculture, forestry, and non-mortality human health have been examined by West and Fiore (*2005*). West et al. (*2006*) conclude that a 20% reduction in global methane emissions, starting in 2010 and continuing through 2030 relative to a business-as-usual scenario, would result in approximately a 1 ppbv reduction in surface ozone concentrations globally with an associated reduction of approximately 370,000 premature mortalities from ozone exposure. West et al. (*2007*) further show that of all the ozone abatement strategies, methane emission controls appear to have the greatest benefit for mitigation of climate change (Fig. 11.14).

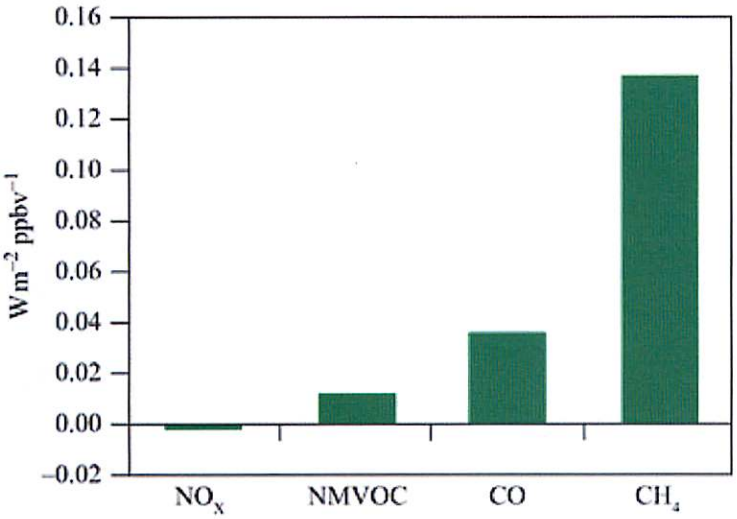

Fig. 11.14 Reductions in ozone precursor emissions have different effects on radiative forcing per unit reduction in surface ozone concentration. Shown here is the radiative forcing decrease per unit (ppbv) decrease in global surface ozone concentrations resulting from 20% global decreases in anthropogenic emissions of NO_x, non-methane VOC, CO, and methane. (Results are from global model calculations by West et al. *2007*)

Ethanol is currently being promoted as a clean and renewable fuel that will reduce air pollution, climate warming and reliance on imported oil. A recent integrated environmental assessment of the production and use of ethanol as a substitute for gasoline indicates, however, that corn-based ethanol results at best in only small reductions in greenhouse gas emissions relative to gasoline (Pimentel and Patzek *2005*; Farrell et al. *2006*), and could cause an increase in ozone pollution due to NO_x produced as a byproduct of nitrogen fertilizer (Jacobson *2007*). A recent study also finds that when the extra N_2O emission from biofuel production is calculated in "CO_2 equivalent" global warming terms and compared with the cooling effect of reducing emissions of fossil fuel derived CO_2, the result is that production of biodiesel and corn ethanol can contribute as much or more to global warming by N_2O emissions than cooling by

fossil fuels savings (Crutzen et al. *2008*). In addition, there are concerns that neither corn-based ethanol nor soybean-based biodiesel can replace substantial petroleum without significantly affecting food supplies. According to Hill et al. (*2006*), only 12% of gasoline demand and 6% of diesel demand would be met if all U.S. corn and soybean production were used for biofuels. On the other hand, if ethanol were produced from non-food crops grown on agriculturally marginal land using little fertilizer, biofuel would be produced with less impact on food supplies and with greater environmental benefits (Hill et al. *2006*). Use of U.S. croplands for biofuels has been found to increase greenhouse gas emissions due to resulting land-use change that brings additional land under cultivation (Searchinger et al. *2008*).

Integrated assessments evaluating co-benefits of coordinated air pollution and climate mitigation efforts have been conducted for different parts of the world. The European Environment Agency (EEA) concluded that coordinated climate and air quality policy has considerable ancillary benefits including lower overall costs of controlling air pollutant emissions (EEA *2004*, *2006*). An examination of four megacities (Mexico City, New York City, Santiago, and Sao Paulo) indicates that greenhouse gas mitigation would lead to large reductions in ozone and particulate matter concentrations with substantial resulting improvements in public health (Cifuentes et al. *2001*). McKinley et al. (*2005*) find that five proposed control measures in Mexico City, that were estimated to reduce annual particle exposure by 1% and maximum daily ozone by 3%, would also reduce greenhouse gas emissions by 2% (i.e., over 300,000 t of carbon equivalent per year) for both periods 2003–2010 and 2003–2020. For both time horizons, McKinley et al. (*2005*) estimate that about 4,400 Quality Adjusted Life Years (QALYs) would be saved.

Assessments of potential co-benefits of greenhouse gas mitigation in China have also identified large associated reductions in the emission of air pollutants. When the resulting health improvements are monetized, the emission reductions are found in many cases to be cost-effective and even profitable (Aunan et al. *2004*, *2006*). Conversely, a recent assessment of the effects of present and potential future emissions of BC, OC, sulfur dioxide and sulfate from China on premature mortality and radiative forcing finds that reductions in the emissions of aerosol precursors would likely reduce premature mortalities globally while increasing radiative forcing (Saikawa et al. *2009*) and hence climate warming. Efforts to improve air quality in China using strategic technological choices such as advanced coal gasification technology have the potential to cost-effectively reduce air pollution and improve public health while permitting the sequestration of carbon dioxide (Wang and Mauzerall *2006*). These types of focused integrated assessments examining the connection between technological options, emissions, atmospheric concentrations, impacts on health and agriculture, and associated costs have not been as common in North America. They could be very helpful in optimizing technological strategies for management of air quality and climate change.

11.8 Conclusions

Expected changes in climate and in worldwide anthropogenic emissions over the coming decades call for a global perspective in addressing future air quality problems in North America. As we enter an era of new international environmental policies directed at mitigating anthropogenic climate change, leveraging and integrating these policies with those directed at improving air quality will be highly beneficial to the achievement of both objectives.

Increasing global emissions could make it increasingly difficult to meet more stringent air quality standards in North America by means of domestic emission controls. The global distribution of pollutant emissions is changing rapidly, with decreases in North America and Europe and increases in Asia. The

influence of rising Asian emissions on the problem of meeting North American air quality objectives is obvious for mercury, which is recognized to be a global pollution problem. It may become increasingly important for ozone. Models based on the IPCC future scenarios for NO_x and methane emissions project increases of 3–7 ppbv in the surface background concentration of ozone in the United States over the next two decades. Unlike mercury or ozone, rising Asian emissions are not expected to have a significant intercontinental influence on PM background in North America because of precipitation scavenging during intercontinental transport. The principal exception to this rule would be the Arctic regions of Canada and the United States.

Climate change may affect North American air quality independently of changes in pollutant emissions through perturbations to the meteorological environment, the chemical environment, and natural emissions. Simulation of regional climate is a major challenge for GCMs, and the skill of these models in describing air pollution meteorology and its trends needs to be evaluated. Nevertheless, empirical evidence exists of a relationship between increased ozone concentrations and rising air temperature. Exploratory modeling studies suggest that ozone concentrations in polluted regions of North America may increase by several ppb over the next decades as a result of climate change alone. Published modeling studies concur that ozone increases due to climate change will be largest in urban areas and where ozone is already high. In locations where ozone is relatively low, climate change may actually be beneficial due to decrease in the ozone background as a result of increasing water vapor. Unlike for ozone, there is no consensus among model studies as to the effect of climate change on PM. This reflects the complexity of meteorological effects on the different PM components. Climate-driven increases in wildfires could have a major effect. Little attention has been paid so far to the effect of climate change on mercury, but this effect could potentially be large through increased ocean volatilization and release of organic-bound mercury from soil.

Some air pollutants and their precursors can play a significant role in anthropogenic climate change and represent a potential policy lever for mitigating this problem in the coming decades. Methane, ozone, and BC combined have a positive radiative forcing (warming) as large as CO_2 according to the IPCC (*2007*). Sulfate, nitrate, and OC PM have a major cooling effect, both directly by scattering sunlight and indirectly by affecting cloud albedo. The cooling effect of sulfate aerosol is sufficiently large that global anthropogenic sulfate formed from the oxidation of SO_2 is thought to have greatly slowed the pace of greenhouse warming over the past century. Future reductions in SO_2 emissions to achieve air quality improvements and acid deposition reduction goals will, therefore, tend to accelerate climate warming. Reducing methane, CO, and BC emissions could offset this loss of cooling effect, while reducing NO_x emissions is thought to be climate-neutral. Reducing methane, CO, and BC emissions provide a means for short-term mitigation of climate change, but long-term mitigation will require large reductions in CO_2 emissions.

Projected changes in global emissions and climate could significantly complicate accountability assessments of domestic emission control policies on a decadal time scale. This is manifest for mercury, as emissions outside North America are changing rapidly and presently dominate large-scale deposition to North American ecosystems. Changes in precursor emissions on a global scale could also have an effect on ozone accountability; however, these changes would mainly affect background concentrations and would, therefore, be separable from ozone pollution episodes.

In the long run, the most consequential effects of climate change on air quality may arise from the technological changes that will be required to achieve long-term stabilization of greenhouse gas concentrations. Energy policies focused on energy conservation and use of renewable energy or other low-carbon or zero-carbon emission energy technologies such as nuclear power are likely to have major

co-benefits for air quality management. However, unless multipollutant considerations are embodied in air quality management strategies, actions to improve air quality could have either positive or negative impacts on climate change. Such considerations, as well as opportunities for achieving air quality and climate co-benefits, should be assessed to ensure that air quality initiatives have no unintended consequences or result in no unintended technological or infrastructure legacy problems with regard to other environmental protection goals.

From the point of view of air quality management, the pace of technological change will generally be sufficiently slow that the air quality effects of new end-use technologies that might be adopted to address climate change can be assessed well before they achieve significant market penetration (see Chap. 8). However, the introduction of new fuels, and their related air quality and climate consequences, could take place quite rapidly if they can be supplied in sufficient quantity and readily adapted to existing technologies and infrastructure. As an example discussed elsewhere in this chapter, early assessments of the effects of increased use of biofuels (e.g., ethanol) have raised questions regarding its benefits for air quality as well as for net reduction of greenhouse gas emissions.

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