

Global Climate Forcing by Criteria Air Pollutants

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Abstract

Ambient air pollution has significant impacts on global climate change in complex ways, involving both warming and cooling, and causes an estimated one million deaths every year. Modeling studies and observations from a suite of platforms, including those that are space based, have revealed that air pollution is a widespread global phenomenon. The net effect of air pollution is a global cooling that is masking 50% of the committed greenhouse gas (GHG) warming from the Industrial Revolution. Aggressive air pollution abatement and climate stabilization strategies that reduce cooling pollutants may lead to a short-term warming surge that is unsafe for ecosystems and the human population, imposing complex trade-offs in policy making. Conversely, selective reduction of warming air pollutants to mitigate near-term climate change may offer opportunities for synergistic policy development. Reducing and preventing the accumulation of fossil-fuel carbon dioxide (CO₂) in the atmosphere is the only sustainable way to protect climate safety in the long term. Here, the current understanding of air pollution effects on global climate change is reviewed, including assessment by individual pollutant, precursor emission, economic sector, and policy-relevant scenarios.

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1. INTRODUCTION

The Industrial Revolution that began in the United Kingdom around 1750 and spread throughout the rest of the world is one of the most important events in the history of humanity. The ability to unleash vast amounts of energy from fossil fuels and the subsequent development of the internal combustion engine, electrical power generation, and steam-powered ships and railways, reinforced by simultaneous increases in agricultural productivity, have led to great social and economic benefits but also to the two most dire

environmental problems of our time: air pollution and global climate change. These atmospheric challenges are intrinsically linked, most discernibly because they originate through several common emission sources, but also through complex mutual feedbacks. On the one hand, air quality is strongly dependent on weather and is therefore sensitive to climate change (1, 2). Adapting air quality management to climate change is crucial. On the other hand, less recognized at the public and political level and a major dilemma for environmental management is that air pollution is a key driver of anthropogenic global climate change.

The most important air pollutants that interact with Earth's radiation budget and therefore influence climate are tropospheric ozone (O₃) and aerosol particulate matter including sulfate, nitrate, black carbon (BC), primary organic carbon (OC), and secondary organic aerosol (SOA). These aerosol components are major contributors to the airborne fine particulate matter with mass concentration of particles ≤ 2.5 μm in aerodynamic diameter (PM_{2.5}). It is well established that O₃ and PM_{2.5} are serious human and ecosystem health problems. Exposures to O₃ and PM_{2.5} have been linked in epidemiological studies to adverse health effects that include premature mortality, exacerbation of acute and chronic respiratory symptoms, and increased hospital admissions (3–6). The global burden of disease due to PM_{2.5} is estimated to be about a million deaths every year (7). At the same time, these air pollutants influence regional and global climate in complex ways; some pollutants cause warming while others cause cooling. Their climate effects are much more uncertain than those of carbon dioxide (CO₂) and the other long-lived greenhouse gases (LLGHGs). This uncertainty compromises understanding of the climate sensitivity (8).

The net effect of air pollution is a global cooling of about -1.2°C that is masking 50% of the 2.4°C committed global warming from greenhouse gases (GHGs) through the industrial era to present (9), previously identified as humanity's Faustian climate bargain by

BC: black carbon
(soot)

OC: organic carbon

SOA: secondary
organic aerosol

LLGHG: long-lived
greenhouse gas

James Hansen (NASA) (10) because humans have enjoyed the benefits of the Industrial Revolution without too much of a cost to climate, yet. Thermal inertia of the oceans may have delayed 0.5°C of the warming, and the actual observed warming is only about 0.7°C. Thus, most of the warming from the Industrial Revolution is still in the pipeline. Air pollution must be reduced to mitigate impacts on human health, ecosystems, the water budget, and agriculture. A large reduction in the cooling air pollutants without a comparable reduction in LLGHG emissions may lead to a warming surge unsafe for ecosystems and push the climate system rapidly toward possible nonlinear responses (11–13). Undoubtedly, reducing air pollution increases the urgency to reduce LLGHG emissions. At this time, air quality legislation does not consider the impacts on climate, which may change in the revision of the Gothenburg Protocol. Climate change policies do frequently consider air quality impacts. Cooling air pollutants may have additional effects on climate beyond the global mean temperature, including affecting the hydrological cycle and circulation patterns (14). Therefore, a cooling effect should not necessarily be considered good for climate (15).

The United Nations Framework Convention on Climate Change states that climate strategies must include all relevant species. Yet air pollutants are not included in international climate agreements. The Cancun Accord in December 2010 did reach a consensus that the global warming since preindustrial times must be kept below 2°C. CO₂ is the most important single contributor to global climate change; for this reason, mitigation policies and actions must focus on this species even though impacts may take decades to be realized because of the extended atmospheric response time of fossil CO₂ (16). However, potential climate mitigation opportunities through selective reduction of the warming air pollutants are being explored (17–20). This idea has received increasing attention since a landmark work that defined an alternative scenario to reduce the danger of dramatic climate change (21), which led to an

interdisciplinary workshop aimed at elucidating the air pollution effects on climate (22). Air pollutants have short atmospheric lifetimes of only days to weeks (compared to decades and centuries for the LLGHGs). Therefore, reducing air pollutant precursor emissions provides a unique way to expedite reduction of anthropogenic climate impact and is receiving attention as a possible way of mitigating near-term warming, reducing the rate of warming (important for adaptation of ecosystems), and simultaneously improving air quality (23, 24). Reductions in warming air pollutants are ineffective for protecting long-term climate safety that can only be achieved by deep and immediate reductions in CO₂ emissions. Indeed, the CO₂ warming impact is largely irreversible for 1,000 years after human-made emissions halt (25). Potential mitigation of the warming air pollutants must be developed in a joint policy framework with CO₂ mitigation; otherwise long-term unwanted consequences may occur (26). Alternatively, deliberate increases in cooling aerosols in the stratosphere have been proposed in geo-engineering climate mitigation strategies (27).

A full assessment of air pollution effects on climate was last provided in the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC), hereafter referred to as the IPCC AR4 (28, 29). In 2009, a comprehensive update fully documented the state of the scientific understanding of linkages between air quality and climate (30). In this review, the purpose is to summarize more recent scientific advances in anticipation of the forthcoming *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC AR5) in 2013. This review focuses specifically on air pollution as a global climate forcing. Stratospheric changes and natural aerosols, such as dust and sea salt, are not discussed. Updates in the origin and formation of air pollution are presented in Section 2. Section 3 describes the mechanisms of known effects of air pollutants on climate. In Section 4, the radiative forcing metric for quantifying climate impact is introduced. Section 5 discusses the key differences between the

IPCC AR4: *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change

IPCC AR5: *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change

NM VOC:

nonmethane volatile
organic compound

climate effects of air pollutants and LLGHGs. Section 6 reviews the impacts of air pollution (Subsection 6.5) on the contemporary climate state, including impacts by individual component (6.1), precursor emission (6.2), human activity (6.3), policy-relevant scenarios (6.4), and impacts of air pollution on biogeochemical cycles. Section 7 reviews the current understanding of the future air pollution control effects on climate, and Section 8 discusses new work on assessing the reduction of warming pollutants in climate mitigation. This review concludes with a summary (Section 9) and a discussion of future research directions (Section 10).

2. ORIGIN AND FORMATION OF AIR POLLUTION

Anthropogenic emissions from burning fossil fuel, biofuel, and biomass for energy use, industry, and agriculture release LLGHGs, including CO₂, nitrous oxide, halogenated compounds, and methane (CH₄), as well as a host of other chemically reactive gas and aerosol particulates that generate air pollution. In addition, there are significant natural sources of O₃ and aerosol precursor gases (31, 32). O₃ is not emitted directly, but it is formed in the atmosphere by complex nonlinear chemical production and loss processes that are variable in space and time. O₃ is produced in the troposphere by photochemical oxidation of carbon monoxide (CO), CH₄, and nonmethane volatile organic compounds (NMVOCs) by the major tropospheric oxidant, the hydroxyl radical (OH), in the presence of sunlight and nitrogen oxides (NO_x). CO, NO_x and NMVOCs have large combustion sources. Vegetation is a large NMVOC source. CH₄ has a range of biogenic and anthropogenic sources. The dominant natural source of atmospheric CH₄ is emissions from continental wetlands (33). Reaction with OH controls the atmospheric lifetime of CH₄; therefore, CH₄ is uniquely and tightly bound to the photochemical cycles that control the O₃ budget. CH₄, CO, and NMVOC emissions tend to reduce OH (oxidation capacity) and

thus increase the CH₄ lifetime. NO_x emissions tend to increase oxidation capacity and thus decrease the CH₄ lifetime. The changes in CH₄ induced by O₃ precursors will also affect O₃ on the longer timescale of the CH₄ adjustment time of ~12 years (34).

BC and primary OC are directly emitted aerosols. BC and OC are formed during incomplete combustion with the main anthropogenic sources being open forest and savanna burning, diesel engines for transportation and industrial use, and residential solid fuels (such as wood and coal) burned with traditional technologies (35). Sulfate and nitrate are secondary pollutants formed from the atmospheric oxidation of precursor gases: sulfur dioxide, ammonia, and NO_x with rates that depend upon the availability of key tropospheric oxidants. Thus, gas-aerosol interactions affect the production of climatically relevant air pollutants. O₃ precursors have important effects on sulfate (36). Sulfate and nitrate aerosol formation are coupled in the atmosphere because of their competition for available ammonia. Sulfate formation has the advantage owing to preferential neutralization and its lower vapor pressure (37, 38).

Atmospheric oxidation NMVOCs can generate products that partition into the particulate phase to form SOA. The NMVOCs that form SOA arise from both anthropogenic and biogenic volatile organic compound (BVOC) sources. BVOCs are mostly isoprene and monoterpene emissions from vegetation. SOA continuously evolves in the atmosphere as a function of multigenerational oxidation and dynamic gas-particle partitioning and is intimately interlinked to gas-phase oxidation chemistry. SOA likely contributes a substantial fraction of total OC (39), but the impact of SOA on the radiative balance of the atmosphere is poorly understood (40). The budget of SOA is very uncertain and current best estimates of 12–70 Tg year⁻¹ (41) may be up to an order of magnitude too small (39, 42). This uncertainty is the result of a number of factors that include (a) limited understanding of the principal SOA precursor

gases, including the relative contribution of BVOCs and anthropogenic VOCs; (b) limited understanding of the SOA interactions with anthropogenic pollution, especially nitrogen oxides (NO_x) that can influence the SOA yield (depending on the VOC precursor species), nitrate-initiated reactions, and formation of peroxyacyl nitrates or alkyl nitrates that allow NO_x to be transported away from source regions and possibly affect SOA formation elsewhere; and (c) limited understanding of heterogeneous reactions, cloud processing, oligomerization/polymerization, and acidic sulfate (43–45). Indeed, BVOC oxidation can lead to the formation of SOA through a suite of multiphase reactions (46, 47). As a consequence of the uncertainties, current global and regional models poorly represent organic aerosol and typically underpredict the magnitude of observed organic aerosol (48–50) and do not capture observed variability (51).

Large increases in anthropogenic precursors have led to large increases in the atmospheric concentrations of O_3 and aerosols since preindustrial times. Up until about a decade ago, O_3 and $\text{PM}_{2.5}$ air pollution was considered a local problem restricted to urban areas. However, recently available space-based observations of air pollutants and precursors, and community-led assessment programs, such as the Task Force on Hemispheric Transport of Air Pollution (52), have revealed unequivocally that air pollutants travel vast distances across oceans and continents and that air pollution is a truly global problem.

3. HOW DO AIR POLLUTANTS AFFECT CLIMATE?

O_3 is a GHG that absorbs infrared terrestrial radiation as well as incoming shortwave radiation and leads to global warming. The direct effect of aerosols on solar and terrestrial radiation and thus global climate is complex and depends on their chemical composition. Reflective aerosols cool the climate by scattering solar radiation to space. Absorbing aerosols warm the planet.

The net direct effect of their interaction with radiation ranges from mostly reflective (sulfate, nitrate, OC, SOA) to mostly absorbing (BC) (53). Relative to BC, the absorbing component of OC, referred to as brown carbon, increases significantly toward shorter wavelengths from the visible to UV. Recent field studies have indicated abundant brown carbon absorption in East Asian-Pacific outflow and biomass burning regions in the tropics (54–57). Brown carbon consists of aromatized compounds from smoldering combustion and biogenic materials and their low-temperature oxidation and polymerization products, reviewed in detail elsewhere (56). To date, brown carbon has not been considered in climate models and assessments of global climate change. OC and SOA are typically treated only as scattering particles, with the exception of one global model (58). The total direct effect of aerosols is global cooling, although the uncertainty on the exact magnitude is still large (28). Recent studies estimate that approximately 20%–50% of SOA could result from anthropogenic activity (59–63). This anthropogenic enhancement of SOA implies an additional aerosol forcing beyond that reported in the IPCC assessments. Some global models have neglected SOA formation from anthropogenic precursor emissions (64), which would also lead to an underestimate of the anthropogenic climate impact from SOA.

Aerosols also affect climate by modifying the properties of clouds. Hygroscopic aerosols that serve as efficient cloud condensation nuclei can increase cloud droplet number concentrations (CDNCs) and reduce cloud droplet effective sizes if cloud liquid water content remains unchanged, resulting in increased optical thickness and cloud reflectivity (65)—the first indirect effect or cloud albedo effect. A consequence of smaller droplet sizes is that they do not grow large enough to participate in cloud droplet coalescence processes, inhibiting precipitation formation and increasing the cloud liquid water path, cloud lifetime, or increased cloud horizontal and vertical extension (66)—the second indirect effect or cloud

SLCF: short-lived
climate forcer

lifetime effect. These indirect aerosol effects are difficult to constrain with measurements and present the most uncertain aspects of global climate change research, but their net effect likely leads to additional global cooling (28, 67). The absorbing BC aerosol has climate effects though solar heating of the boundary layer that leads to the evaporation of clouds—the semidirect effect (68). Deposition of dark particles, such as BC on snow, reduces the surface albedo and promotes snowmelt, called the BC snow albedo effect (69). There are further possible aerosol indirect effects, including those on mixed-phase, cold clouds (70–75). Existing published modeling results suggest large potential climate impacts; however, some of the effects are speculative, and in many cases, the sign is not understood. In addition to the direct radiative effect, SOA is important for the growth of newly formed particles up to cloud condensation nuclei sizes of tens of nanometers (76) and can therefore affect climate through the aerosol indirect effect. New particle formation is observed in the air above terrestrial ecosystems all around the world (77).

Hereafter, the radiatively active air pollutants (O_3 , sulfate, nitrate, BC, OC, SOA) are referred to as the short-lived climate forcers (SLCFs). In addition, the powerful GHG CH_4 that has an intermediate atmospheric lifetime of about a decade is included as a SLCF because of its role as an O_3 precursor.

4. DEFINITION OF RADIATIVE FORCING

The effects of LLGHGs and SLCFs on climate are quantified using a convenient theoretical metric: radiative forcing of climate (RF), which is defined as the change in net irradiance at the tropopause due to a perturbation after allowing for stratospheric temperatures to readjust to radiative equilibrium but with surface and tropospheric temperatures and state held fixed at unperturbed values with standard units of watts per meter squared (Wm^{-2}) (28). On the global and annual average, the RF metric is a useful indicator of the equilibrium surface

temperature response to a given perturbation ($\Delta T = \lambda \times RF$; where λ is the climate sensitivity). A positive RF implies warming, and a negative RF implies cooling. RF is the bedrock of the global warming potential (GWP) metric adopted in the Kyoto Protocol. The purpose of the GWP is to quantify and compare the climate impacts of different component emissions on a common scale. GWP is defined as the integrated global mean RF out to a chosen time of an emission pulse of 1 kg of a compound relative to that for 1 kg of CO_2 (78). GWPs are thus based on radiative impact and atmospheric residence time and can include both the direct radiative effect of emitted species and radiative effects from indirect chemical responses. GWP was designed for LLGHGs, and there are limitations in the application of GWP for SLCFs (79). The atmospheric physics behind RF is well accepted and understood. In climate change research, what is more uncertain, and the cause of much of the scientific debate, is the magnitude of the response of the climate system to the RF. Interactive feedbacks in the Earth system can either amplify or dampen the response in ways that are not fully understood at present.

The RF concept as defined above can diagnose direct aerosol and the cloud albedo effects. Semidirect and cloud lifetime effects imply modifications to clouds that prevent the tropospheric state from being held fixed. The strict RF definition does not allow for such changes in the climatic state of the troposphere. The situation is complicated because these aerosol indirect effects are not feedbacks through surface temperature change but are fast feedbacks occurring on the same timescale as the other SLCF mechanisms. An approach to evaluate the semidirect effect and cloud lifetime effect is the application of an alternative metric called adjusted forcing, which accounts for rapid responses on the radiation balance. Adjusted forcing is defined as the change in net irradiance at the top of the atmosphere after allowing for atmospheric and land temperatures, water vapor, clouds, and land albedo to adjust, but with sea surface temperature and sea ice cover unchanged (67, 80–82).

RF is a flexible metric and can be diagnosed for perturbations corresponding to a change in the atmospheric concentration of an individual species, precursor emissions, emission sectors, or policy-relevant scenarios. The radiative perturbation can correspond to past or future changes. Historical RF is essentially the contribution to the global mean surface temperature change during the past time period and the committed future temperature increase already in the system. RF can be presented for projections of future atmospheric conditions either by using a pulse approach (e.g., the time-dependent forcing due to a single year's worth of current emissions) or for sustained emissions that may be held constant or change in time. Future RF may be more appropriate for some policy applications. Transient time-dependent RF can also be calculated, which is useful for probing climate sensitivity (83, 84).

For LLGHGs, paleoatmospheric and preindustrial atmospheric concentrations are available from ice core measurements, and it is relatively straightforward to determine the RF on the basis of this concentration change. For the SLCFs, there are no reliable comprehensive measurements of their atmospheric concentrations in the preindustrial world. Therefore, complex four-dimensional models must be used to determine the RF, and the climate impact of the short-lived compounds is much more uncertain than for the LLGHGs because preindustrial concentrations are based on models alone (28). In recent years, improvements in observations of aerosols in the current climate state have been substantial with availability of remote sensing from the ground-based optical observational network (AERONET) and the launch of the MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multi-Angle Imaging SpectroRadiometer) instruments a decade ago as well as other satellite data helping constrain the impacts of aerosols on the radiative balance in the current atmosphere, e.g., Reference 85. Estimates of longwave RF by O_3 can be made from satellite measurements, such as NASA's Tropospheric Emission Spectrometer (86).

5. DIFFERENCES BETWEEN SHORT-LIVED CLIMATE FORCERS AND LONG-LIVED GREENHOUSE GAS MECHANISMS

LLGHGs are well mixed in the atmosphere, and therefore, the effect of emissions on the atmospheric concentration and RF is independent of location, source type, and season. In contrast, the SLCF impact on the radiative balance is highly sensitive to the latitudinal and altitudinal location of the precursor emission and the emission source type. Different chemical and meteorological background environments and chemical coupling from colocated emissions affect the production efficiency and lifetime of the SLCF, which influences the resultant atmospheric concentration perturbation. Thus the SLCF RF depends on the local and regional conditions. O_3 and aerosol precursor emissions generally have larger climate impacts when emitted at lower (more photochemically active) latitudes (87–89). The interaction of the SLCF with shortwave and longwave radiation depends upon the local surface albedo and cloud cover. For instance, reflective aerosols have a larger impact over dark than bright surfaces, and the opposite is true for absorbing aerosols. O_3 is more efficient as a GHG in the upper troposphere than in the lower troposphere mostly because of the thermal vertical structure of the atmosphere (90). Aerosol RF also has strong vertical dependence (91).

It is critically important to recognize that regional forcing does not imply regional climate response. Regional climate change can arise from three different effects: regional changes to the amount of radiative heating that reaches Earth's surface, an inhomogeneous response to globally uniform changes in radiative heating, and variability without a specific forcing. The relative importance of these effects is not clear in both historical and future climate projections. In any particular year or decade, the anthropogenic global warming signal can be overwhelmed by natural variability that drives cooling (92). It is established that, in the case

of the spatially concentrated anthropogenic aerosols, the regional climate response does not closely follow the spatial pattern of the forcing (93, 94). Conversely, a recent study does suggest that complete removal of US anthropogenic aerosol sources would increase annual mean temperatures in the eastern United States by 0.4°C – 0.6°C , with larger increases of 1°C – 2°C during summertime heat waves owing to feedbacks with soil moisture and low cloud cover (95).

6. IMPACTS OF AIR POLLUTION ON CONTEMPORARY CLIMATE

There are two established scientific community-led model intercomparison programs focused on the assessment of SLCFs in global models: the Aerosol Model Comparison Project (AeroCom) and the Atmospheric Chemistry and Climate Model Intercomparison Project (ACC-MIP) (96, 97). These projects facilitate the ongoing evaluation of models against observational data sets and will provide updated multimodel O_3 and aerosol RFs in support of the next IPCC AR5 assessment. Here, we summarize key updates in SLCFs since the IPCC AR4 was published.

6.1. Individual Components

The best estimates of air pollution RF in terms of individual SLCFs and their effects from the IPCC AR4 are summarized in **Table 1**. The IPCC AR4 presents historical RFs for changes between 1750 and 2005. In the case of the LLGHGs, the full emission history since the preindustrial period is required to calculate the historical RFs over the period. Although for the SLCFs that have adjustment times of less than one year, the RF from one year of current emissions gives the RF relative to the preindustrial RF (98). The historical RF perspective represents the fixed legacy to which we are committed and therefore is not particularly relevant for policy making but is useful to understand and attribute past human impact on the climate system. CO_2 provides

the largest single RF of $+1.66 (\pm 0.17) \text{ Wm}^{-2}$. The total LLGHG RF (including CH_4) is $+2.63 (\pm 0.26) \text{ Wm}^{-2}$. The uncertainty is substantially larger for the SLCFs than for the LLGHGs. It is apparent that the combined SLCF effects rival that of CO_2 . A comprehensive RF update to year 2007 has been provided for each component (30). This update included the only existing quantitative assessment of the nitrogen dioxide direct shortwave RF, which is $+0.04 \text{ Wm}^{-2}$ (99), interestingly the same magnitude as a new estimate of RF from linear contrails and contrail-cirrus ($+0.03 \text{ Wm}^{-2} \pm 25\%$) (100), although it receives considerably less attention from a mitigation perspective.

Since the IPCC AR4, an updated historical anthropogenic precursor emission inventory for 1850–2000 has been developed specifically to provide consistent harmonized gridded emissions in support of the IPCC AR5 (101). Recently published studies that apply this inventory and tackle SLCFs are presented in **Table 1**. Some studies address a subset of RF components (102, 103), and one considers all of the components (83). In addition, studies that use alternative emission inventories are included; one derives the aerosol direct effect by combining a high resolution $1^{\circ} \times 1^{\circ}$ latitude by longitude model with a multiobservation evaluation (104), and another incorporates feedbacks from the chemical composition changes to the climate system and the transient climate response (84).

6.1.1. Methane. The IPCC AR4 estimate of the RF for the increase in CH_4 over the industrial era is $+0.48 \text{ Wm}^{-2}$ (28). Thus, increases in CH_4 during the industrial era produced the second largest RF of the well-mixed GHGs after CO_2 . CH_4 has a stronger infrared absorption capacity than CO_2 on a per molecule basis and has a higher efficacy than CO_2 , owing mainly to its tendency to increase tropospheric O_3 and stratospheric water vapor (81, 105–107). The CH_4 atmospheric concentration increase is well measured; therefore, the RF has a high certainty. Global average surface

Table 1 Estimates of the global mean annual average radiative forcing from the preindustrial period to the present day by an individual short-lived component (Wm^{-2}) including the IPCC AR4 best estimates and updates from new studies as indicated

SLCF Component ^a	IPCC AR4 ^b (28)	Myhre et al. (104)	Skeie et al. (83)	Cionni et al. (103)	Koch et al. (84)	Bellouin et al. (102)
Present day time period definition	2005	2005–2007	2010	2000	1990–2000	2000
Model	Multimodel	Oslo CTM2	Oslo CTM2	NCAR CAM3.5	NASA GISS	HadGEM2-ES
Short-lived greenhouse gases						
Methane	0.48 (± 0.05)	NV	NV	NV	NV	NV
Tropospheric ozone	0.35 ($-0.1, +0.3$)	NV	+0.44	+0.23	NV	NV
Direct aerosol effects						
Sulfate	−0.4 (± 0.2)	−0.44	−0.62	NV	−0.39	NV
Black carbon (fossil and biofuel)	0.2 (± 0.15)	0.26	+0.35	NV	NV	+0.2
Organic carbon (fossil and biofuel)	−0.05 (± 0.05)	−0.09	−0.13	NV	NV	NV
Nitrate	−0.1 (± 0.10)	−0.023	−0.046	NV	−0.12	−0.12
Biomass burning	0.03 (± 0.12)	0.07	−0.07	NV	NV	NV
Secondary organic aerosol	NV	−0.09	−0.09	NV	NV	NV
Total direct aerosol effect	−0.5 (± 0.4)	−0.35	−0.48 \pm 0.32	NV	−0.41	−0.28
Indirect aerosol effects						
Cloud albedo	−0.7 ($-1.1, +0.4$)	NV	−0.83	NV	NV	−1.3
Black carbon on snow	+0.1 (± 0.1)	NV	+0.016	NV	−0.02	NV

^aAbbreviations: IPCC AR4, Intergovernmental Panel on Climate Change *Fourth Assessment Report*; NV, no value given; SLCF, short-lived climate forcer. The global model definitions are as follows: HadGEM2-ES, UK Meteorological Office Hadley Centre Earth System Model; Oslo CTM2, University of Oslo and the Center for International Climate and Environmental Research Global Chemistry Transport Model; NASA GISS, NASA Goddard Institute for Space Studies general circulation model; and NCAR CAM3.5, National Center for Atmospheric Research Community Atmosphere Model version 3.5.

^bFor the IPCC AR4 column, the uncertainties in general are based on the range of existing published estimates. Ninety percent value uncertainties appear in parentheses: When adding these numbers to the best estimate, the 5 to 95% confidence range is obtained. When two numbers are quoted for the value uncertainty, the distribution is non-normal.

CH_4 concentrations rose from 715 to 1774 parts per billion by volume (ppbv) between 1750 and 2005. During the past five years, CH_4 concentrations have increased by 25 ppbv, leading to a small additional RF. Much more challenging is unraveling the relative contribu-

tions of changes in the CH_4 sources and sinks that determine the atmospheric concentration (29, 108). This lack of process understanding limits confidence in the ability to project accurately the future evolution of CH_4 . The CH_4 lifetime is affected by competition from natural

NMVOCs emitted from vegetation, in particular isoprene. Most of the CH_4 oxidation takes place in tropical regions. Recent fieldwork in the Amazonian and Malaysian rainforests has suggested that isoprene oxidation efficiently recycles OH in such low NO_x conditions (109, 110). Reaction kinetic laboratory studies have begun to offer possible explanations for the efficient recycling of OH during isoprene oxidation in low NO_x or pristine conditions, for example, involving alternative pathways for reactions of organic peroxy radicals whose cross-reactions have previously been considered to represent a radical termination step, although the exact mechanisms are not yet fully understood (111, 112). Accounting for the enhanced regeneration and recycling of OH in the photooxidation of isoprene implies a significant decrease in the CH_4 lifetime of 35% in the preindustrial era (113).

6.1.2. Tropospheric ozone. The IPCC AR4 best estimate of the RF for the increase in tropospheric O_3 over the industrial era is $+0.35 \text{ Wm}^{-2}$, making O_3 the third most important anthropogenic GHG. A much lower possible O_3 RF ($+0.23 \text{ Wm}^{-2}$) for the year 2000 has been suggested due largely to a smaller increase in biomass burning emissions in the historical inventory (103). Another study has similarly suggested a lower O_3 RF of $+0.21 \text{ Wm}^{-2}$, although that result was attributed to excessive model stratospheric O_3 changes (84). In contrast, for year 2010 emissions, a greater O_3 RF of $+0.44 \text{ Wm}^{-2}$ has been suggested that includes tropospheric and stratospheric impacts of O_3 precursors but not changes in stratospheric O_3 or O_3 -depleting substances (83).

New advances in atmospheric chemistry have implications for O_3 RF. Accounting for the recently observed HNO_3 forming branch of the $\text{HO}_2 + \text{NO}$ reaction (114) in the global chemistry transport model, Oslo CTM2, reduced the O_3 RF by 20% from $+0.33$ to $+0.26 \text{ Wm}^{-2}$ (115). Oceanic reactive halogen species released into the atmosphere by the photodecomposition of organohalogens (including iodine-containing species) and via autocatalytic

recycling on sea-salt aerosols contribute to O_3 destruction and may play an important role in the O_3 budget and tropospheric oxidizing capacity (116). Typically, models only include carbon-based chemistry. In a few novel studies, inclusion of halogen chemistry is found to be an important component of the natural background O_3 budget and thus preindustrial O_3 baseline concentrations, but further research is needed to fully examine its climatic importance (117).

6.1.3. Direct aerosol effect. The IPCC AR4 provided for six individual aerosol components and the total RF of the direct aerosol effect. The RF of the total direct aerosol effect had a best estimate of -0.5 Wm^{-2} with a range from -0.1 to -0.9 Wm^{-2} . This estimate is based on global aerosol model calculations and observation-based estimates. The total direct aerosol is cooling because scattering aerosols overwhelm the effect of the absorbing BC aerosols, even with very high estimates of BC from total sources of fossil-fuel and biomass burning (118). In a multimodel assessment, it was found that global models underestimate observed aerosol absorption optical depth, suggesting a low model bias of BC (119). Scaling model aerosol absorption optical depth to match observations resulted in a BC multimodel average direct effect of $+0.55 \text{ Wm}^{-2}$. In a study based on a high-resolution model and satellite observations, the individual aerosol component RFs were found to be stronger than in the IPCC AR4, but the overall total direct effect is weaker (owing to the cancelling of positive and negative RFs) (104). Including enhanced absorption of BC, resulting from aerosol internal mixing, increases the BC RF to $+0.33$ and decreases the net direct RF further to -0.28 Wm^{-2} . This study also newly identified a SOA RF that is a small cooling, -0.09 Wm^{-2} . An identical value was found using the same modeling system at lower resolution and with different emissions (83). A recent study using the ECHAM5-HAM model also found a negative direct SOA shortwave RF, but with a much larger value (-0.31 Wm^{-2}) (120). Interestingly, this particular model reported a

positive indirect effect of SOA of $+0.23 \text{ Wm}^{-2}$, which is a result of the enlargement of particles, owing to condensation of SOAs, together with an enhanced coagulation sink of small particles. For the year 2000, simulations using the HadGEM2-ES report a weaker total direct effect than the IPCC AR4 of -0.28 Wm^{-2} but present a similar nitrate RF of -0.1 Wm^{-2} (102). The largest disagreement between models is for the nitrate RF (a factor of 5).

6.1.4. Cloud albedo and black carbon snow albedo.

In the IPCC AR4, the cloud albedo effect (-0.7 Wm^{-2}) is the second largest RF after CO_2 , although it is the most uncertain effect. An estimate based on satellite data yielded a smaller cloud albedo effect of -0.2 Wm^{-2} , potentially suggesting that models may be overestimating the effect (121). Indeed, a larger value (-0.83 Wm^{-2}) has been found based on year 2010 emissions (83). A major uncertainty is the contribution of different aerosol components to the aerosol indirect effect. Some studies have quantified the cloud albedo radiative effect of BC-containing particles (122–125). There is still considerable uncertainty on the magnitude of the semidirect and cloud lifetime effects (126).

The IPCC AR4 gives a best estimate for BC effects on snow albedo of $+0.1 \text{ Wm}^{-2}$. Recent model-based estimates of the BC snow albedo RF range from $+0.01$ to 0.2 Wm^{-2} (127). In new model studies, the global effect is extremely small (83, 84, 128). However, this RF mechanism may be important in polar regional climate change, including the Tibetan Glacier (129, 130).

6.2. Precursor Emissions

The RF resulting from changes in the atmospheric concentration of a single forcing agent can have contributions from emissions of several compounds. **Table 1** shows the RF relative to the preindustrial era by changes in atmospheric concentrations of individual components. The RF can also be calculated in terms of the primary emission that may

include indirect RFs related to perturbations of other forcing agents (131). This approach is particularly useful for policy making that addresses individual emission sources, although controlling an individual pollutant in isolation is often not practical. A recent study found that gas-aerosol interactions substantially alter the relative importance of the various emissions. In particular, CH_4 emissions have a larger impact than that used in current carbon-trading schemes or in the Kyoto Protocol (132). In that work, O_3 precursor emissions (NO_x , CO , and CH_4) have substantial impacts on aerosols by altering the abundance of oxidants, especially OH, which converts sulfur dioxide into sulfate, but coupling in the other direction was weak. Thus, reactions of gas-phase species on aerosol surfaces had only a small effect on the global burden of the short-lived GHGs O_3 and CH_4 . This result is sensitive to the model representation of heterogeneous chemistry and the choice of uptake coefficient for the conversion of dinitrogen pentoxide to nitric acid on aerosol surfaces. The impacts of gas-aerosol interactions have been explored for the potential release of vast quantities of CH_4 into the atmosphere as a result of clathrate destabilization (133). The examined catastrophic CH_4 release results in a tenfold increase in the CH_4 atmospheric concentration and a 70% increase in the atmospheric lifetime of CH_4 . The impacts on OH provide a pathway to influence aerosol production and therefore aerosol-cloud interactions. Indeed, an 18% decrease in global CDNC was driven by the CH_4 release. The CDNC change causes a RF that is comparable in magnitude to the RF of the added CH_4 . Together, the indirect CH_4 - O_3 and CH_4 -OH-aerosol RFs could more than double the warming effect of large CH_4 increases.

6.3. Human Activity

Policy makers are responsible for making decisions on the trade-offs and synergies between air pollution abatement and GHG mitigation. It is the responsibility of the scientific community to provide quantitative information in the

most useful format to support the decision making. Previously, the standard approach to quantifying climate impact was in terms of changes in atmospheric concentrations of individual chemical species. This approach is useful for understanding the contribution of an individual species to anthropogenic climate change and for policy making directed toward individual species. An alternative approach is to quantify the climate impact by emission sector, which is relevant for understanding the contribution of different human activities to climate change and for policy making that targets specific activities. Human activities are the fundamental drivers of anthropogenic climate change. The climate impact of the SLCFs is dependent on emission location and chemical interactions with co-emitted species and, therefore, varies strongly by emission sector, whereas for LLGHGs, the climate impact is independent of geographical location and emission sector. The net climate impact of an activity can only be determined using explicit calculations. Mitigation actions focused on regulating a specific sector may affect multiple chemical species with opposing or enhancing climate impacts. An advantage of the sector-based approach is that it inherently includes interactions and nonlinearities between the different chemical species emitted from the same sector. The sector-based approach is not new and arose out of aviation research, which from early on recognized the important contribution of the SLCFs to the net climate impact of this activity, possibly because of the visible impact on contrail formation and concerns about releasing NO_x into the upper troposphere, where the forcing sensitivity is greatest to O_3 changes. More recently, there have been significant research advances in extending the sector-based approach to a wide range of other activities.

The transportation subsectors have received the greatest attention (134–145). The net climate impacts of biomass burning (146, 147), electric power production (148, 149), and household fuel burning (150) have also been assessed. There have been some studies that investigate regional sector impacts (150–153).

Many studies focus on only the gas or aerosol phase components of the activity, but some have begun to provide impacts across a broad range of components, including aerosol-cloud interactions (37, 136). Future sectoral RF impacts based on perpetual constant year 2000 emissions from a study that accounts for all sectors and a broad range of effects are shown in **Figure 1** (37). Dramatic profile changes occur for the industry, power, and biomass burning sectors whose large aerosol cooling (about -200 mWm^{-2}) is offset by CO_2 warming at different rates depending on the balance of those emissions. For power, the RF rapidly becomes positive in about 10–15 years. For sectors dominated by CH_4 effects (animal husbandry and agriculture), the RF increases for about 10–15 years and then levels off to a constant value. On the basis of this work (37), the power generation and industrial sectors have the largest contributions to global warming over the next 50–100 years if the emissions are kept constant at current levels. Road transportation and household biofuel usage are also large contributors to warming, especially on shorter timescales. These analyses need to be extended to incorporate future changes to emissions. Consistent transportation sector results across different modeling systems and emission inventories for future impacts of current emissions are as follows: Road transportation is the largest contributor to warming on short to long timescales, aviation has a small net warming impact, and shipping is net cooling even on century timescales (15, 136, 144).

6.4. Policy-Relevant Scenarios

A limitation of the sector-based approach is that it refers to a fixed mix of emissions. The most desirable approach is to quantify the climate impact of specific policy-relevant energy shifts or emission control policies. Progress has been made in this direction for a few case scenarios; examples include investigating the trade-offs of emissions in electrification of transport (148), the impacts of tighter vehicle emission standards (19), ethanol versus gasoline fuel use

in US fleets (154), and hydrogen vehicle fuel (155). All of these studies find that the SLCFs play a major role in the near-term climate impact of the proposed technology shift.

6.5. Air Pollution Effects on Biogeochemical Cycles

The SLCFs have additional impacts on climate by altering biogeochemical cycles. O₃ pollution is also known to damage ecosystem health by reducing plant productivity. Gross primary production (GPP) is a measure of the total amount of CO₂ removed from the atmosphere every year to fuel photosynthesis. A mechanistic flux-gradient model of the anthropogenic O₃ effect on vegetation found a significant suppression of GPP of up to 260 petagrams carbon by the year 2100 (2% cumulative suppression over the century) for a future world following the IPCC *Special Report: Emissions Scenarios* A2 scenario, which assumes no pollution control or climate policy (156). Damage in the tropical rainforest biome was large, with >30% reduction in GPP across extensive regions of South America, Central Africa, and Southeast Asia. Thus, suppression of the land carbon sink results in additional anthropogenic CO₂ emissions accumulating in the atmosphere. The additional anthropogenic CO₂ left in the atmosphere caused by the O₃-induced damage to vegetation is an equivalent emission and thus provides an indirect RF. Remarkably, the magnitude of this indirect forcing and the direct radiative effect of the tropospheric O₃ increases are comparable. Aerosols can have a positive effect on photosynthesis by enhancing the ratio of diffuse to direct radiation (at least for some forest canopies) when aerosol loading is not so large as to dramatically reduce total surface irradiance. Diffuse radiation penetrates deeper into the canopy than direct radiation, so that the loss of direct beam intensity is more than compensated for by increased penetration of diffuse light (157–159). A first assessment of the aerosol indirect effect on climate through biogeochemical feedbacks (mostly reduced atmospheric CO₂ concentrations) indicates

a cooling of similar magnitude to the direct aerosol radiative forcing (160). It is significant that the O₃ and aerosol climate impacts through perturbation of the carbon cycle operate on much longer timescales than their atmospheric lifetimes of a few days to weeks (161). To date, there are only a limited number of studies with a few models, and further research is needed to understand these effects.

7. FUTURE AIR POLLUTION CONTROL EFFECTS ON CLIMATE

It is likely that air pollution levels will be reduced in the future. A previous study assessed the maximum climate impact from substantial rapid air pollution abatement and found a 0.8 K warming within less than a decade (162). It has been suggested that air pollution changes over the past three decades have contributed up to 70% to recent enhanced Arctic warming, mostly as a result of sulfate reductions from the implementation of air quality controls in the United States and Europe since the 1970s and BC increases from development in southeast Asia (163). Is this result a harbinger of future quality control impacts on climate? Is accelerated warming caused by future air pollution abatement inevitable?

Advanced model studies have begun to address these questions (94, 164, 165). The decadal climate impact of the future evolution of the SLCFs was compared in three different transient chemistry-climate simulations for a rapid economic growth scenario using both fossil-fuel and renewable energies. The three models applied different emissions projections, especially for BC. By 2050, two models showed additional global warming, from SLCFs, of 20% to 40% compared with GHGs alone; the third model showed virtually no global mean effect from short-lived species (**Figure 2**). In a related study that assumed full implementation of state-of-the-art technologies for aerosol control (166), the combined effects from aerosol reductions and GHG increases led to a projected increase in

global mean temperature of 2.2°C by 2030 relative to today, nearly doubling the effect of GHGs alone. Maximum abatement in the industry and power sectors (dominated by sulfate aerosol) yielded a somewhat lower response of 1.9°C; maximum abatement in the domestic and transport sectors (dominated by BC) still caused an increase of 1.4°C. To put these temperature changes in perspective, the temperature thresholds for critical policy-relevant “tipping elements” in the climate system at which the state is altered into a different mode of operation have been assessed (23). For instance, the global warming thresholds for the tipping elements, including the loss of Arctic summer ice, Greenland ice sheet, Amazon rain forest, Atlantic thermohaline circulation, and West Antarctic ice sheet, are in the ranges 0.5 to 2°C, 1 to 2°C, 3 to 4°C, 3 to 5°C, and 3 to 5°C, respectively. Disturbingly, the first published model results that quantify possible future air pollution control impacts on global climate do demonstrate that the resultant temperature changes would lie dangerously in the vicinity of the climate system tipping elements (9). The heterogeneous spatial distributions of the SLCFs may activate specific regional climate responses (163), although the relationship between the regional tipping points and regional RF by the SLCFs still needs to be understood.

Further quantitative insights into the impacts of future air pollution abatement on climate can be afforded by next-generation model studies that apply a new set of future scenarios termed the representative concentration pathways (RCPs) (167). Four scenarios were selected that are identified according to their total RF in 2100. The highest scenario is a reference case with no additional policies in place to limit GHG emissions and has a 2100 total anthropogenic forcing of 8.5 Wm⁻² with forcing still increasing. The remaining three scenarios assume the successful implementation of climate policies with one scenario stabilizing RF at 6.0 Wm⁻², one scenario stabilizing at 4.5 Wm⁻², and one scenario with RF that peaks and then declines to 2.6 Wm⁻² in 2100. Applying radiative efficiencies determined in

previous work (37), **Figure 3** presents the approximate future net short-lived RF (including O₃, sulfate, BC, and OC, but not aerosol-cloud interactions or CH₄) for seven key global sectors and the four RCP scenarios. There is great variability between these scenarios and sectors. However, in general, both warming and cooling SLCFs decrease in the future world. Estimates of the future RF from O₃ and aerosols have also been calculated explicitly using the National Center for Atmospheric Research climate model for the RCPs (168). RCP 8.5 leads to an increase in the O₃ RF by an additional +0.2 Wm⁻² by 2100, whereas the other projections lead to a decrease in the O₃ RF that is between -0.07 and -0.2 Wm⁻². Intriguingly, the importance of nitrate aerosol will increase in the future world as sulfur is removed, and ammonia emissions will increase also (102). In this study, nitrate becomes the single most important aerosol forcing agent in the future world, ranging from -0.4 to -0.7 Wm⁻² by 2090 depending on the RCP scenario. Full assessments across a range of transient coupled chemistry-aerosol-climate models will be provided in the forthcoming IPCC AR5 report.

8. REDUCTION OF WARMING POLLUTANTS IN CLIMATE MITIGATION

Reducing and preventing the accumulation of fossil-fuel CO₂ in the atmosphere is the only way to protect long-term climate safety. However, selective reductions in warming air pollutants may provide a way to mitigate near-term warming until CO₂ reductions take effect (169). CH₄ emission reductions provide a cost-effective means to abate global baseline O₃ levels while simultaneously addressing climate goals (170). Quantitative estimates of the temperature response to various strategies are emerging. Worldwide implementation of current CH₄ emission control technologies in waste management, agriculture, and the extraction and transport of fossil fuels by 2030 would lead to a reduction in anthropogenic CH₄ emissions of 24% relative to 2010 levels and

decrease the global mean warming by an estimated central range of 0.2 to 0.4 K relative to a business-as-usual scenario (171). Implementation of a range of air quality measures [including diesel particle filters for road and off-road vehicles, replacing traditional brick kilns with vertical shaft and Hoffman kilns, replacing traditional coke ovens with modern recovery ovens, eliminating high-emitting vehicles in road and off-road transport, banning open burning of agricultural waste, and substituting clean-burning cookstoves using modern fuels (liquefied petroleum gas or biogas) for traditional biomass cookstoves in developing countries] that cut the emissions of CH₄ and BC-containing particles could result in 0.5 K of avoided warming by 2050 with several environmental cobenefits, including 0.7–4.7 million avoided deaths from outdoor air pollution and increases in annual crop production (20). Other work has suggested little climate mitigation potential from BC controls in the United States (172). Although there is scientific consensus on the climate and human health benefits (through surface O₃ decreases) of CH₄ reductions, the net impact of BC mitigation strategies on surface temperature is still under debate owing to uncertainties in the various cloud feedbacks (123, 173, 174, 175).

9. SUMMARY

There is now a large body of scientific evidence from a broad spectrum of different observational and model studies supporting that anthropogenic increases in O₃ and aerosols impact the global radiation budget in the contemporary climate state and have played a substantial role in anthropogenic global climate change since the Industrial Revolution. The absolute magnitude of the impact is subject to substantial uncertainty in part because of a lack of knowledge of the preindustrial levels of O₃ and aerosols. Furthermore, possible quantitative insights into air pollutant RF from reconstructions of past observed temperature changes using climate model simulations are somewhat hampered by uncertainties in other

aspects of climate sensitivity (176). The air pollutants have complex climate effects involving both warming and cooling mechanisms. The first studies of future air pollution abatement effects on global climate demonstrate a potentially large rapid warming penalty. Therefore, climate change policies may have to include a pollution safety margin in LLGHG reduction targets (177). Reducing and preventing the accumulation of fossil-fuel CO₂ in the atmosphere is the only way to protect long-term climate safety. However, selective reductions in warming air pollutants may provide a way to mitigate near-term warming until CO₂ reductions take effect. The sectoral approach to determining climate impact is valuable in identifying policy options that tackle a range of different pollutants and activities. The electric power generation and industry sectors have the largest contributions to warming over the next 50–100 years. Road transportation and household biofuel burning are large contributors to warming on short timescales. The scientific community is on the brink of providing new quantitative insights into SLCFs in the future world, in particular whether air pollution reductions will mitigate or accelerate global climate change, on the basis of the new RCP scenarios and a suite of advanced coupled chemistry-aerosol-climate models as part of the forthcoming IPCC AR5 assessment through the community-led programs: the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the ACC-MIP.

10. FUTURE RESEARCH DIRECTIONS

This review has focused on global climate impact and surface temperature response. However, the O₃ and aerosol RFs likely have additional important impacts on regional climate change. The relationship between the heterogeneously distributed SLCFs and the regional temperature response is still being understood, in particular whether the response to SLCFs follows the local forcing pattern. Several studies suggest that the regional

impacts are not necessarily collocated with the forcing (81, 87, 93, 163, 178, 179), whereas others do indicate a correlation (172, 180). A multimodel analysis has begun to unravel these previous findings, identifying a strong sensitivity of the surface temperature response to the latitudinal forcing distribution but limited sensitivity to longitude (181). The SLCFs impact regional hydrology in vulnerable regions with possible consequences for the water supply to humans (182–184). Future work is needed to better understand the past and future impacts of air pollution on regional climate. Efforts to quantify the economic damages of energy production and use typically consider only LLGHGs in the climate impacts and the air pollutants in human health effects (185). Such assessments must additionally incorporate the climate effects of the air pollutants.

Global climate models are often employed to determine the RF impacts of the SLCFs, but the calculations usually do not extend to the more computationally expensive climate response. Very few published studies consider the SLCF climate response by sector (12, 166). The RF metric is problematic for the SLCFs and does not take into account the different

efficacies of the forcing mechanisms or the vast differences in atmospheric response times across the radiatively active components. A useful future research direction is to simulate the spatially resolved climate response (including effects on hydrological cycle, temperature, and circulation) thus bypassing any limitations in the RF metric. However, identifying a statistically significant signal detectable over internal climate model variability for the relatively small net climate impact represents a nontrivial challenge and may be impossible.

Further research is needed to understand couplings between biogenic and anthropogenic emissions and the direct and indirect radiative forcing by SOA. Chemistry-climate models need to move beyond carbon-only oxidation chemistry and incorporate reactive halogen chemistry to understand potential climate implications. The climate consequences of interactions between terrestrial and marine ecosystems, biogeochemical cycles, and air pollution need to be assessed, necessitating the development of a new generation of Earth system models that incorporate efficient atmospheric chemistry into coupled climate-carbon-nitrogen cycle models.

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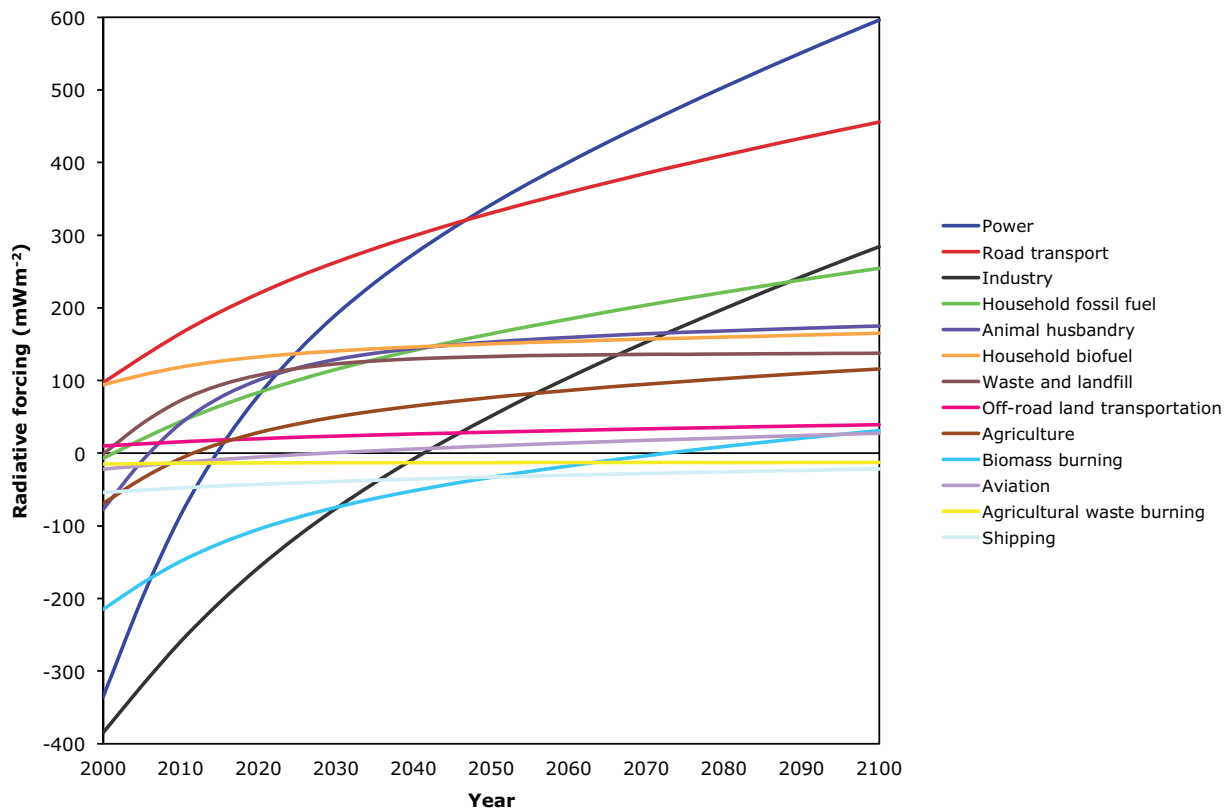


Figure 1

Future evolution over the coming century of the total radiative forcing (RF) [including short-lived climate forcers (SLCFs), long-lived greenhouse gases, aerosol-cloud interactions, and methane] owing to perpetual constant year 2000 emissions by sector. The SLCFs and aerosol-cloud RF values remain constant across the time period. Adapted with permission from Reference 37, Unger et al., 2010, Attribution of Climate Forcing to Economic Sectors, *Proceedings of the National Academy of Sciences of the USA*.

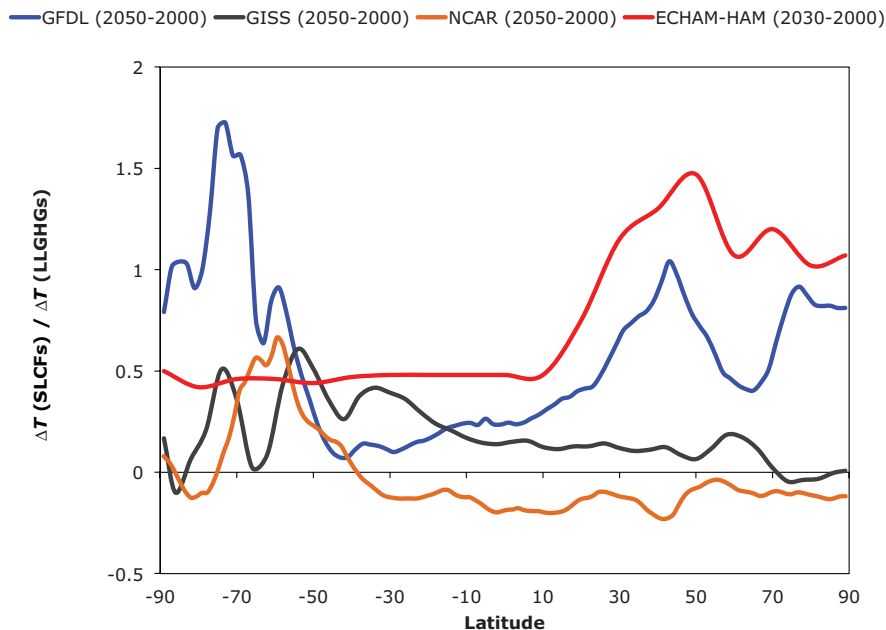


Figure 2

Future zonal average temperature changes ($\Delta T^{\circ}\text{C}$) owing to short-lived climate forcers (SLCFs) relative to the temperature change caused by long-lived greenhouse gases (LLGHGs). Model data are collated from the maximum feasible reduction scenario in Reference 166, using values from figure 4B, and three different models using three different emission scenarios based on the A1B storyline in Reference 164. The four total general circulation models are NOAA Geophysical Fluid Dynamics Laboratory (GFDL), NASA Goddard Institute for Space Studies (GISS), National Center for Atmospheric Research (NCAR), and the Max Planck Institute for Meteorology (ECHAM5-HAM). The data refer to differences between two time periods (2050–2000) and (2030–2000) as indicated in the legend. Southern latitude numbers are shown with a minus sign.

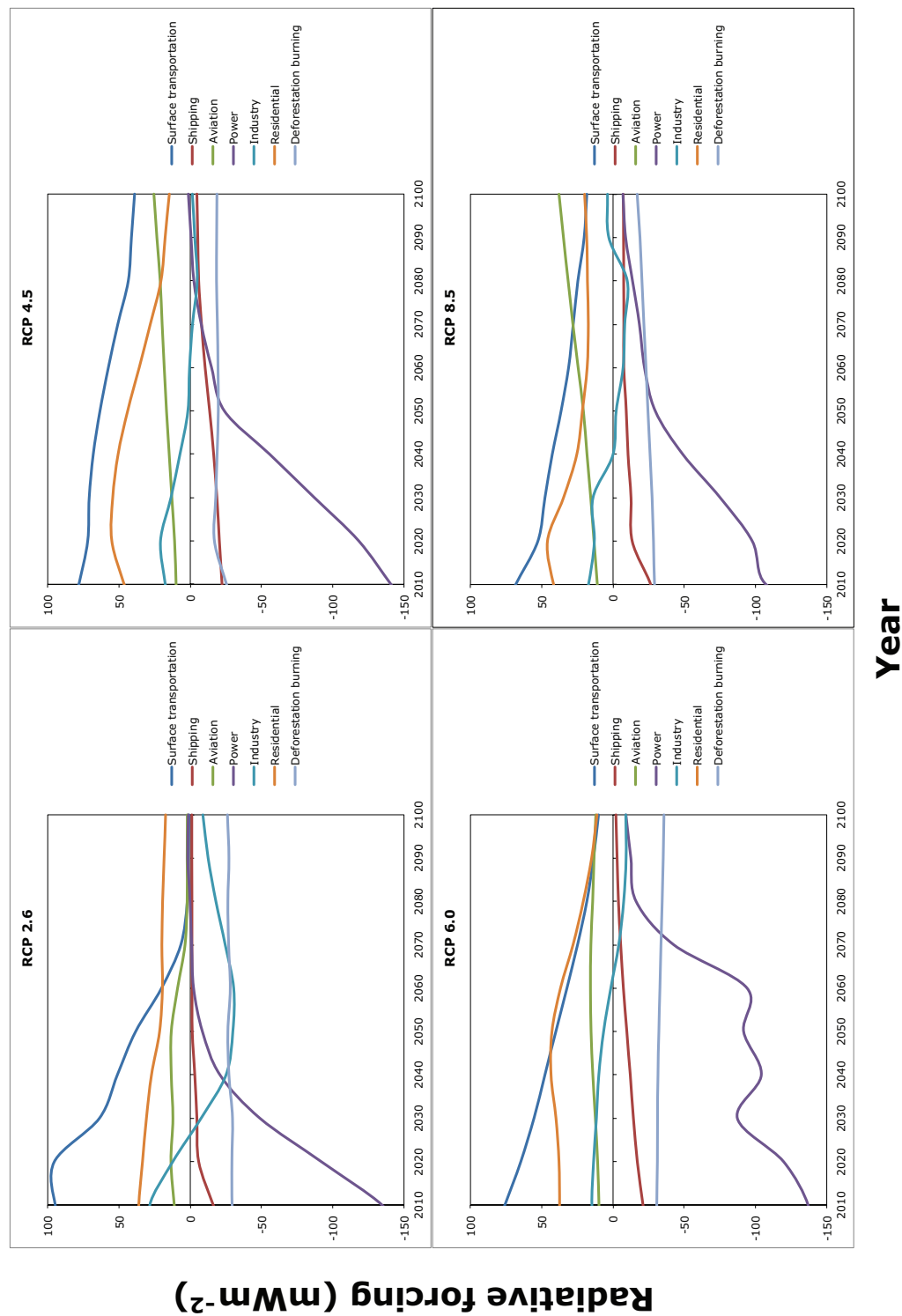


Figure 3

Projections of global sector-based future net radiative forcing (mWm^{-2}) by short-lived climate forcers, including ozone, and the direct effects of sulfate, black carbon, and organic carbon, but not aerosol-cloud interactions or methane, calculated using a simplified approach. Abbreviation: RCP, representative concentration pathway.



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Errata

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