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The net climate impact of coal-fired power plant emissions

D. T. Shindell and G. Faluvegi

NASA Goddard Institute for Space Studies and Columbia University, 2880 Broadway,
New York, NY 10025, USA

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Correspondence to: D. T. Shindell (drew.t.shindell@nasa.gov)

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Abstract

Coal-fired power plants influence climate via both the emissions of long-lived carbon dioxide (CO_2) and short-lived ozone and aerosol precursors. For steadily increasing emissions without substantial pollution controls, we find that the net global mean climate forcing ranges from near zero to a substantial negative value, depending on the magnitude of aerosol indirect effects, due to aerosol masking of the effects of CO_2. Imposition of pollution controls on sulfur dioxide and nitrogen oxides leads to a rapid realization of the full positive forcing from CO_2, however. The long-term forcing from stable (constant) emissions is positive regardless of pollution controls, with larger values in the case of pollutant controls. The results imply that historical emissions from coal-fired power plants until ~1970, including roughly 1/3 of total anthropogenic carbon dioxide emissions, likely contributed little net global mean climate forcing during that period. Those emissions likely led to weak cooling at Northern Hemisphere mid-latitudes and warming in the Southern Hemisphere, however. Subsequent imposition of pollution controls and the switch to low-sulfur coal in some areas kept global SO_2 emissions roughly level from 1970 to 2000. Hence during that period, RF due to emissions during those decades and CO_2 emitted previously was strongly positive and likely contributed to rapid global and regional warming. Most recently, construction of coal-fired power plants in China and India has been increasing rapidly with minimal application of pollution controls. Continuation of high-growth rates for another 30 years would lead to near zero to negative global mean climate forcing in the absence of expanded pollution controls, but severely degraded air quality. However, following the Western pattern of high coal usage followed by imposition of pollution controls could lead to accelerated global warming in the future.

1 Introduction

Coal combustion currently produces roughly 27% of the world's electricity, second only to crude oil, and coal is also a major industrial and residential fuel in some countries. At current consumption rates, enough reserves are available to last more than a century (Energy Information Administration, 2009; hereafter EIA, 2009). Nearly half the known reserves are in the US, China and India, countries with large projected increases in energy demand over coming decades. Coal-fired power plants are also currently the least expensive power source in cost to generators per kWh of electricity. Hence there are enormous economic and socio-political incentives to expanded construction of coal-fired power plants. However, emissions from coal-fired plants have substantial impacts on both air quality and climate change. Large amounts of carbon dioxide (CO_2) are emitted, which lead to warming of the Earth and associated climate changes. Coal-fired power plants also emit substantial amounts of sulfur dioxide (SO_2), a precursor of fine particulate and acid rain, and of nitrogen oxides (NO_x), a precursor of tropospheric ozone as well as particulate, in addition to producing other pollutants such as mercury and solid waste. Tropospheric ozone and particulate are both harmful to human health, with ozone and sulfur-containing species also damaging to both managed and natural ecosystems, and both influence climate. While the separate impacts of short-lived pollutants on air quality and of CO_2 on climate are relatively well characterized, the interplay between the two has not been examined closely.

Tropospheric ozone, methane, sulfate and nitrate aerosols all change in response to NO_x and SO_2 emissions, which we term the "air quality pollutant" emissions. All these constituents influence climate. Methane responds indirectly to changes in its oxidation rate induced by NO_x and SO_2 emissions, and hence we include it along with the other short-lived air quality pollutants though it is relatively long-lived. The balance between the positive radiative forcing (RF) (leading to warming) from CO_2 and the sum of RF from the various shorter-lived species is not well known. This balance will determine the net RF due to emissions from coal-fired power plants, which will be neither spatially

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nor temporally uniform owing to the vast difference in lifetime among these pollutants (days to months for aerosols and ozone, roughly a decade for methane, and centuries for CO_2). Here we investigate the spatial and temporal dependence of the net climate forcing due to emissions from coal-fired power plants.

2 Scenarios

Several simple illustrative scenarios for 2000–2075 with different rates of growth in the number of power plants, timing of air quality pollutant controls, and fuel use were explored (Table 1). We first examined the impact of a static number of coal plants, for simplicity using current emissions from China and India. We then looked at hypothetical future growth focusing on China and India since they are projected to account for 80% of the growth in coal-fired power generation over coming decades (EIA, 2009). We begin our scenarios at 2000 as this is the most recent year for which we have complete emissions inventories. The year-on-year growth rate in Gt C used in coal-fired plants in China has been 10.1% during 2000–2006, with a growth rate of 16.4%/year from 2003–2006 (EIA, 2009). The long-term growth rate has averaged 5.9% from 1981 to 2006. Hence we examined high-growth scenarios, assuming a 10%/year increase in coal power plant emissions in China and India, and moderate growth using 5%/year. While the global recession has caused a recent slowdown in power plant construction, and future growth rates may well be lower, the government has said that coal will remain its major energy source despite the impact on global warming (The China Post, 2009). Hence investigation of the impact of growth rates analogous to those in past years seems warranted.

World coal reserves are estimated at 930 Gt coal (EIA, 2009). In the high-growth scenario, usage grows very rapidly as time progresses due to the geometric increase when applying a constant percentage growth. We stop the increase in power plant capacity when 1/4 of world reserves have been used up solely by the additional usage in China and India (i.e. 232 Gt used), which is in year 40 for a 10%/year growth rate.

Maintaining constant usage after 2040 exhausts current reserves at 2075 under that scenario. As the date at which growth ceases has a strong effect on the total usage, we also include a high-growth scenario where growth terminates at 2030 instead of 2040. Air quality pollution controls (removal of SO_2 and NO_x) are imposed either at the start of the scenario or at the end of the addition of coal-fired power plants (2030 or 2040). In the former case, we assume full air quality pollutant controls are put in place as new plants are constructed, so there are zero emissions. In the latter, we assume air quality pollutant controls are gradually retrofitted to the plants constructed since 2000 over 20 years (2031–2050 or 2041–2060). An additional scenario never imposes pollution controls, even after all new construction ceases in 2040. This provides another view of the emissions of a constant number of power plants, as in the first "constant current emissions" case, but this time including their historic CO_2 emissions (i.e. RF at a given time in this scenario after 2040 is due to SO_2 and NO_x emissions at that time plus the effect of all CO_2 emitted from 2000 to that time).

Finally, we include a scenario for comparison in which growth of 10% per year in year 2000 coal-fired power capacity is again assumed, but all additional capacity is generated through natural gas plants rather than coal. CO_2 emissions are 15 kg C/GJ from gas-fired power plants, as compared with 25 kg C/GJ from coal-fired plants (Ramanathan and Feng, 2008), but virtually no SO_2 or NO_x is generated from gas combustion. Hence the effect is a 40% drop in CO_2 emissions relative to coal and a complete removal of air quality pollution effects.

3 Experimental setup

We examined the radiative forcing due to these hypothetical scenarios for emissions of CO_2, SO_2 and NO_x. We first performed full three-dimensional chemistry-climate model calculations of the effect of increasing SO_2 and NO_x from China and India. In these calculations, aerosol and ozone precursor emissions from coal-fired power plants were increased throughout China (20–48° N, 100–125° E) and India (5–30° N,

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65–90° E). Base case emissions for all species and sectors are the 2000 inventory of the International Institute for Applied Systems Analysis (IIASA) which is based on the 1995 EDGAR3.2 inventory, extrapolated to 2000 using national and sector economic development data (Dentener et al., 2005). For the power sector, the IIASA inventory provides the spatial distribution of emissions. The magnitude of emissions specifically originating in coal-fired power generation is taken from a detailed species- and sector-specific 2000 inventory for Asia (Streets et al., 2003) (Table 2).

Calculations were performed using the composition-climate model G-PUCCINI to calculate the atmospheric composition response to the SO_2 and NO_x emissions changes and their radiative forcing. This model incorporates gas-phase (Shindell et al., 2006), sulfate (Koch et al., 2006) and nitrate (Bauer et al., 2007) aerosol chemistry within the GISS ModelE general circulation model (Schmidt et al., 2006). The model used here has 23 vertical layers and 4 by 5 degree horizontal resolution. Evaluations of the present-day composition in the model against observations are generally quite reasonable (as documented in the references given above). The model was initially integrated for 5 years to allow adjustment of ozone and aerosol concentrations to emissions. Annual average all-sky aerosol optical depths (AOD) during the initial 5-yr period are 0.040 for sulfate and 0.020 for nitrate. A recent comparison of multiple models (Schulz et al., 2006) shows a mean sulfate AOD of 0.035 (range 0.015 to 0.055), so that our values are mid-range. Following initialization, the response to increasing emissions was simulated in transient runs from 2000 to 2040. Aerosol indirect effects (AIE) were not simulated in the model as these are highly uncertain (Penner et al., 2006). To provide a rough idea of the magnitude of potential AIE, we include their effect using the conservative estimate that they are equal to the direct effect from sulfate aerosols. Calculations based on detailed modeling and observations suggest that the ratio of AIE to direct sulfate RF is 1.5 to 2.0 (Kvalevåg and Myhre, 2007), but we use a lower value of 1.0 as AIE may saturate at the very large regional sulfate loadings reached in our simulations, and recent analyses based on satellite data suggest that at least a portion of the AIE may be fairly weak (Quaas et al., 2008). The AIE estimate is included in

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a single high growth, late air quality pollutant controls scenario for illustrative purposes. The direct RF due to ozone and aerosols was calculated internally within the climate model.

The response to CO_2 emissions was calculated using impulse response functions derived from the Bern Carbon Cycle Model (Siegenthaler and Joos, 1992) based on the version used in the IPCC TAR. Exponential fits to those functions are used to calculate the CO_2 concentration at a given year resulting from all emissions in prior years. We also perform an offline calculation of the steady-state methane response to changes in modeled oxidants, as in prior work (Shindell et al., 2008). With methane prescribed at present-day values in the chemistry model, changes in modeled methane oxidation result solely from changes in oxidizing agents. Note that the model's oxidation rate fully captures spatial and seasonal variations. We also include the feedback of methane on its own lifetime (using $\delta \ln(OH) = -0.32 \delta \ln(CH_4)$ as recommended in Prather et al., 2001). We include the slow response of ozone to the decadal timescale changes in methane based on prior modeling (Shindell et al., 2005). Radiative forcing from CO_2 and methane are calculated using the standard IPCC TAR formulation (Ramaswamy et al., 2001).

4 Radiative forcing results

The net radiative forcing from CO_2, sulfate, ozone, methane and nitrate for the constant number of power plants without pollution controls is shown in Fig. 1. There is a nearly immediate negative forcing that slowly decreases with time and eventually turns into a positive forcing as CO_2 accumulates in the atmosphere. The negative forcing is dominated by increased sulfate (due to the SO_2 emissions), with a small addition from reduced methane (due to increased ozone and hence OH) and small offsets from increased ozone (due to the NO_x emissions) and decreased nitrate aerosol. The latter arises from a greater formation of ammonium sulfate at the expense of ammonium nitrate. Hence the short-term climate impact of coal burning in power plants without

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pollution controls is opposite to the long-term impact, with the transition time strongly dependent upon the uncertain magnitude of the AIE. Note that while the simulation for the air quality pollutants used emissions from Asia, the results were highly linear in the various scenarios despite pollutant increases up to a factor of 40. Hence these results provide a rough estimate for the effects of US (or European) emissions during the early 1970s, which were comparable in magnitude to those from China and India in 2000. However, photochemical regimes and background concentration do vary with geographic location, and can lead to differences as large as a factor of 2 in the RF per unit SO_2 emission change (Shindell et al., 2008).

We next examine results from the hypothetical scenarios (Fig. 2). The high growth scenarios (red-orange) show that the timing at which pollutant controls are imposed has an enormous effect on the net RF over the next several decades. The scenario with early pollution controls shows a net forcing of nearly 0.7 W/m^2 at 2040, while the scenarios with late pollution controls have forcings ranging from near zero to substantial negative values depending on the assumed magnitude of the AIE. Hence the net effect of air quality pollutants ranges from offsetting approximately all the forcing from CO_2 to exerting even a more powerful, but opposite sign, forcing than CO_2. However, the timing of pollution controls has no effect on the radiative forcing once those controls are in place, leading to identical values past 2060 in the high growth scenarios with early and late pollution controls (there will be an effect on the integrated RF felt by the Earth however, which will impact the trajectory of the climate response even if not the final state). The high growth scenarios show a continued increase in RF throughout the period studied despite constant emissions after 2040. The continued increase, which is still fairly rapid at 2080 (0.25 W/m^2 per decade) results from the long adjustment time of atmospheric CO_2 to emissions.

The high growth scenarios in which growth ceases at 2030 instead of 2040 show substantially less forcing during the latter part of the century. Forcing at 2080 is roughly half that in the scenarios in which growth persists until 2040. This is not surprising given that adding 10% per year coal-fired power generation capacity from 2030–2039

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increases annual average total coal usage by 260%.

The greatest difference between the forcing in the various scenarios in the later decades is between those with high and those with moderate growth rates. A more modest 5% per year growth rate all the way though 2060 leads to 60% less RF at 2080 than a 10% per year growth rate through 2040. Use of gas instead of coal also leads to decreased forcing, but not as dramatic a reduction as lowering the growth rate by half.

Though the global mean forcing provides a reasonably good indication of the global mean temperatures response, the forcing in the cases with substantial pollution from aerosols and ozone is highly uneven spatially (e.g. Fig. 3). The forcing from air quality pollutants is the sum of several components with varying atmospheric residence times, as discussed previously. The net effect is dominated by sulfate, whose global mean negative RF is approximately six times larger than the sum of positive ozone and nitrate forcings. All three are greatest locally over the Asian source regions, but the forcing spreads zonally (east-west) around the Northern Hemisphere given the days to weeks lifetime for ozone and aerosols. In contrast, the indirect methane decreases are globally fairly uniform owing to methane's much longer residence time, and offset a small portion (~7%) of the global CO_2 forcing. Net forcing at 2040 in the high growth, late air quality pollutant controls scenario is positive (0.3–0.7 W/m^2) over most of the tropics, Southern Hemisphere and the Arctic. Negative forcing of −5 to −10 W/m^2 occurs over much of China and India, with negative values of a few tenths of a W/m^2 extending across most of the Northern Hemisphere. Zonal mean forcing is strongly negative in the Northern Hemisphere subtropics and mid-latitudes, and positive elsewhere (Fig. 4). In contrast, forcing is positive and fairly uniform with early pollution controls. We note that zonal mean forcing is likely to be a reasonably good indicator of the zonal mean climate response, which does not closely follow the RF at regional scales but is strongly related for broad latitude bands (Taylor and Penner, 1994; Shindell et al., 2007; Shindell and Faluvegi, 2009; Levy et al., 2008; Mitchell et al., 1995).

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5 Discussion of uncertainties

There are many sources of uncertainty in estimating the climate impact of future emissions. The first is that the socio-economic factors that govern the future growth rate cannot be reliably predicted. While we investigated two possible growth rates to explore sensitivity, actual trends will vary from either of those idealized projections. Under the high growth scenario, coal usage is 9.6 Gt coal in China and India for power generation at 2030, while under the moderate growth scenario it is 2.3 Gt coal. EIA projections have 3.8 Gt coal usage by China at 2030 and 0.6 Gt coal by India for all purposes (~60–70% of current coal usage in China and India is for power (Streets et al., 2003), so ~2.6–3.1 Gt of the total), so our scenarios bracket those projections although our moderate scenario is much closer. The EIA projected growth rate for China decreases from 6% during 2005–2010 to less than 3% after 2015, however. As noted, historical growth rates have been substantially greater, so it is not obvious which path will be closer to actual future emissions.

Our scenarios also assume that when air quality pollutant controls are introduced, they are 100% effective. Though this is clearly unrealistic, the impact of residual emissions when controls are in place is likely to be quite small based on current US emissions and trends. Current air quality pollutant emissions from the US create an annual average RF of less than one one-hundredth of a watt per meter squared despite CO_2 emissions more than double those of China and India (Table 2). Furthermore, from 1998 to 2007, US emissions of SO_2 and NO_x decreased by 3.3 and 4.3%/year, respectively. This occurred despite an overall growth in coal usage (resulting in CO_2 emissions increasing by ~0.8%/year). Hence technology exists to remove the vast majority of SO_2 and NO_x emissions, so that the RF from residual air quality pollutant emissions would be very small (and well within the uncertainty due to AIE).

Our scenarios explored only the impact of hypothetical emissions from China and India. EIA projections of total coal usage for 2005 to 2030 show 80% of total growth in these two countries, with the remainder divided nearly equally between the US and the

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developing world (the latter mostly in other Asian countries). It is not completely clear how much of this growth is due to usage in power plants, and residential and industrial use of coal may have rather different effects as it also leads to substantial emissions of carbon monoxide, black and organic carbon. Nonetheless, we can roughly estimate the contributions from other regions. The contribution of additional coal burning plants in Asia would add ~14% to the estimated contribution from China and India using the EIA growth rates. The contribution of added US power plants, which are projected to grow at 1.1%/year (EIA, 2009) and we assume generate exclusively CO_2 emissions, would be an additional RF of 0.08 W/m^2 at 2030 and 0.19 W/m^2 at 2080 from plants added between 2005 and 2030. This adds ~10–30% to the total 2080 forcing from power plants in China and India, depending upon the scenario assumed for those countries (Fig. 2).

Another large source of uncertainty comes from our incomplete knowledge of the emission factors for coal combustion and from the substantial variation from location to location that results from differences in coal burning techniques and in the composition of the source coal, especially its sulfur content. The leads to a very large range in emission factors for SO_2, which spans 4–113 g SO_2/kg coal for China and 8–16 g/kg for India (Streets et al., 2003). Values for NO_x are more consistent, with a range of 5–12 g/kg for both countries, while the emission factors for CO_2 are quite well known, with a range of only 2243–2313 g/kg. We used emission factors of 16 g/kg for China and 12 g/kg for India for SO_2, and 8 g/kg NO_x and 2278 g/kg CO_2 for both countries, leading to the current emissions given in Table 2. For comparison, another estimate gives 8.9 Mt for Chinese SO_2 emissions from coal-burning power plants in 2000 (Yang and Schreifels, 2003), and hence is somewhat larger than the 5.4 Mt value we used, highlighting the uncertainty in current sulfur emissions. Future emission factors could be substantially different, depending, for example, on the availability of low-sulfur coal as demand increases. This would clearly affect the magnitude of air quality pollutant RF during the period prior to full pollution controls taking effect.

Future technology may also be developed to limit carbon dioxide emissions. Were

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carbon capture and sequestration (CCS) technology to be eventually commercialized and deployed, additional CO_2 emissions after CCS was installed might be dramatically lower. However, emissions up through the time of CCS installation would continue to drive a slow increase in atmospheric CO_2, leading to a continued increase in RF (albeit a much slower one than in our scenarios). Given the time required to perfect and expand the technology, as well as to deploy an enormous network of CO_2 pipelines, it seems extremely unlikely that CCS will be operating on a majority of power plants during the next several decades. We note also that even with CCS, emissions of CO_2 are still estimated at 255–442 g/kWh from extraction and transportation of coal and residual emissions versus 790–1020 g/kWh without CCS (Jacobson, 2009). This highlights how consideration of the full life-cycle of coal use would become increasingly important as pollution controls at the power plants themselves become more effective.

6 Climate response and historical context

We estimate the surface temperature response to the calculated radiative forcings using prior results from transient simulations with the GISS climate model (Shindell and Faluvegi, 2009; Hansen et al., 2007). We obtain a rough approximation of global and regional responses by multiplying the calculated RF by the global or regional transient sensitivity, accounting for inertia by including a tapering influence of forcing during the prior 20 years (based on a fit to the prior model runs) (Fig. 5). Regional responses are calculated including the influence of both local and remote forcings from (Shindell and Faluvegi, 2009) and the spatial patterns of forcing calculated here (e.g. Fig. 3). These estimates of surface temperature change are meant to be illustrative, as the transient response may be different for forcing with alternate spatial and temporal behavior to the forcing used in the simulations from which we took the sensitivities. While ensemble simulations of a full climate model could examine the response in a more realistic manner, we feel that such experiments would not be the best use of computational resources given that forcing by coal burning emissions is only one of many important forcing affecting past and future climate, and hence the results cannot be compared with historical observations directly nor do they constitute quantitative future projections suitable for impact and adaptation analyses. They are nonetheless useful in providing a qualitative picture of the historical and potential future impacts of coal-burning emissions on surface temperature. Note that in the case of the high growth until 2040 with early pollution controls, for which forcing is from CO_2 alone, our response is ~1.8 C per trillion tons of cumulative carbon released, well within the range of ~0.9–2.2 C per trillion tons carbon inferred from observations (Matthews et al., 2009).

The Northern Hemisphere mid-latitude band responds more strongly than the global mean owing to its greater climate sensitivity, while the Southern Hemisphere extratropics respond more slowly. The timing of pollution controls has an enormous influence on the climate response during the first few decades, but only a moderate influence remains a decade or two after controls are imposed. Perhaps most significant is that the rates of warming are dramatically different in the cases with early or late pollution controls. The maximum decadal warming at Northern Hemisphere mid-latitudes in the early pollution controls case is 0.13 C/decade, whereas it is 0.26 C/decade in the late pollution controls case. This may have profound effects on biological systems which face increasing difficulty in adapting to more rapid warming.

A similar analysis can be done for the 20th century. Total sulfur emissions from coal burning increased markedly from the late 19th century until World War I, remained fairly level during the interwar years, and then again began a steady increase. These patterns largely followed usage, as there were only minimal pollution control efforts prior to the 1970s. Due to both pollution controls and a switch to low-sulfur coal, the rate of increase in sulfur emissions from coal burning began to slow during the 1970s, peaking around 1990 and then decreasing so that 2000 emissions are comparable to 1970 levels (Smith et al., 2001, 2004). Global sulfur emissions from all sources follow a fairly similar pattern (Lefohn et al., 1999). Hence globally, the period prior to 1970 was similar to the "late pollution controls" case in our study, in which large increases in emissions of both CO_2 and SO_2 largely offset one another, leading to little net cli-

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mate forcing. Thus despite increases in coal usage from only a few MtC during the preindustrial to ~1.3 Gt C by 1970 (roughly one-third of total global carbon emissions (Marland et al., 2008)), the net global mean climate forcing from coal-burning emissions from power plants (the primary use of coal in the latter half of the 20th century) may have been near zero or even negative up to that time. The CO_2 emissions from that time will continue to influence climate for centuries however, eventually leading to a substantial net positive climate forcing. An example of this is the latter half of the high growth, no pollution controls case (2040–2080), in which all emissions remain constant but radiative forcing steadily increases owing to the slow buildup of atmospheric CO_2 (Fig. 2).

In contrast, the past ~30 years have been consistent with the "early pollution control" scenarios in this study in the sense that CO_2 emissions increased greatly while those of air quality pollutants remained roughly constant. The location of coal burning is also important. Total production of coal in the US followed a similar trend to global usage, increasing greatly from the late 19th century through about 1915 and then leveling off, but production increased sharply again from 1960 onwards (Lefohn et al., 1999). As early usage was greatest in the US and Europe (Smith et al., 2004; Lefohn et al., 1999), the period up to 1970 would have seen substantial negative forcing at Northern Hemisphere mid-latitudes, with positive forcing over most of the Southern Hemisphere and the tropics (similar to that shown in Fig. 4, but shifted slightly northward). Since the 1970s, RF is likely to have increased more at Northern Hemisphere mid-latitudes than at lower latitudes owing to reductions in air quality pollutant emissions in developed nations and increases in emissions in developing countries. Estimating the surface temperature response to these forcings shows that the broad shift from pre-1970 coal-fired power plant emissions without pollution controls to post-1970 emissions with pollution controls likely contributed to the accelerated global warming of recent decades relative to the mid-20th century, and to the relatively slower than faster rise in Northern Hemisphere mid-latitude temperatures (Fig. 5) Though our values are only rough estimates, we note that from 1970 to 2000 global mean temperatures increased by

~0.4 C (Hansen et al., 2001), while Northern Hemisphere mid-latitude temperatures rose about 0.8 C and the Southern Hemisphere extratropics warmed ~0.2 C (Shindell and Faluvegi, 2009). Hence it seems plausible that coal burning emissions from power plants could account for a substantial portion of the post-1975 global and regional warming trends. A definitive attribution is difficult, however, owing to uncertainties in aerosol forcing, the time lag between radiative forcing and climate response, and the influence of internal variability.

The influence of coal-burning in the early 20th century is more difficult to assess. The rapid increase in US coal usage from ~1900, when it was ~200 Mt, to 1915, when it reached ~550 Mt (EIA, 2009), was accompanied by concomitant increases in sulfur emissions which likely masked much of the warming from CO_2. However, coal usage at that time primarily consisted of residential and industrial uses, not electricity generation. These types of combustion are typically much less complete, and hence emit large quantities of black carbon, a powerful positive short-lived radiative forcing agent. Consistent with this, the abundance of black carbon in ice cores from Greenland, downwind of the US, peaks in the early 20th century (McConnell et al., 2007). Hence even if the warming effect of CO_2 was largely offset by increased sulfur emissions, the net effect of emissions from the rapid increase in early 20th century coal burning would likely have been a positive RF. This may have contributed to the observed global and regional warming during roughly 1915–1930 (assuming a 1–2 decade lag in climate response to forcing). From ~1950 to 2000, usage of coal to generate electricity increased from ~20% of the total US usage to ~90% (it was ~54% in China in 2000, and ~70% in India). Hence current emissions from coal burning without pollution controls are much more likely to have near-zero net short-term forcing than those of the early 20th century.

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7 Impacts and conclusions

Masking of CO_2's warming effect by air quality pollutants, or even a net overall cooling effect, will lead to a comparatively slower global warming rate, but should not be taken as a reason for complacency in the need to curb CO_2 emissions. In contrast, application of pollution control technology in use in Western developed countries and Japan along with continued CO_2 emissions would lead to strong positive forcing in the long term irrespective of whether the pollution controls are applied immediately or several decades from now. Continued emissions at current (year 2000) pollutant and CO_2 levels may have little near-term effect on climate, but the climate "debt" from CO_2 forcing will continue to mount. Once pollution controls are put into place as society demands cleaner air it will rapidly "come due". The only way to avoid this would be not to impose pollution controls and to perpetually increase sulfur-dioxide emissions, which would lead to a staggering cost in human health and is clearly unsustainable (even then the very long-term forcing would still be positive).

The results demonstrate that decisions made for the sake of air quality policy will have an enormous impact on climate forcing from coal-fired power plants over the next several decades. For comparison, the total forcing from all activities and emissions was estimated to range from 2.8 to 6.6 W/m^2 at 2080 under the scenarios used in recent IPCC assessments (Intergovernmental Panel on Climate Change, 2001). Hence the $\sim$1.5–2 W/m^2 forcing under the high growth scenarios (Fig. 2 for Asia plus the US contribution discussed in the text) indicates the potential of continued addition of coal-burning power plants in China, India and the US to contribute a substantial fraction of the total projected climate forcing. A relatively steady warming would result from the gradual rise in RF under the early pollution control scenarios. In contrast, the late pollution controls would lead to coal-burning emissions from power plants contributing virtually nothing, or even a moderate cooling depending on the strength of the AIE, to global temperature increases during the first half of the century in the various scenarios. Such an effect could in fact already be contributing to the slower rates of warming

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during the 21st century relative to the latter decades of the 20th, though this might also result from internal variability (Easterling and Wehner, 2009). However, emissions under the late pollution controls case would exert a strong warming influence in the latter part of the century as the aerosol masking of CO_2 RF is removed. While the relatively high growth rates assumed here may provide an upper estimate of the total magnitude of climate forcing, in January 2009 the Chinese government announced plans to increase coal production 30% by 2015 to meet its energy needs (The China Post, 2009), so substantial growth does seem likely.

Aside from their impact on climate and air pollution, coal plants are the largest anthropogenic source of mercury emissions, with emissions from Chinese coal burning alone accounting for ~5% of global discharge in 1995 (Zhang et al., 2002). With usage of coal in China having increased by ~75% between 1995 and 2006 (EIA, 2009), China's mercury emissions from coal burning may already be nearly 10% of global emissions. In addition, coal burning generates more than 125 million tons of waste (ash, sludge and slag) each year in the US annually (The New York Times, 2009), roughly the same amount of waste as the municipal solid waste sent to landfills from every city in the country. This coal combustion waste contains lead, mercury, and arsenic, and the EPA has identified 63 sites where heavy metals from coal waste ponds have contaminated ground water in the US (The New York Times, 2009). Coal mining itself generates additional emissions, including methane vented from mines and emissions from mechanical extraction and transportation of coal, and can lead to environmental damage such as filling in streams with earth from mountaintop removal. As discussed previously, there are substantial adverse impacts on human health from the fine particulate formed from coal burning emissions, with estimated impact on more than 20 000 US lives each year and substantially larger numbers in Asia where hazardous trace elements such as arsenic or fluorine are emitted during residential coal burning (Finkelman et al., 1999). Ideally, assessment of the environmental effects of coal power plants should include all these effects, especially when the "cost" of electricity from coal-fired power plants is compared with alternative sources of electricity generation.

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Table 1. Simple scenarios for emissions from power plants China and India.

Scenario (2000–2075)	CO_2 emissions	Air quality pollutant emissions
Constant current emissions	1132 Tg	7.3 Tg SO_2, 4.0 Tg NO_x
High growth, late air quality pollution controls	+10%/year to 2040, constant thereafter	+10%/year to 2040, linear decrease to zero 2040–2060
High growth, early air quality pollution controls	+10%/year to 2040, constant thereafter	None
High growth, no air quality pollution controls	+10%/year to 2040, constant thereafter	+10%/year to 2040, constant thereafter
High growth, gas	+6%/year	None
Moderate growth, late air quality pollution controls	+5%/year to 2060, constant thereafter	+5%/year to 2040, linear decrease to zero 2040–2060
Moderate growth, early air quality pollution controls	+5%/year to 2060, constant thereafter	None
High growth until 2030, late air quality pollution controls	+10%/year to 2030, constant thereafter	+10%/year to 2030, linear decrease to zero 2030–2050
High growth until 2030, early air quality pollution controls	+10%/year to 2030, constant thereafter	None

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Table 2. Year 2000 emissions from coal-fired power generation (Tg or Mt).

	China	India	US
CO_2	771	361	2442 (2517)
SO_2	5.4	1.9	12.0 (9.0)
NO_x	2.7	1.3	5.6 (3.7)

Emissions are in Tg CO_2, Tg SO_2 and Tg NO_x. Conversion from PJ coal used for power to emissions based on 29.3 GJ per ton of coal. Emission factors are 16 g/kg SO_2 for China and 12 g/kg for India, 8 g/kg NO_x for both, and 2278 g/kg CO_2 for both based on mid-range values (Streets et al., 2003). US data is also given for 2007 in parentheses (US data from EIA, 2009) (http://www.eia.doe.gov/cneaf/electricity/epa/epates.html).

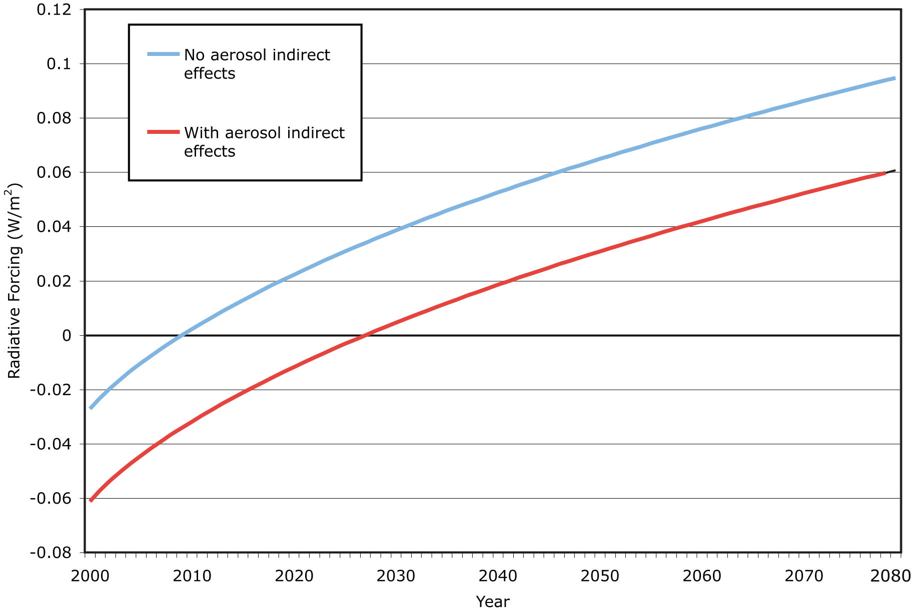

Fig. 1. Timeseries of global mean annual average instantaneous radiative forcing at the tropopause for constant emissions from coal burning power plants without pollution controls. Emissions are based on year 2000 emissions from China and India. Values are shown both with and without an estimate of aerosol indirect effects.

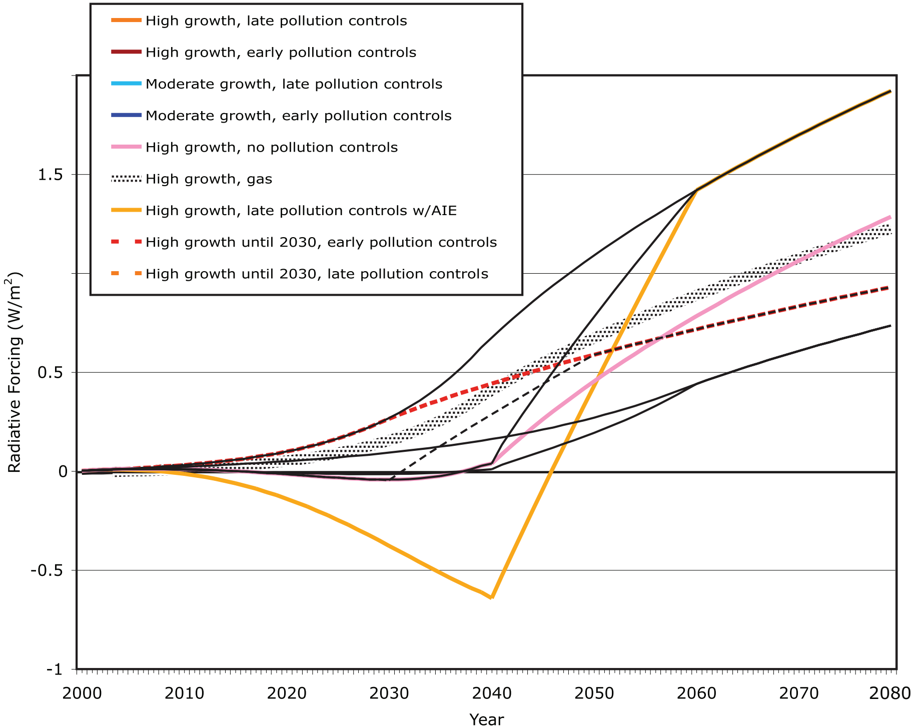

Fig. 2. Timeseries of global mean annual average instantaneous radiative forcing at the tropopause in the various indicated scenarios. Note that the high growth scenarios are shown in red-orange colors, the moderate growth in blues, growth until 2030 with dashed lines, and the gas scenario is the thick black line. Forcing is the sum of contributions from carbon dioxide, sulfate, ozone, methane and nitrate. w/AIE is with aerosol indirect effects.

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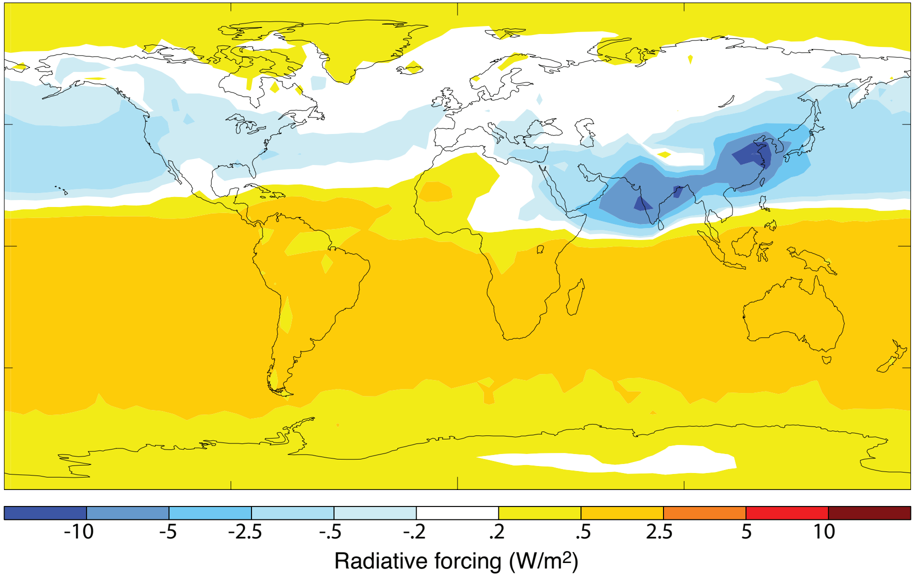

Fig. 3. Annual average instantaneous radiative forcing at the tropopause in 2040 for the high growth, late air quality pollution controls scenario. The forcing includes contributions from CO_2, methane, ozone, sulfate, and nitrate, whose global mean values are 0.68, −0.05, 0.04, −0.73 and 0.08 W/m^2, respectively.

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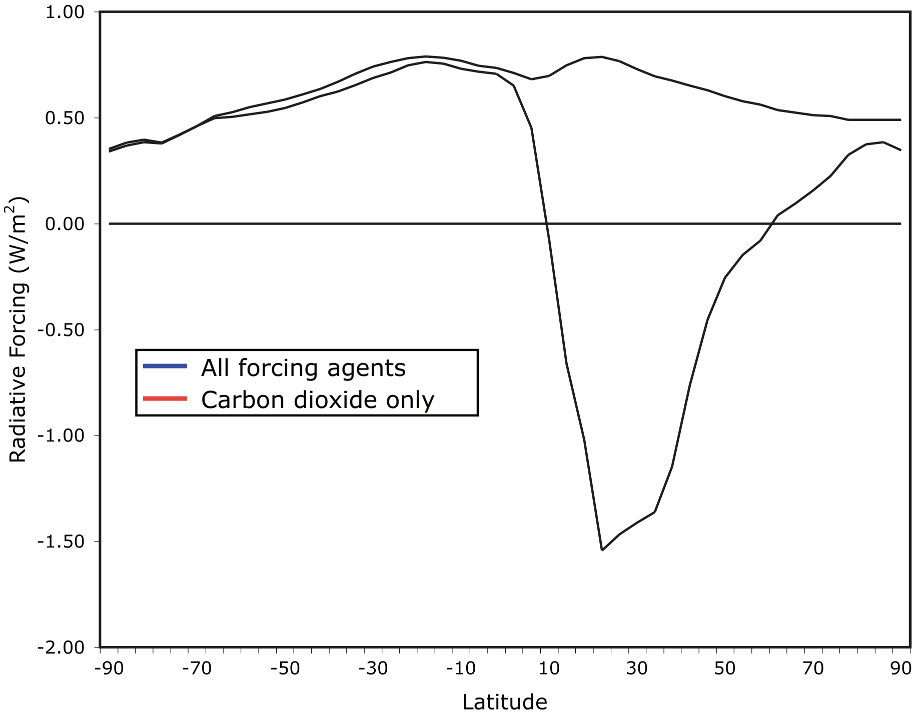

Fig. 4. As in Fig. 3, but zonal mean of net forcing and of CO_2 forcing only.

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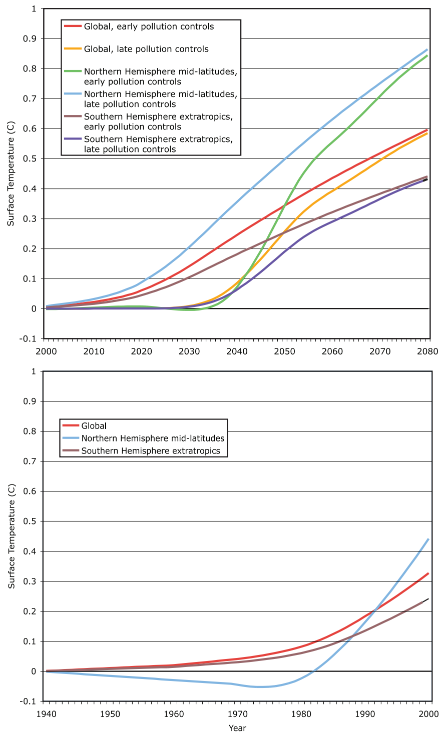

Fig. 5. Illustrative estimates of surface temperature response to the radiative forcing due to coal-burning emissions in the scenarios with high growth through 2040 (top) and in the past (bottom). Estimates are based on the transient climate sensitivity in prior GISS GCM simulations. For the Northern Hemisphere mid-latitudes (28–60° N) and Southern Hemisphere extratropics (28–90° S), we use the response to local and remote forcings from (Shindell and Faluvegi, 2009) and the spatial pattern of forcing shown in Fig. 3 for the future or from prior modeling of North American emissions for the past (Shindell et al., 2008). Values are global or zonal means.