Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios

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Abstract

New scientific understanding could increase the cost-effectiveness of local and regional air quality management policies, enhance the acceptance of mitigation measures for long-lived greenhouse gas (GHG) emissions, and reveal win-win portfolios of controls for short-lived substances that yield immediate health and crop benefits while limiting temperature increase in the near term. However, although substantial efforts have been devoted to global analyses of the emissions of carbon dioxide (CO_2) and other long-lived GHGs, air pollutant emissions have received only limited attention in the global context. Past and likely future trends in air pollutant emissions evolve rather differently from those of long-lived GHGs, so that superficial extrapolations of GHG trends would lead to misleading conclusions. In many world regions, the evolution of air pollutant emissions has effectively decoupled from economic growth. Since 1990, air pollutant emissions declined (sulfur dioxide, SO_2), stabilized (nitrogen oxides, NO_x), or increased slightly (black carbon, BC; organic carbon, OC; and ammonia, NH_3). This review discusses to what extent structural changes, technological improvements, and dedicated environmental legislation have contributed to these changes. The scenarios of future emissions in the literature span a wide range, mainly owing to different assumptions about future environmental policies. Although the more recent scenarios agree on declining air pollutants up to 2030, avoiding potential rebounds of emissions after 2030 will require additional policy interventions.

Contents

1. INTRODUCTION

Emissions of air pollutants cause a variety of adverse impacts, including premature mortality, morbidity, crop losses, risks to biodiversity, and acidification of soils and surface waters. As these effects occur at the local scale and in the near term, the past and future evolution of such emissions usually has been addressed by scientific communities and policy institutions at the local, national, or regional scale. Although substantial efforts have been devoted to global analyses of the emissions of carbon dioxide (CO_2) and other long-lived greenhouse gases (GHGs), air pollutant emissions have received only limited attention in the global context. However, as is shown in this review, past and likely future trends in air pollutant emissions evolve rather differently from those of long-lived GHGs, so superficial extrapolations of GHG trends may lead to misleading conclusions. In recent years, new scientific insights revealed linkages and mechanisms that raise interest in the global evolution of air pollutant emissions. With a solid understanding of global emission trends, these insights could increase the cost-effectiveness of local and regional air quality management policies; they could enhance the acceptance of mitigation measures for long-lived GHG emissions by highlighting their local and near-term benefits on human health and ecosystems; and they could reveal win-win portfolios of controls for short-lived substances that yield immediate health and crop benefits while limiting temperature increases in the near term. Policy institutions have begun to harness such potential co-benefits in a systematic way.

Convention on Long-range Transboundary Air Pollution: establishes a broad international framework for cooperative action on air pollution

There is now solid scientific evidence about the importance of the hemispheric transport of air pollutants (1), which has immediate consequences for local and regional air quality management strategies. Work under the Convention on Long-range Transboundary Air Pollution explores how coordinated strategies that would reduce hemispheric background pollution in the Northern Hemisphere could universally alleviate the challenges for local air quality management (2).

Numerous case studies have highlighted important co-benefits for human health and vegetation from the co-control of long-lived GHGs and air pollutants, which could offer incentives for mitigation measures that not only are beneficial for global climate protection in the long run but also produce concrete benefits in the near term at the local scale (3). To develop a global perspective of such co-benefits, and how these could influence the evolution of long-term emission trajectories of GHGs, the "representative concentration pathway" (RCP) studies of global integrated assessment models have recently added future emission scenarios of air pollutants to their projections of long-lived GHGs (4).[1] This

[1] Representative concentration pathways (RCPs) are based on selected scenarios from four modeling teams working on integrated assessment modeling, climate modeling, and modeling and analysis of impacts. These pathways are consistent sets of projections of the components of radiative forcing that serve as inputs for climate modeling.

work will inform the forthcoming Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

Over the past years, scientific understanding of the radiative impacts of aerosols and other short-lived air pollutants has significantly improved, although important uncertainties remain (5). The current generation of global circulation models now includes aerosol impacts in their climate calculations, and recent model experiments employ global scenarios of the relevant precursor emissions developed by the RCP process. The seminal study reviewing the near-term climate impacts of specific mitigation measures of black carbon (BC) and other air pollutants (6), which has informed the United Nations Environment Programme/World Meteorological Organization's (UNEP/WMO's) *Integrated Assessment of Black Carbon and Tropospheric Ozone* (7), has triggered the formation of a new global political initiative under the Climate and Clean Air Coalition (**http://www.unep.org/ccac/**). As a voluntary coalition, the Climate and Clean Air Coalition aims to realize the opportunities for win-win mitigation strategies that yield benefits to human health and development objectives, and to slow down near-term climate change.

All these scientific activities and policy initiatives require a solid understanding of the past and future evolution of the emissions of air pollutants at the global scale. However, there is only little analysis on current and future sources of air pollution emissions at the global scale, and the reasons for differences in the published projections are often not clearly identified. Although air pollution comprises a large variety of substances, this review focuses on a few key pollutants and compares their trends with those of CO_2. Owing to a variety of factors, emissions of air pollutants develop differently from those of CO_2, and targeted policy interventions can lead to significant changes in emission trends.

The article discusses sulfur dioxide (SO_2) as an important precursor of secondary inorganic aerosols, which constitute a substantial fraction of fine particulate matter ($PM_{2.5}$) in ambient air. $PM_{2.5}$ has been identified as the air pollutant with largest impacts on premature mortality and morbidity [see, e.g., the recent analysis of the Global Burden of Disease Study (8)]. In addition, SO_2 is a main component in acid deposition, which causes acidification of soils and surface water (9), and sulfate aerosols, of which SO_2 is a precursor, act as cooling agents (e.g., Reference 10). The review also addresses emissions of nitrogen oxides (NO_x) as other precursors of $PM_{2.5}$, acid deposition, and ground-level ozone; in addition, NO_x contribute to excess nitrogen deposition, which imposes a significant threat to the biodiversity of ecosystems in many world regions (11). The article addresses emissions of BC and organic carbon (OC), which receive increasing attention because of their health impacts (as part of $PM_{2.5}$) (12) and their impacts on radiative forcing (13, 14). Finally, to provide a more comprehensive picture of the risks to biodiversity from excess nitrogen deposition, the review addresses ammonia (NH_3) emissions, which originate predominantly from agricultural activities (15). We review the current understanding of past and future trends of the emissions of these substances and their anthropogenic sources, but we do not touch on open biomass burning, the associated changes in air quality, and the resulting health and ecosystem impacts.

This review provides a brief summary of existing global emission inventories (see Section 2). Section 3 discusses recent trends of air pollutant emissions in various world regions and identifies key factors that have determined the increases and decreases of emissions in Europe in the past two decades. Section 4 reviews available projections of future air pollutant emissions and discusses key factors that will critically influence future emission levels at the global scale.

IPCC: Intergovernmental Panel on Climate Change

BC: black carbon

SO_2: sulfur dioxide

$PM_{2.5}$: fine particulate matter with an aerodynamic diameter of less than 2.5 μm

NO_x: nitrogen oxides

OC: organic carbon

NH_3: ammonia

2. INVENTORIES OF HISTORIC AIR POLLUTANT EMISSIONS

In contrast to GHGs, which are addressed under the UN Framework Convention on Climate Change (UNFCCC) and for which

NMVOCs: nonmethane volatile organic compounds

GAINS: Greenhouse Gas Air Pollution Interactions and Synergies

emission data are regularly reported by governments to UNFCCC, there are no institutionalized processes with a focus on establish inventories for air pollutants at the global level.

A synthesis of various estimates of historic emissions has been compiled into a global inventory by Lamarque et al. (16) for use in climate model runs for the *Fifth Assessment Report* of the IPCC (17) and as a common starting point for the emission projections in the RCP studies (4). This comprehensive database covers the key air pollutants, i.e., SO_2, NO_x, carbon monoxide (CO), BC, OC, NH_3, and nonmethane volatile organic compounds (NMVOCs), for the time period 1850–2000 and brings together earlier inventories, such as EDGAR-HYDE (18), RETRO (19, 20) and REAS (21), as well as several other studies (e.g., References 22–26).

Granier et al. (27) review the available global, national, and regional SO_2, NO_x, CO, and BC emission inventories of governmental institutions, as well as the scientific efforts to put together air pollutant inventories at the regional and global levels. For SO_2 and NO_x, global estimates range within $\pm 10\%$ for most inventories, but at regional levels, large variations are found, especially for China and India (up to factor of two). Discrepancies tended to increase in recent decades owing to fast economic growth, uncertainties about the statistics of fuel consumption and fuel quality, and different opinions about the effectiveness of recent emission control legislation. For BC, most inventories vary by about $\pm 25\%$ for the period before 2000, whereas for more recent years, the few available estimates show much better agreement ($\pm 5\%$). This is in contrast to modeling and remote sensing studies, which indicate that global BC emissions might be largely underestimated (5).

3. RECENT GLOBAL AND REGIONAL EMISSION TRENDS

Only a very few papers analyze the global evolution of air pollutant emissions in the past decades (27–29), but a growing number of regional assessments has been published recently, especially for Asia, Europe, and the United States. These assessments clearly demonstrate that in many world regions the evolution of air pollutants has been effectively decoupled from economic growth.

Although energy consumption is a major source of both CO_2 and air pollutants, these emissions developed rather independently. Between 1990 and 2010, global CO_2 emissions from anthropogenic sources grew by about 60%, while SO_2 emissions fell by about 20%, NO_x stabilized, and BC, OC, and NH_3 grew by 10–25%. The extent to which this decoupling occurred varied among world regions, economic sectors, and pollutants as illustrated in **Figure 1**. The regional trends are calculated with the Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) model (30) and are consistent with the energy statistics of the International Energy Agency (31), data used in the recent United Nations Environmental Programme/World Meteorological Organization assessment (7), and global (e.g., Reference 27) and regional trends (28, 32–37) discussed in more detail below.

3.1. Sulfur Dioxide

Power generation from coal and oil constitutes the dominant source of anthropogenic emissions of sulfur dioxide (SO_2) in the world, followed by industrial energy combustion (**Figure 1**). In the past two decades, SO_2 emissions in North America and Europe have fallen by more than two-thirds, as a result of improved energy efficiencies, shifts in fuel mixes, and the widespread application of end-of-pipe desulfurization in the power sector (33, 35, 36). However, emissions in Asia have risen sharply and compensated for the decrease in other world regions between 2000 and 2005 (21, 26, 32). Thus, global SO_2 emissions fell until 2000, then rebounded to peak around 2005, and declined again toward 2010 (29).

Of particular importance are developments in China, where emissions contribute about one-third of the global SO_2. The Chinese

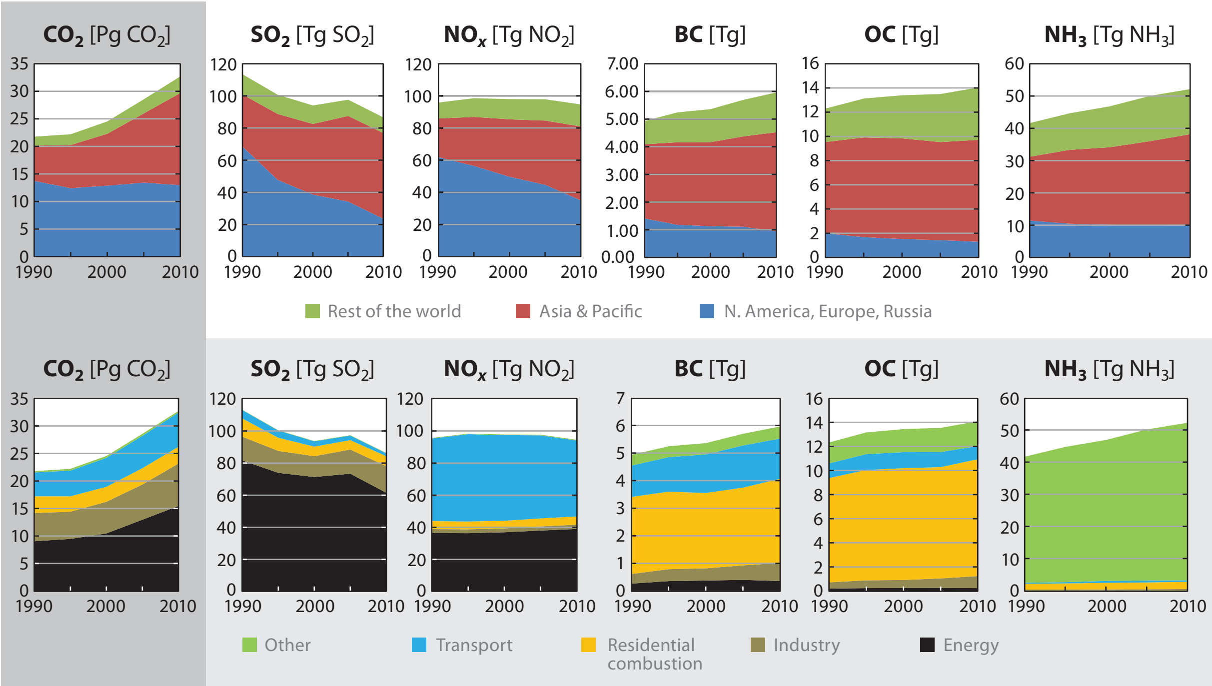


Figure 1

Evolution of anthropogenic emissions of CO_2 and key air pollutants, 1990–2010 by source sectors and world regions, excluding international shipping and aviation. The graphs were created from Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) model results found in Reference 7. Abbreviations: Pg, petagram; Tg, teragram.

government has set very ambitious SO_2 reduction targets, which have not been fully achieved in the past (38, 39). The effectiveness of newly introduced emission controls in China is still under debate (40, 41), but there are indications that after 2006 Chinese emissions started to decline slowly (37, 42–45). Remote sensing data seem to confirm declining trends for recent years (46–50). However, while progress has been made in controlling SO_2 emissions in the power sector, in absence of strict legislation, industrial emissions are now already higher than those from the power sector and are poised to continue to grow (29, 37, 45).

Currently, India contributes about three times less to global SO_2 emissions than China; however, Indian emissions grew by a factor of two in the past decade (29, 32), and there is no legislation in sight to constrain further growth.

Emissions from international shipping, which are not included in **Figure 1**, have increased strongly and accounted in 2000 for about nine percent of global SO_2 emissions (16, 26, 51). Although some RCP emission scenario studies suggest declining trends after 2000 (52), a recent evaluation (29) for the past decade reveals, in spite of the economic crisis, continued growth and for 2010 nearly 40% higher emissions than in 2000, so that in 2010 international shipping contributed 13% to global emissions.

3.2. Nitrogen Oxides

Mobile sources are responsible for the majority of anthropogenic NO_x emissions in the world. In spite of the rapid growth of the vehicle fleet, the share of vehicle emissions decreased in past years, following the widespread introduction of emission control devices (**Figure 2**). Although

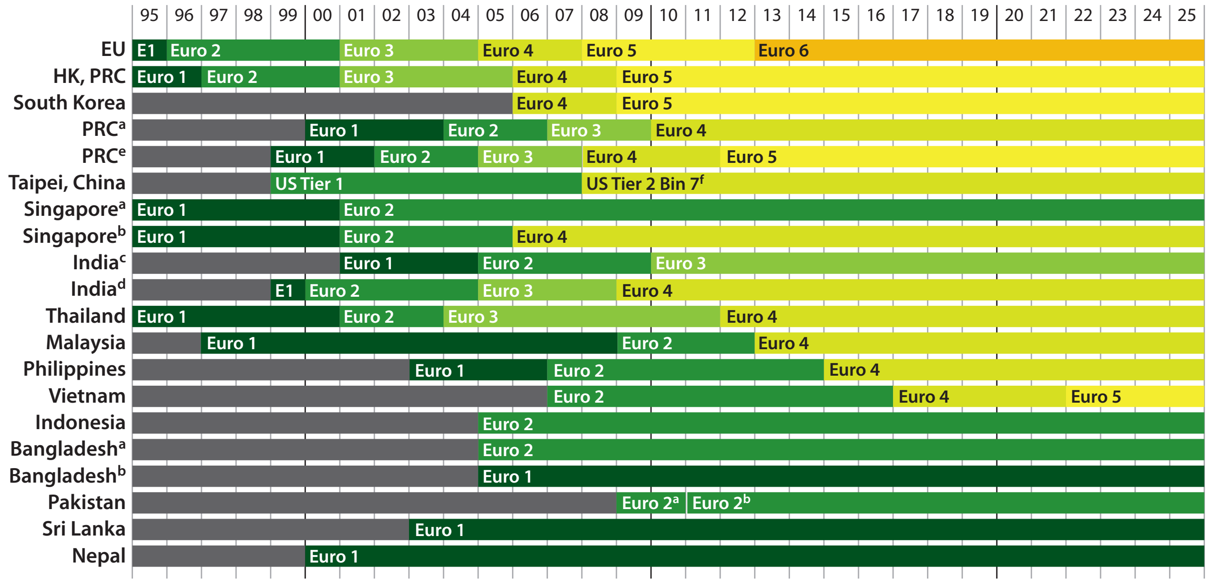


Figure 2

Emission standards for new light-duty vehicles in Asia as of September 2011 (95). European standards (Euro) 1–6 refer to progressively stringent emission limit values for light-duty vehicles established by the European Union from 1993 onward. Vietnam will implement Euro 3 standards for motorcycles by 2017. The levels of adoptions vary by country and by urban areas in India. Abbreviations: a, gasoline; b, diesel; c, other areas except d; d, Delhi, Mumbai, Kolkata, Chennai, Hyderabad, Bangalore, Lucknow, Kanpur, Agra, Surat, Ahmedabad, Pune, and Sholapur; Euro 2 for other cities in India; e, Beijing (Euro 1 in January 1999; Euro 2 in August 2002, Euro 3 in 2005, Euro 4 in March 2008, Euro 5 in 2012); Shanghai (Euro 1 in 2000; Euro 2 in March 2003, Euro 3 in 2007, Euro 4 in 2010); Guangzhou (Euro 1 in January 2000; Euro 2 in July 2004, Euro 3 in September–October 2006, Euro 4 in 2010); f, equivalent to Euro 4; HK, Hong Kong; PRC, People's Republic of China.

European legislation has imposed increasingly strict limit values on NO_x emissions from vehicles, which are usually met by new cars under test cycle conditions, experience shows that emissions from diesel light-duty vehicles have hardly declined under real-world driving conditions (53). Similar experience has been recently reported in Asia (54, 55). Emissions from power generation continued their growth and contributed in 2010 about 40% to the global total.

Also for NO_x, emissions developed rather differently in industrialized and developing countries. Emissions from North America and Europe declined sharply (34–36, 56), while Asian emissions almost doubled in the past two decades (7, 21, 37, 39, 57–59). At the global level, these two opposing trends have cancelled out in the past. The NO_x increase in developing countries was mainly caused by the growth of the power sector, which currently lacks emission control legislation. Despite the boost in the vehicle fleet, emissions of road transport showed only a modest increase in developing countries as efficient emission controls have been widely introduced.

A global trend is also absent for CO emissions for the same reasons. Decreases in traffic emissions in North America and Europe have been compensated by higher emissions from industry, especially in Asia. However, emissions from solid fuel combustion in the residential sector remained almost constant and contributed about 40% to the total CO emissions in 2010.

International shipping accounted in 2000 for nearly 20% of the total anthropogenic NO_x emissions (51, 60). Although no studies have assessed the development in the past decade, the 40% increase in shipped freight volume between 2000 and 2010 suggests the 20% growth assumptions in the RCP scenarios (52) to be conservative.

3.3. Black Carbon and Organic Carbon

Heating and cooking with coal and biomass constitute the largest global source of anthropogenic emissions of BC and OC, contributing approximately 50% and 70% to the total emissions, respectively (61). However, in Asia and Africa, this source represents up to 80% of BC emissions. Global emissions have grown by 10–20% in the past two decades, but regional trends vary strongly. Emissions in North America and Europe declined by about one-third. However, emissions in developing countries, especially in Asia, increased by a similar percentage, so that global BC and OC emissions grew in the last decade (7, 27, 43, 62, 63). Part of this growth was caused by the increase in diesel vehicles, which contribute currently about a quarter to the total BC emissions in the world. In some European countries with a high share of diesel vehicles, they account for up to 70% of BC emissions.

In general, there remain large uncertainties about the magnitude of BC and OC emissions (5, 61, 64, 65), especially because many inventories do not include all sources (e.g., flaring in the oil and gas industry), and measurements of emission factors are still poor and not necessarily representative of many regions (61). Moreover, for some sources, emission factors were measured only recently [e.g., for brick kilns (66), kerosene wick lamps (67)], and for coke ovens and small industrial coal boilers, they are not available even now. In spite of the large uncertainties about the magnitude, the reviewed emission inventories and modeling studies show consistent trends at the global and regional levels.

3.4. Ammonia

For NH_3 emissions, agricultural activities, especially from livestock breeding and fertilizer application, are the dominant sources (15, 68) with livestock contributing about two-thirds to global anthropogenic emissions, especially in North America and Europe. However, in developing Asia, application of nitrogen fertilizers (especially urea and ammonium bicarbonate) often contributes more than 50% of regional NH_3 emissions.

The rapid growth in world population and NH_3 synthesis by Haber-Bosch led to an increase of nitrogen fertilizer use by a factor of 20 since 1950, and animal populations have typically grown by a factor of two for cattle, pigs, poultry, sheep, and goats (69, 70). For the past two decades, an increase in global emissions of about 25% has been estimated (**Figure 1**).

3.5. Uncertainties and Validation

The emission inventories and trends presented above are usually derived with bottom-up methodologies, which can only be compiled with hindsight by using statistical data and emission factors that are measured under laboratory or real-world conditions. Such emission inventories are limited by the availability and completeness of data, for both activity data and emission factors. In particular, activity data can only be compiled after statistical data on socioeconomic and other activities have been published, and emission factors for some sectors/regions are often based on laboratory condition measurements.

The recent UNEP/WMO's *Integrated Assessment of Black Carbon and Tropospheric Ozone* (7) concluded that emissions of NO_x and SO_2 are generally well understood, whereas estimates of BC, OC, CO, and NMVOC emissions remain quite uncertain for many source types. This is consistent with the findings and recommendations of the UN Task Force in *Hemispheric Transport of Air Pollution* (2, 28, 71).

A recent study addressing the uncertainties in current Chinese emissions inventories estimated a range of −14% to +13% for SO_2 and −13% to +37% for NO_x (72), which are somewhat lower than the spread shown in international studies quoted by Granier et al. (27), especially considering the uncertainties of the coal consumption statistics (73).

Environmental Kuznets curve: a hypothesis suggesting that pollution increases at low levels of income up to a turning point beyond which it decreases

As uncertainties in BC inventories remain high [a factor of two is estimated by Bond et al. (61)], regional estimates compiled by different authors show large discrepancies, especially for China and India. With a −25% to +136% uncertainty range for recent Chinese BC emissions, Zhao et al. (72) confirm the earlier calculations of Bond et al. (61). However, the modeling and remote sensing studies indicate that global BC emissions might be underestimated, depending on the region, by up to a factor of four (5).

To validate emission inventories by independent means, top-down methods, e.g., satellite observations of concentrations of air pollutants (aided by in situ monitoring) coupled with inverse modeling methods, have been developed. Such remote sensing techniques have potentially global coverage, high temporal resolution, and homogenous quality, even for regions for which bottom-up data are sparse. They also have a short time lag, so that recent trends can be detected almost in real time. A combination of remote sensing data with source apportionment studies can be used to estimate sectorial emissions.

In recent years, observations from various satellite-borne sensors were combined to estimate concentration levels of NO_2 (59, 74, 75), BC (65), OC, SO_2, and CO (50, 76). In general, these remote sensing analyses confirm the trends derived from bottom-up estimates (48, 49). However, satellite measurements of aerosol optical depth indicate potentially higher absolute emission levels of BC and SO_2 compared to estimates derived from bottom-up inventories.

3.6. Factors Influencing Changes in Emissions

As shown above, during the past decades, emissions of most air pollutants have decreased in North America and Europe and increased in developing countries, especially in Asia. There are various hypotheses about the underlying driving forces responsible for the observed changes in air pollutant emissions. Many of these factors have also changed substantially in the past, including demographic composition, lifestyles, economic development, energy, transport, climate and agricultural policies, fuel prices, and the application of dedicated emission control measures.

Economists have proposed the concept of the environmental Kuznets curve (77), whereby pollution increases at low levels of income up to a turning point beyond which it decreases, as in the original Kuznets curve for economic inequality (78). Reasons for such an inverted U-shaped relationship are hypothesized to include income-driven changes in (*a*) the composition of production and/or consumption, (*b*) consumer preference for environmental quality, (*c*) institutions that are needed to internalize externalities, and/or (*d*) increasing returns to scale associated with pollution abatement (79–81). Other voices point to the structural changes in energy and industrial systems that occurred as a consequence of the increase in global energy prices after the oil price crisis of the 1970s, which also reduced the consumption of the most-polluting fuels. Environmentalists often emphasize the elaborate national and international frameworks of environmental legislation in which countries agreed to take dedicated measures to reduce their emissions, inter alia, by applying advanced end-of-pipe emission control technologies (82).

A recent paper by Rafaj et al. (83) examines the impacts of key factors that could explain the observed evolution of SO_2, NO_x, and CO_2 emissions in Europe from 1960 to 2010. During this time, SO_2 and NO_x emissions have risen to historical peaks and then declined below the 1960 levels. In contrast, the growth rate of CO_2 emissions has hardly changed. In this period, Europe experienced rapid economic growth along with profound structural changes in the economy toward less energy-intensive production; in response to the increased oil price, energy efficiency has improved substantially, and the fuel mix changed. Targeted end-of-pipe emission control measures were introduced on a large scale, inter alia, triggered by international environmental agreements [e.g., the protocols under the Convention on Long-range Transboundary Air Pollution (84, 85)].

With reference to the hypothesized environmental Kuznets curve, Rafaj et al. (83) examine the observed time series of emissions along a modified Kaya identity [*emissions* = *population* × (*gross domestic product, GDP/population*) × (*energy/GDP*) × (*fuel type/energy*) × (*emissions/fuel type*)] (86, 87) to quantify the impacts of changes in affluence, energy intensity, changes in fuel mixes, and dedicated environmental policy interventions.

With constant energy intensity and efficiency, fuel mix, and emission controls at the 1960 levels, SO_2 emissions in Europe would have grown by a factor of four up to 2010 following the GDP increase (**Figure 3**). However, by 2010, actual SO_2 emissions declined by about 90% compared to 1960, or by 99% compared to the levels that could have been projected without structural changes or policy interventions. Although environmental policies in Europe have prominently pushed the large-scale application of technical end-of-pipe SO_2 control measures (such as flue gas cleaning and fuel oil desulfurization), this analysis (83) highlights that only one-quarter of the difference between hypothetical and actual emissions can be attributed to targeted end-of-pipe abatement measures. About

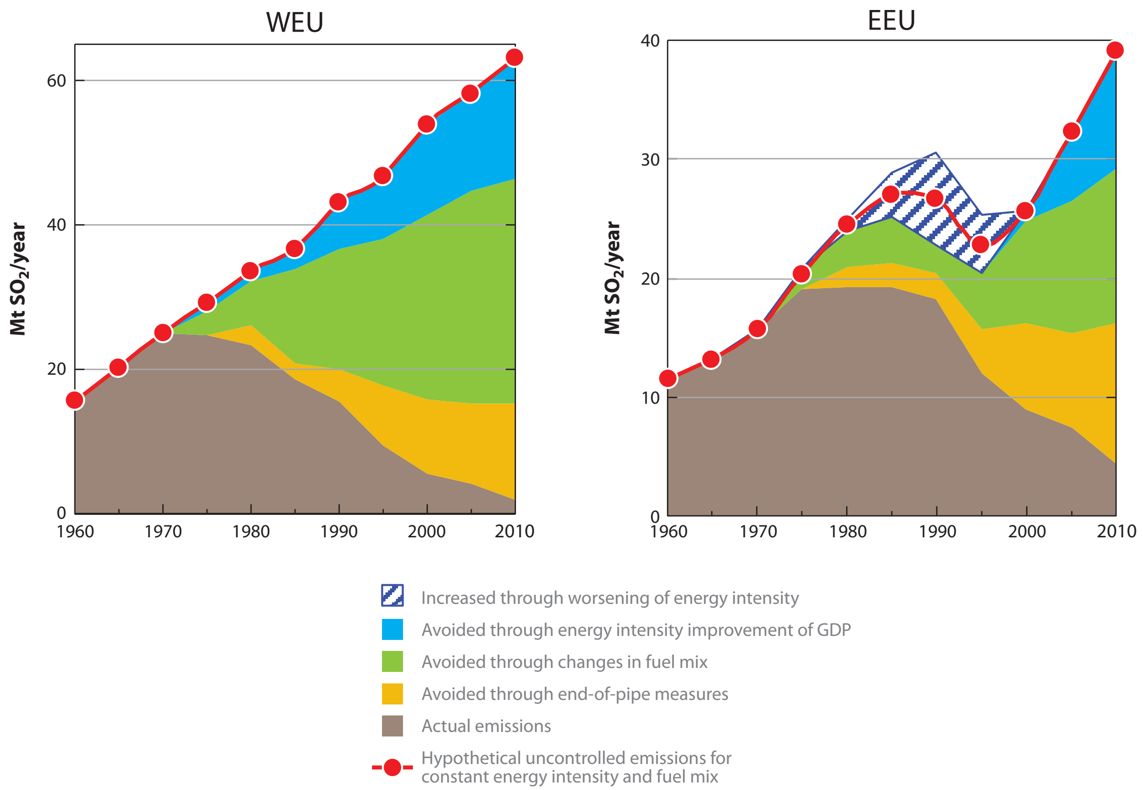


Figure 3

Factors contributing to the reductions of SO_2 emissions in Western Europe (WEU) and Eastern Europe (EEU) from 1960 to 2010. The black areas reflect actual emissions; the red lines indicate hypothetical emissions that would have occurred if all determining factors except gross domestic product (GDP) growth would have remained at their 1960 levels. The different wedges quantify the impacts of three drivers to emission reductions: changes in energy intensity of GDP (*blue*), changes in fuel mix (*green*), and application of end-of-pipe emission control measures (*yellow*) (83). Abbreviation: Mt, megaton.

Special Report: Emissions Scenarios (SRES): a report by the Intergovernmental Panel on Climate Change that was published in 2000

GEA: *Global Energy Assessment*

three-quarters of the avoided SO_2 emerged from energy intensity improvements and changes in the fuel mix, which were not primarily driven by air pollution concerns. It is important to note that the impact of dedicated emission control measures clearly increased after 2000 in the eastern European countries when they prepared for accession to the European Union, highlighting the important role of governing institutions in emission reductions.

For NO_x, targeted emission control technologies were more important. For stationary sources, application of dedicated end-of-pipe measures made a similar contribution to the avoidance of NO_x emissions as the shift toward less energy-intensive production. Changes in the fuel mix had a much smaller impact compared to the case of SO_2 as emission factors differ less for NO_x. Emissions from mobile sources were mainly determined by the effectiveness of applied end-of-pipe measures because energy efficiency improvements were compensated by higher transport intensities.

The observed decoupling between GDP and CO_2 emissions in Europe resulted primarily from the declining energy intensity of GDP and fuel efficiency improvements; changes in the fuel mix contributed about one-third. However, a comprehensive assessment needs to account for the shift of production of energy-intensive goods to non-European countries (carbon leakage).

For the United States, Lu et al. (88) analyze the reasons behind the 24% drop in SO_2 emissions from the power sector between 2008 and 2009. They conclude that 15% of the decrease can be attributed to the drop in demand for electricity triggered by the economic recession and 28% to switching fuel from coal to gas in response to a decrease in prices for the latter owing to the enhanced availability of shale gas. The largest factor in the decrease, close to 57%, resulted from an overall decline in emissions per unit of power generated from coal. This is attributed in part to selective idling of older, less efficient coal plants, which generally do not incorporate technology for sulfur removal, and in part to continued investments by the power sector in removal equipment in response to the requirements for limiting emissions imposed by the US Environmental Protection Agency.

The analysis shows that, in general, SO_2 and NO_x emissions in Europe and the United States have empirically followed the environmental Kuznets curve. On the basis of such findings, various scenario studies have developed quantitative projections of air pollutant emissions in which the future levels of emission controls are endogenously linked to income (81). However, Rafaj et al. (83) clearly demonstrate that observed turning points occurred for different countries and pollutants at different income levels, and no turning point has yet been identified for CO_2. Especially for SO_2, factors that are unrelated to environmental concerns (such as changes in fuel prices and shifts in industrial structures, leading to declining energy intensities of the GDP) had larger impacts on emission reductions than dedicated environmental policies [see the discussion by Stern (80) of other important drivers of emissions changes and alternative parameterizations of the environmental Kuznets curve]. Thus, it appears as questionable whether the concept of environmental Kuznets curves alone could provide a meaningful rationale for precise quantitative projections of future emissions of air pollutants.

4. SCENARIOS OF FUTURE EMISSIONS

Only recently has the future evolution of air pollutant emissions in a global context received more systematic attention. Four major exercises have produced families of emission scenarios as input to different global assessments:

- The IPCC *Special Report: Emissions Scenarios* (SRES) (89) in 2000
- "The Representative Concentration Pathways" (4) of 2011 as an input to climate model calculations for the forthcoming Fifth Assessment Report of the IPCC
- Scenarios developed for the *Global Energy Assessment: Toward a Sustainable Future* (GEA) (90) in 2010–2011

- Air pollutant emission scenarios developed with the GAINS model in 2010–2012 for the UNEP/WMO's *Integrated Assessment of Black Carbon and Tropospheric Ozone* (7) and the Task Force on Hemispheric Transport of Air Pollutant (71) of the Convention on Long-range Transboundary Air Pollution

All these exercises estimate future emissions as a product of projected activity data (e.g., energy consumption, industrial production, agricultural activities) and emission factors, but they rely on different socioeconomic assumptions and employ different hypotheses about future environmental legislation.

Early global scenarios of future SO_2, NO_x, CO, and VOC emissions were published in the SRES (89) prepared for the IPCC in 2000. These scenarios (their emission ranges are indicated in **Figures 4** and **5**) explore a range of future GHG trajectories for different assumptions on driving forces, such as socioeconomic and technological developments. They do not take into account

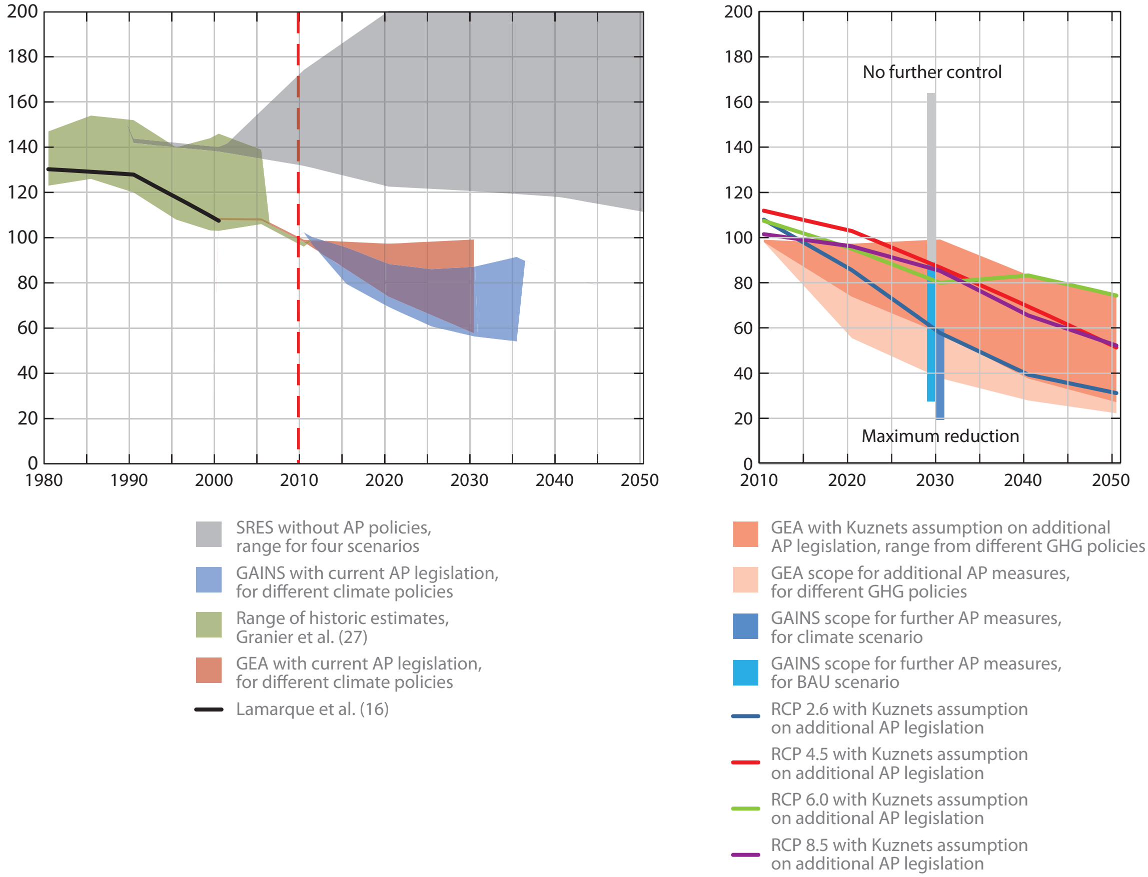


Figure 4

Historic trends and scenarios of future SO_2 emissions in teragrams (Tg)/year). (*left*) The range of historic inventories (*green*), scenarios that do not assume additional air pollution controls beyond 1990 (*gray range* for the SRES, scenarios) (89), and beyond the legislation of 2010 [after the *dashed red line*, the GEA (90) and GAINS (30) scenarios]. (*right*) Future scenarios assuming further air pollution controls beyond current legislation. Abbreviations: AP, air pollution; GAINS, Greenhouse Gas Air Pollution Interactions and Synergies; GEA, *Global Energy Assessment*; RCP scenarios (RCP 2.6, 4.5, 6.0, and 8.5), the representative concentration pathways aiming to limit global radiative forcing at 2.6, 4.5, 6.0 and 8.5 W/m^2, respectively; SRES, *Special Report: Emissions Scenarios*.

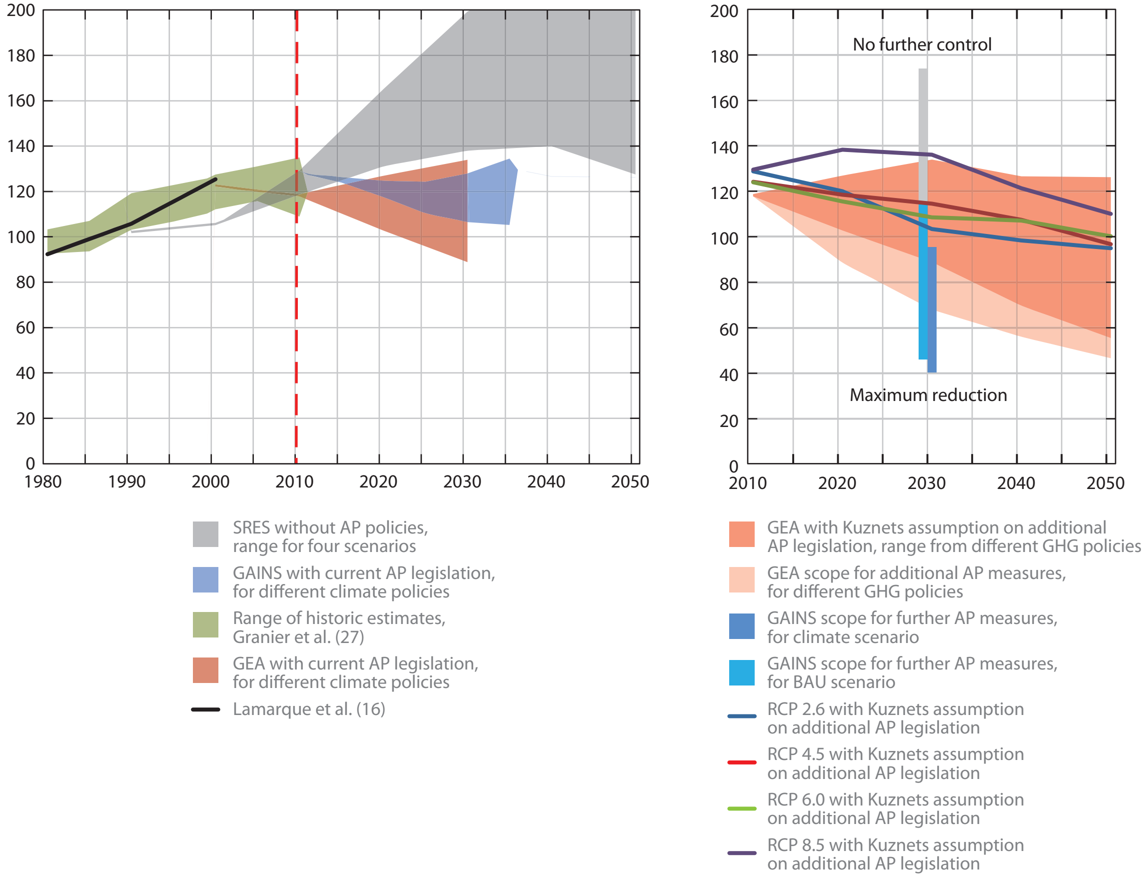


Figure 5

Historic trends and future scenarios of NO_x emissions. (*left*) The range of historic inventories (*green*) scenarios that do not assume additional air pollution controls beyond 1990 (*gray range* for the SRES scenarios) (89), and beyond the legislation of 2010, after the *dashed red line*, the GEA (90) and GAINS scenarios (30). (*right*) Future scenarios assuming further air pollution controls beyond current legislation. Abbreviations: AP, air pollution; GAINS, Greenhouse Gas Air Pollution Interactions and Synergies; GEA, *Global Energy Assessment*; RCP scenarios (RCP2.6, 4.5, 6.0, and 8.5), the representative concentration pathways aiming to limit global radiative forcing at 2.6, 4.5, 6.0 and 8.5 W/m^2, respectively; SRES, *Special Report on Emissions Scenarios*.

any current or future measures to limit GHG emissions. The same assumptions were applied for future policies to reduce air pollutants, so that emission factors were kept at their 1990 levels throughout the twenty-first century (81, 91). As these scenarios, which have not been specifically developed for the analyses of future air pollution, do not consider the emission controls that were introduced after 1990 (see **Figure 2**), they project significantly higher emissions than later scenarios.

As an input to climate model calculations for the forthcoming Fifth Assessment Report of the IPCC, a set of emission scenarios has been developed that would result in RCPs of GHGs (4). In addition to GHGs, these RCP scenarios include emission projections for SO_2, NO_x, VOC, BC, OC, CO, and NH_3, although they were not developed with a primary focus on air pollution concerns. The RCP scenarios employ a range of assumptions on climate policies and also assume for all countries additional control measures for air pollutants in the future beyond those currently included in national legislation (92, 93). For the quantification of future air pollution controls, the scenarios use parameterizations of the environmental Kuznets hypothesis implying that, after full implementation of current air pollution legislation, emission factors for air pollutants will decline further with increasing per capita income. Thereby, these scenarios internalize additional air pollution policies, which might or might not materialize in the future. However, because the RCP scenarios explore a wide range of future climate policies, they provide indications about the impacts of GHG reductions on air pollutants.

In contrast to the RCP pathways, the energy scenarios developed for GEA (90) assess a wider range of assumptions on air pollution controls in the future (94). In addition to the baseline case that follows after 2030 the same Kuznets hypothesis for additional air pollution controls as in the RCP scenarios, a variant assumes more aggressive air quality legislation, which is, however, less ambitious than the maximum feasible reductions in the GAINS model.

The above-mentioned emission scenarios have been developed with global energy models that represent spatial detail by distinguishing between 11 and 28 aggregated world regions. More explicit spatial emissions for future years are derived through downscaling approaches that apportion emissions calculated for the aggregated world region to individual countries or grid cells on the basis of historic emission patterns and generic rules that reflect urbanization dynamics and economic concentration processes. Thereby, future emissions are first determined for a limited number of world regions with an assumed development of regional mean emission factors, and then, the result is downscaled to specific locations based on certain rules. In regions that exhibit large spatial heterogeneities (e.g., in environmental policy governance) such an approach might lead to inaccurate results, as differences in trends within such large world regions are neglected.

As an alternative approach, the GAINS model (30) has been employed to estimate—for exogenous projections of energy consumption and other emission generating activities—the possible range of future air pollutant emissions, using a bottom-up approach that explicitly accounts for detailed emission control legislation in 162 world regions. With this model, it is possible to explore, for different energy and climate pathways, the scope for future air pollutant emissions that could be achieved by different levels of policy interventions. For each of these 162 regions, more than 1,500 specific emission control measures have been considered.

Using the energy projections of the *World Energy Outlook 2009* (31) of the International Energy Agency, global emissions scenarios have been developed with the GAINS model for the UNEP/WMO's *Integrated Assessment of Black Carbon and Tropospheric Ozone* (7) and the Task Force on Hemispheric Transport of Air Pollution (28) of the Convention on Long-range Transboundary Air Pollution. These scenarios consider the implementation schedules of currently agreed national emission control legislation (see, e.g., **Figure 2**) and explore, for different energy and climate policy scenarios, the scope for emission reductions that could be achieved with additional air pollution control measures that are beyond current policies.

4.1. Comparison of Global Emission Scenarios

The scenarios described above span a strikingly wide range of future emissions. For instance for SO_2, global emissions in 2030 differ by more than a factor of 10, i.e., between 20 and 220 teragrams (Tg)/year. Obviously, the SRES scenarios, which exclude climate policies and do not consider further air pollution emission control measures beyond those already implemented in 1990, result in highest emissions, with a 15% decline in 2030 compared to 1990 in the most optimistic case (**Figure 4**). The baseline cases of GAINS and GEA, with current legislation on air pollution, suggest a decline in global SO_2 emissions between 0% and 10% by

2030, depending on the assumed energy policies. For stringent climate policies, SO_2 emissions in these estimates decline by up to 40% in 2030 as a mere consequence of the decarbonization of the energy system without additional measures to reduce SO_2 emissions (**Figure 4**, left panel). This range emerges also in the RCP scenarios as a consequence of different assumptions about climate policies. However, both the GEA and GAINS scenarios indicate the scope for additional SO_2 mitigation through technical measures; full implementation of the most effective technical emission control measures that are currently on the market could cut SO_2 by up to 80% in 2030 (**Figure 4**, right panel).

Although there is general agreement among the more recent emission projections about the trends up to 2030, scenarios diverge for the time period beyond. The RCP scenarios, owing to their assumed autonomous further improvements in emission factors, project a sustained decline of SO_2 emissions until 2050. By contrast, without additional environmental policies, the GAINS and GEA scenarios point to a potential rebound of global SO_2 emissions once the current air pollution legislation is fully implemented.

The importance of dedicated environmental legislation is highlighted by the wide range of possible future SO_2 emissions for different assumptions on the extent and effectiveness of end-of-pipe emission controls. For instance, in 2030, global emissions could range from 20 Tg/year in the most optimistic case up to 160 Tg/year if emission factors were kept at the 2005 level and no new measures—even those already laid down in national policies—were introduced (**Figure 4**, right panel). Note that this no further control estimate is well within the range of the SRES scenarios that have applied this exact assumption.

A similar picture emerges for NO_x emissions (**Figure 5**). The early SRES scenarios, essentially ignoring the impacts of the already adopted emission control measures for vehicles listed in **Figure 2**, proposed a drastic increase in global emissions, inter alia, because of the rapid growth in vehicle stock. According to these scenarios, NO_x emissions could double in the next few decades and grow even further in the long term. The more recent scenarios, however, demonstrate that the already adopted legislation would stabilize or slightly reduce global emissions until 2030. After that time, the further development will be shaped by future environmental policies, and without new emission control legislation, emissions might rebound at the global level. Alternatively, GAINS scenarios indicate that additional end-of-pipe measures could reduce NO_x emissions by up to 70% below current levels if targeted policies were effectively established and implemented. The RCP scenarios with their environmental Kuznets hypothesis fall in between but clearly highlight that climate mitigation strategies, in general, also lead to lower NO_x emissions in the long run.

For carbonaceous particles, i.e., BC and OC, all scenarios suggest decreasing trends beyond 2010, essentially as a consequence of the decline of biomass and coal combustion in households because of improved access to modern forms of energy in developing countries (**Figure 6**). The GAINS scenarios indicate a large potential for further emission reductions, through both dedicated end-of-pipe emission control measures and a hypothetical complete replacement of biomass in cooking stoves by cleaner forms of energy. This could reduce global BC and OC emissions from anthropogenic sources by up to 90%. However, there are no clear relationships between climate policies and BC/OC emissions, as enhanced combustion of renewable biomass for residential heating (with higher particle emissions) in industrialized countries is often employed as a means for GHG reduction.

In contrast to the more optimistic perspectives for SO_2, NO_x, BC, and OC, all scenarios suggest steady increases for the emissions of NH_3, owing to the intensification of agricultural activities driven by population growth and lifestyle/diet changes. Even though there is no obvious connection to GHG mitigation strategies, technical measures are available that could maintain global NH_3 emissions at current levels.

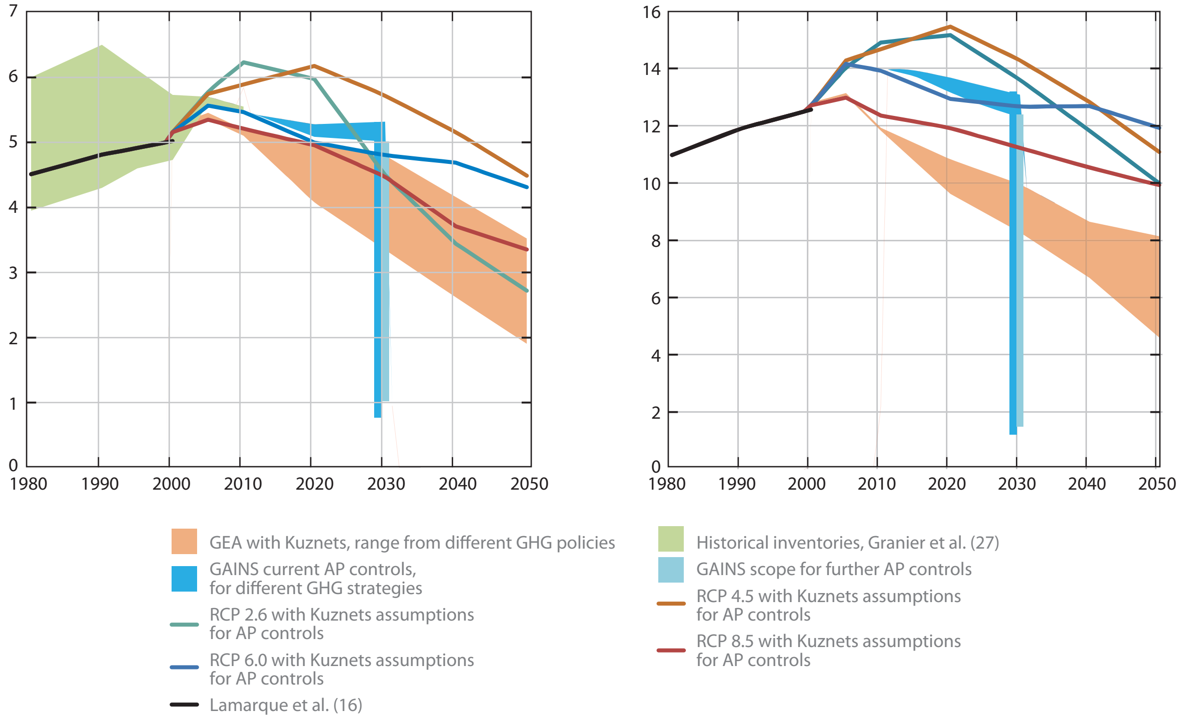


Figure 6

Historic trends and future scenarios of black carbon (*left*) and organic carbon (*right*) emissions. Abbreviations: AP controls, air pollution controls; GAINS, Greenhouse Gas Air Pollution Interactions and Synergies (30); GEA, *Global Energy Assessment* (90); RCP scenarios (RCP 2.6, 4.5, 6.0, and 8.5), the representative concentration pathways aiming to limit global radiative forcing at 2.6, 4.5, 6.0 and 8.5 W/m^2, respectively.

In summary, the major discrepancies between different emission projections emerge from varied assumptions on the stringency and effectiveness of emission control measures. Although the early (SRES) global scenarios have ignored already implemented policies, the more recent RCP scenarios imply an endogenous strengthening of legislation and compliance beyond what is currently agreed. Other projections adopt intermediate assumptions and result in intermediate emission levels. It is difficult to accurately predict future policy regimes, and the available scenarios highlight the critical impact of dedicated policy interventions on future emission levels.

4.2. Regional Trends

Even though the recent projections suggest a future decline in the emissions of many air pollutants at the global scale, trends diverge across world regions as a consequence of differences in the anticipated dynamics of economic development and the stringency and effectiveness of emission control policies. Thus, conclusions about future air quality at the regional level cannot be drawn from global emission trends.

Although regional quantitative estimates show some variation, there is overall agreement among the available scenarios about general trends for the various world regions, at least among scenarios that reflect recent levels of policy interventions. Thus, regional trends are discussed here for GAINS emission projections, which have bottom-up estimates for 162 world regions and are based on the energy projections of the *World Energy Outlook 2009* (31) of the International Energy Agency.

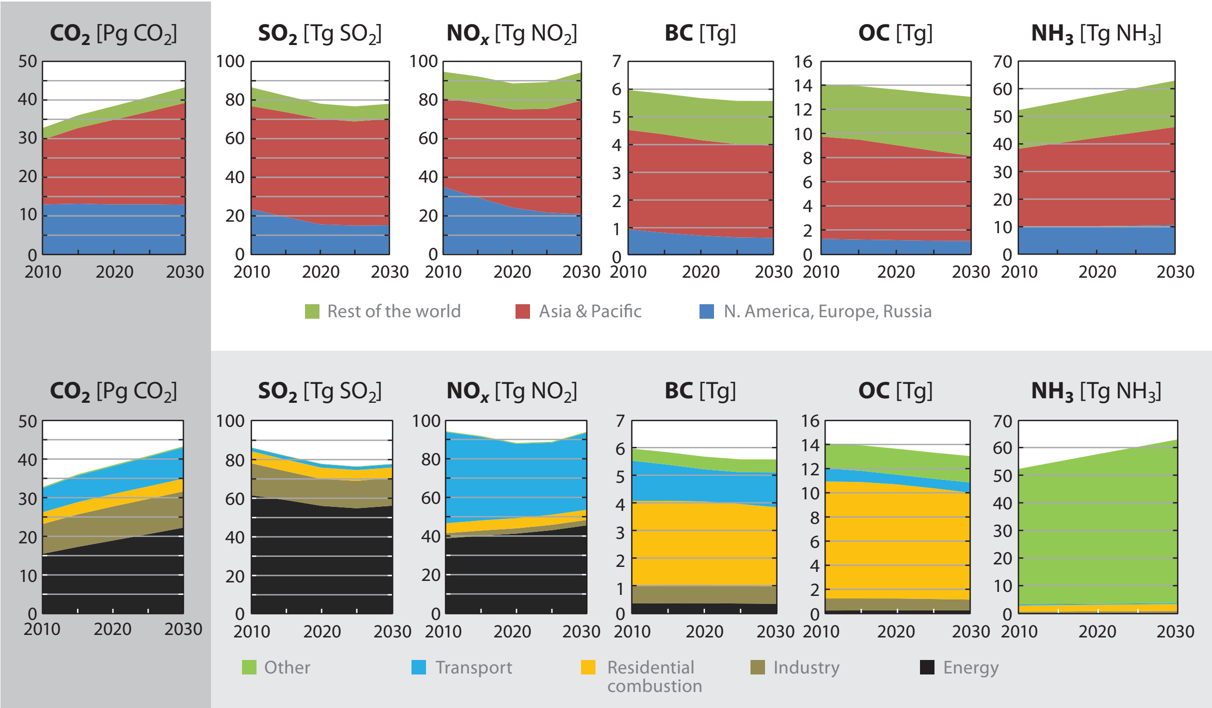


Figure 7

Estimates of future anthropogenic emissions of CO_2 and key air pollutants, 2010–2030, by world region and source sector, excluding international shipping and aviation. Most pollutants are expected to decline in industrialized countries as a consequence of stringent air quality legislation (*blue areas* in the top row). The importance of the Asia-Pacific region (*red*) is shown in the top row. As shown in the bottom row, power generation is the largest global source of anthropogenic carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) emissions. Black carbon (BC) and organic carbon (OC) emissions emerge mainly from domestic fuel combustion, and agriculture is the major source of ammonia (NH_3) emissions. The graphs were created from Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) model results found in Reference 7. Abbreviations: Pg, petagrams; Tg, teragrams.

Most notably, emissions of all pollutants (with the exception of NH_3) are expected to decline in industrialized countries as a consequence of stringent air quality legislation (as shown in the top row in **Figure 7**). In the developing world, future evolution is critically influenced by the assumptions of the effectiveness of emission control measures, with Asia and the Pacific as the most critical regions. Effective implementation of current emission legislation should stabilize SO_2 emissions in the Asia-Pacific region, but it will not be sufficient to prevent a steep increase in NO_x emissions (see the top row in **Figure 7**). For the anticipated evolution of use of coal and biomass, BC emissions would remain at current level in this region, while OC would decline. NH_3 would steeply increase in response to intensified agriculture to feed the growing population.

It is noteworthy that, for all world regions, the available scenarios suggest a strong decoupling between emissions of CO_2 and of the other air pollutants, mainly as a consequence of dedicated policy interventions that are assumed for the reduction of air pollutant emissions. The divergence between CO_2 and other air pollutants highlights the need to assess future air pollution trends separately from those of GHG emissions.

From a sectorial perspective, most of the anticipated global decline in SO_2 emissions will emerge from additional controls in the power sector (bottom row in **Figure 7**). For NO_x, current legislation on vehicle emission controls will compensate the emission increase from a growing vehicle fleet in the next few decades, but these laws will not be sufficient to counteract the increase of emissions from the power sector in absence of more stringent legislation. The fate of future BC and OC emissions will be mainly determined by the trends in the residential sector.

The divergence of regional emission trends for different sectors is highlighted in **Figure 8**. Between 2005 and 2030, areas with high densities of SO_2 emissions almost disappear in North America and Europe. For China, current legislation is expected to alleviate the situation to some extent, although high emission densities are expected to prevail over large areas, especially in the northeastern section. By contrast, given the lack of emission control legislation and the expected growth in power generation from coal, the Indian subcontinent will emerge as a new global hot spot of SO_2 emissions. No major changes, however, are envisaged for the Russian Federation.

Similar regional trends emerge for NO_x from surface transport, where dramatic improvements are foreseen for North America and Europe, which are counterbalanced at the global level by stark increases in southern and eastern Asia (**Figure 8*b***).

In contrast, BC emissions from residential heating and cooking (mainly from biomass and coal combustion) are currently highest in Asia, parts of Africa, and some countries in Europe. Emissions are expected to diminish greatly in Europe as well as in China, where improvements should result from the transition to cleaner forms of energy. By contrast, the same global energy projection would imply significantly higher BC emissions from the residential sector in southern Asia and Africa.

5. CONCLUSIONS

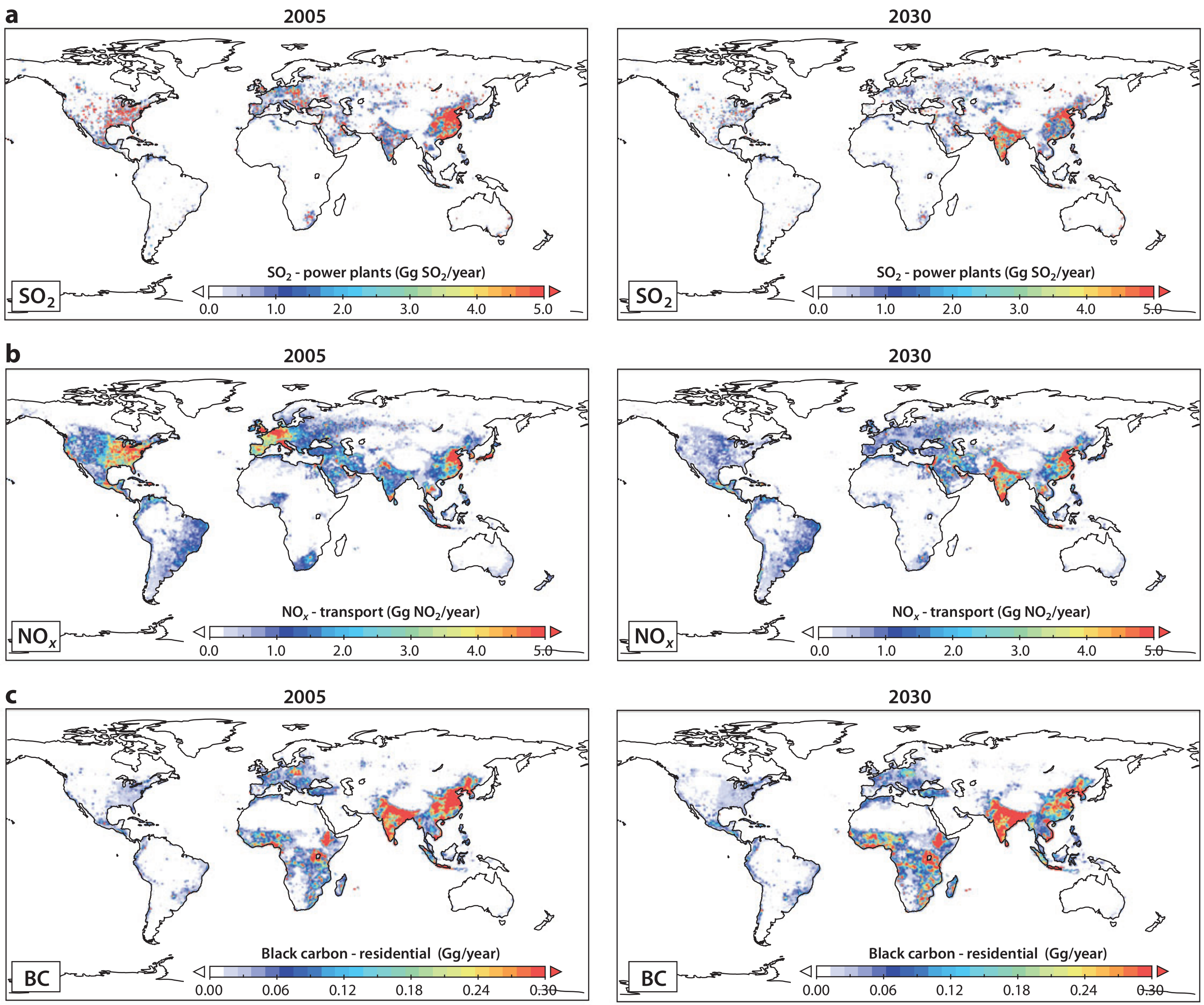
New scientific understanding of the intercontinental transport of air pollutants and their impacts on radiative forcing has raised interest in the global trends of air pollutant emissions. New policy initiatives are emerging to reap potential benefits from internationally coordinated air pollution controls for local air quality management and near-term climate change and to highlight the tangible local and immediate co-benefits from the mitigation of long-lived GHGs.

In contrast to GHGs, which are addressed by the UNFCCC and for which emission data are regularly reported by governments to UNFCCC, there are no institutionalized processes with a focus on established inventories of air pollutants at the global level. However, in view of the potential benefits mentioned above, a solid understanding of past and future air pollutant emissions at the global scale, and of the factors that decoupled their evolution from economic growth trends and CO_2 emissions, could provide important information to enhance air quality management.

In the past, the evolution of air pollutants has been effectively decoupled in many world regions from economic growth as a consequence of structural changes, technological improvements, and dedicated environmental legislation. Although energy consumption is a major source both of CO_2 and of air pollutants, these emissions developed rather independently in the past decades. Between 1990 and 2010, global CO_2 emissions from anthropogenic sources grew by about 60%; while SO_2 emissions fell by about 20%; NO_x stabilized; and BC, OC, and NH_3 grew by 10–25%.

Emissions in Asia have risen sharply and compensated the decrease in other world regions. Of particular importance are developments in China, whose emissions contribute about one-third to global SO_2. Although ambitious Chinese SO_2 reduction targets were not fully achieved in the past, there are indications that Chinese SO_2 emissions started to decline slowly after 2006.

SO_2 and NO_x emissions in Europe and the United States have followed the environmental Kuznets curve. However, observed turning points occurred for different countries and


a
2005
2030
SO_2
SO_2 - power plants (Gg SO_2/year)
0.0
1.0
2.0
3.0
4.0
5.0
b
2005
2030
NO_x
NO_x - transport (Gg NO_2/year)
0.0
1.0
2.0
3.0
4.0
5.0
c
2005
2030
BC
Black carbon - residential (Gg/year)
0.00
0.06
0.12
0.18
0.24
0.30

pollutants at different income levels, and factors that are unrelated to environmental concerns (such as changes in fuel prices and shifts in industrial structures leading to declining energy intensities of the GDP) had larger impacts on emission reductions than dedicated environmental policies. Thus, it appears questionable whether the concept of the environmental Kuznets curve alone could provide a meaningful rationale for precise quantitative projections of future emissions of different air pollutants.

Global emission scenarios in the literature span a strikingly wide range of future emissions, and typically vary by more than a factor of 10 for the coming decades. Although, in principle, the same mechanisms for emission changes apply that have been identified for the past, major differences in the projections can be explained by different assumptions about future air quality legislation. Climate policy efforts emerge as additional factors that reduce SO_2 and NO_x emissions in the future, but impacts on BC and OC emissions are less clear.

Up to 2030, the more recent scenarios agree on declining global emissions of SO_2, NO_x, BC, and OC. However, scenarios that do not assume additional air pollution policies indicate a potential rebound of global emissions after 2030, whereas emissions decline further in the scenarios that assume autonomous further reductions in emission factors based on the Kuznets hypothesis. Thus, even though air pollution might appear as a diminishing issue in the widely used RCP scenarios, the hypothesized autonomous further improvements in air quality will only occur if environmental policy interventions are enhanced in the future.

At the regional scale, differences in economic development and institutional arrangements for air quality management (e.g., enforcement of existing legislation) lead to different trends in future air pollutant emissions. Energy-related emissions are expected to strongly diminish further in North America and Europe, but current emission controls seem insufficient to prevent increases in NO_x emissions in Asia and to achieve reductions of SO_2, BC, and OC emissions there. However, the literature also clearly indicates that there is a significant potential for further reductions of these pollutants in developing countries, provided that environmental policies lead to effective implementation of additional emission control measures that are already applied on a large scale in other world regions.

A solid understanding of the potential gains from coordinated international action on air pollution would critically benefit from an improved quantification of emissions of specific pollutants (e.g., BC, OC, NH_3), source sectors (e.g., international shipping), and world regions (especially fast-developing economies). Such activities should be coordinated at the global level.

Although there is basic insight into the emissions of energy-related activities, there are large uncertainties in the inventories of nitrogen emissions, especially from agricultural activities. A sharpened focus on NH_3 emissions would help provide a solid knowledge base to counteract the projected steady increase in nitrogen emissions.

As highlighted in the review, air pollutant emissions are critically influenced by the effectiveness of the implementation of dedicated emission control measures. This is especially true in countries and sectors where institutional arrangements for the enforcement of compliance with existing regulations are only weakly developed; close monitoring of real-life emissions could significantly improve the accuracy

Figure 8

(*a*) Evolution of sulfur dioxide (SO_2) emissions from the power sector, (*b*) nitrogen oxide (NO_x) emissions from surface transport, and (*c*) black carbon (BC) emissions from the residential sector between 2005 (*left column*) and 2030 (*right column*) in the Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) current legislation emission projections. Emission densities are expected to decline in North America and Europe, and increase in Asia. Data produced by the GAINS model (30).

of current emission inventories. This applies particularly for emissions from mobile sources and industrial activities.

In the future, the development of global emission scenarios must consider the dominant influence of environmental policy decisions about emission controls and address the scope for policy interventions in a more explicit way. This would avoid misleading conclusions that air pollution is a problem that will diminish even in the absence of further policy efforts.

Air pollution scenarios should not only address alternative futures for economic development, but also explore alternative institutional and governance regimes. This would widen the range of possible emission developments and highlight the importance of environmental policy interventions.

SUMMARY POINTS

1. New scientific understanding of the intercontinental transport of air pollutants and the impacts of short-lived air pollutants on radiative forcing has raised interest in the global trends of air pollutant emissions. New policy initiatives have emerged to reap potential benefits from internationally coordinated air pollution controls.
2. In contrast to GHGs for which emission data are regularly reported by governments to the UNFCCC, there are no institutionalized processes with a focus on inventories of air pollutant emissions at the global level.
3. In many world regions, the evolution of air pollutants has been effectively decoupled from economic growth.
4. Although energy consumption is a major source of both CO_2 and air pollutants, these emissions developed rather differently in the past. Between 1990 and 2010, global CO_2 emissions from anthropogenic sources grew by about 60%, while SO_2 emissions fell by about 20%; NO_x stabilized; and BC, OC, and NH_3 increased by 10–25%.
5. Emissions in Asia have risen sharply and compensated decreases in other world regions. Of particular importance are developments in China, where emissions contribute about one-third to global SO_2. Although ambitious SO_2 reduction targets have not been fully achieved in the past, there are indications that Chinese emissions started to decline slowly after 2006.
6. SO_2 and NO_x emissions in Europe have followed the environmental Kuznets curve, whereby pollution increases at low levels of income up to a turning point beyond which it decreases. However, observed turning points occurred for different countries and pollutants at different income levels, and factors that are unrelated to environmental concerns had larger impacts on emission reductions than dedicated environmental policies.
7. Global emission scenarios in the literature span a strikingly wide range of future emissions and typically differ by more than a factor of 10. Major differences can be explained by different assumptions about future environmental legislation. To a lesser extent, differences are also related to decarbonization measures in GHG mitigation scenarios, especially for SO_2 and NO_x emissions, but the consequences for BC and OC emissions are less clear.

8. Scenarios that do not assume additional air pollution policies beyond current legislation indicate a potential rebound of emissions after 2030, whereas emissions decline in scenarios that assume autonomous further reductions in emission factors on the basis of the environmental Kuznets hypothesis. Thus, although air pollution might appear as a diminishing issue in the widely used RCP scenarios, this positive development will only occur if environmental policy interventions are enhanced in the future.

FUTURE ISSUES

1. A solid understanding of the potential gains from coordinated international action on air pollution would critically benefit from an improved quantification of emissions of specific pollutants (e.g., BC, OC, NH_3), source sectors (e.g., international shipping), and world regions (especially fast-developing economies). Such activities should be coordinated at the global level.
2. Even though there is basic insight into the emissions of energy-related activities, there are large uncertainties in the inventories of nitrogen emissions, especially from agricultural activities. A sharpened focus on NH_3 emissions would help provide a solid knowledge base to counteract the projected steady increase in nitrogen emissions.
3. As highlighted in the review, air pollutant emissions are critically influenced by the effectiveness of the implementation of dedicated emission control measures. Especially in countries and sectors where institutional arrangements for the enforcement of compliance with existing regulations are only weakly developed, close monitoring of real-life emissions could significantly improve the accuracy of current emission inventories, particularly for emissions from mobile sources and industrial activities.
4. The development of global emission scenarios must consider the dominant influence of environmental policy decisions about emission controls and address the scope for policy interventions in a more explicit way. This would avoid misleading conclusions that air pollution is a problem that will diminish even in absence of further policy efforts.
5. Air pollution scenarios should not only address alternative futures for economic development, but also explore alternative institutional and governance regimes. This would widen the range of possible emission developments and highlight the importance of environmental policy interventions.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Errata

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