Supplementary Material

Two Hundred Fifty Years of Aerosols and Climate

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A. Sectoral and Technology Representations

GCAM energy use data is derived from global energy balances developed by the international energy agency. The sectoral representations used in the GCAM results discussed in this paper are described below.

GCAM Sector	Definition
Energy and Industrial Emissions	
Building*	Residential Buildings Commercial Buildings Heat plant consumption (proportional allocation)* IEA "ONONSPEC"
Industry	Manufacturing Industries Cement and Agriculture Miscellaneous energy transformation (blast furnaces, coke ovens) Mineral and fossil-fuel extraction and transformation (inc. smelting) Heat plant consumption (proportional allocation)*
Transportation	On-road passenger & freight vehicles Rail (freight, passenger, & high-speed rail) Domestic Shipping
(International) Shipping	International Shipping

Electric Generation	Electric Generation, including co-generation, from all fuels and technologies
Land-Use and Land-Use Change Emissions	
Forests	Forest fires (natural + anthropogenic).
Grasslands	Grassland fires (natural + anthropogenic), including savannah burning.
Ag Waste Burning	Agricultural waste burning on fields. Emissions from agricultural wastes used as traditional or modern biofuel are accounted for in the appropriate energy sector.

* *See notes below.*

- As common in the energy analysis field, the term "building" includes residential and commercial buildings, but excludes structures used in manufacturing or construction, which are included in the Industry sector.
- Because the version of GCAM used in the RCP scenarios does not represent district heating as a separate energy delivery form, energy consumption by heat plants, along with associated emissions, are assigned to the building and industrial sectors proportional to their heat consumption.
- International shipping and air transport are explicitly modeled, and reported separately from the surface transportation sector.
- The rate of natural fires in forests and grasslands (e.g., emissions per unit forest area) is assumed constant through the 21st century: the impact of climate changes are not taken into account.

The sector definitions used in the GCAM projections generally follow those used for the RCP scenario historical emissions database (Lamarque et al. 2010; Smith et al. 2011), with the exception of fuels consumed in heat plants, which are accounted for in end-use sectors instead of the RCP ENE sector, and net fuel consumed in energy transformation and extraction, which is assigned to industry in GCAM, instead of the RCP ENE sector. These differences should be kept in mind when conducting detailed data comparisons.

The GCAM has a relatively rich set of technology detail, as compared to other integrated assessment models that span a century time scale, although less detailed than many models focused on shorter-term analysis. An overview of the technology detail within each region of the GCAM, as used for the RCP scenario development, is given below.

- Surface transportation in this version of GCAM is represented as on-road vehicles, trains, aircraft, and domestic shipping.
- Industrial energy use is represented as an aggregate sector by fuel. Cement manufacture and liquid fuel refineries are explicitly represented.
- Building sector is represented as an aggregate sector by fuel, with traditional biofuels as a separate fuel option in developing countries.
- Electric generation is represented as specific fuels and technologies (natural gas turbines, gas combined-cycle turbines, pulverized coal, coal with integrated gasification and combined-cycle, petroleum turbines, gen III nuclear, wind farms, geothermal, photovoltaic cells, CSP solar).

The latest version of the GCAM model is available at http://www.globalchange.umd.edu/models/gcam/gcam-community/. The latest versio of GCAM has a number of improvements relative to the version used to produce the RCP scenarios, as described in on-line documentation (wiki.umd.edu/gcam/).

B. GCAM REFERENCE SCENARIO

The underlying socio-economic and technology assumptions are drawn from the MiniCAM (now GCAM) scenario described in Clarke et al. (2007) and assume a growing population, increasing standard of living, and energy technologies that improve over time. A variety of technology options are available, including current and new fossil combustion technologies, nuclear energy, wind, solar, geothermal power, CO_2 capture and storage (CCS), bioenergy, hydrogen production and use, and improved end-use energy technologies in the buildings, industry, and transportation sectors.

Regional income is a major driver of emission factor decreases in the GCAM reference scenario. The GDP per capita pathways assumed in this scenario are shown in the figure and table below.

Both technology shifts, such as electrification of end-uses, modeled explicitly by the GCAM, and changes in emission controls, as represented through decreasing emission factors, will impact future pollutant emissions in these scenarios. As incomes increase in developing countries, the fuels and technologies used in the building and industrial sectors shift toward cleaner technologies, particularly a shift away from coal and traditional biofuels (Brenkert et al. 2003). While some technological changes are explicitly modeled, such as possible replacement of pulverized coal with IGCC technology, other changes, such as lower emission wood stoves, are only implicitly modeled by assuming emission factors improve over time as incomes increase.

The pollutant emission scenarios were developed to achieve consistency between regional incomes and surface pollutant levels as simulated by a global atmospheric chemistry model (Smith, West, & Kyle 2011). This implies that emission factors fall faster in developing countries: at least once incomes have been assumed to increase in a given region.

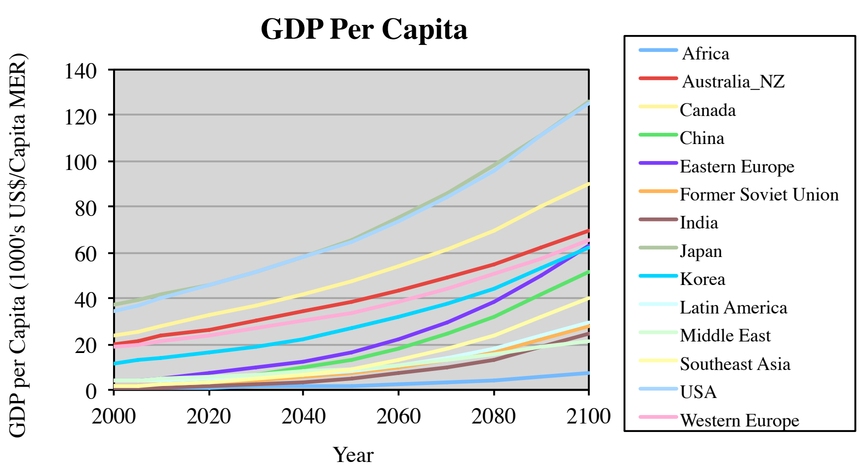


Figure S-1 – GDP per capita for the 14 GCAM world regions in year 2000 $US at a Market Exchange Rate basis.

Table S-1 – GDP per capita (as in Figure S-1).

	2000	2025	2050	2075	2100
Africa	0.8	1.1	1.6	3.8	7.7
Australia_NZ	20	28	38	52	70
Canada	24	35	48	65	90
China	1.1	5.1	13	28	51
Eastern Europe	3.7	8.3	17	34	63
Former Soviet Union	1.9	3.7	7.5	15	27
India	0.5	1.7	4.7	12	25
Japan	37	49	66	92	126
Korea	11	18	27	41	62
Latin America	3.9	5.3	7.9	16	29
Middle East	4.0	6.2	9.1	14	22
Southeast Asia	1.5	4.0	9.1	21	40
USA	34	49	65	90	125
Western Europe	19	25	34	47	65

Scenarios where the global levels of air pollutant emissions do not decline can also be constructed (Smith et al. 2005, Smith 2005). In order for such scenarios to be consistent with historical experience, these scenarios require relatively low income growth in developing countries, which is generally assumed to be associated with larger population growth (Nakicenovic and Swart 2000). In such scenarios demand growth is larger than can be accommodated by pollution controls deployed at historical levels and, as a result, net emissions increase. Scenarios where there is little action on air pollution due to low income levels are, arguably, most consistent with similarly low levels of action on climate change. This may not be consistent with the presumption that a climate policy is successfully implemented as assumed in the policy case here. Higher pollutant levels would also be inconsistent with the recent evidence of emissions reductions in China and Asia. However, the generalized global growth in income that is assumed in many future scenarios may not occur in all regions. Regions with lower income growth may be less able to control pollutant emissions, leading to larger emissions than in these scenarios.

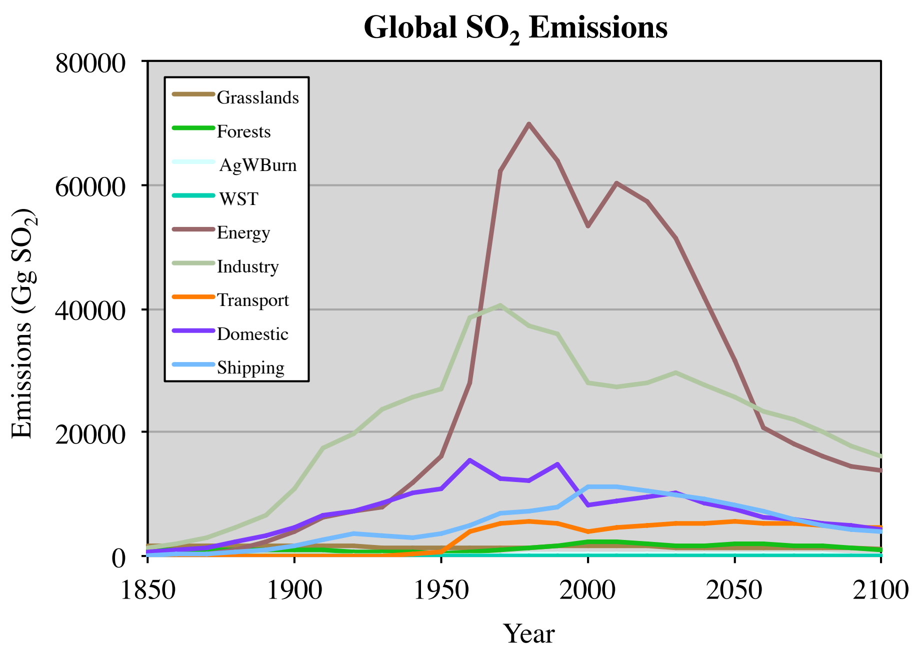
C. RCP 4.5 SCENARIO

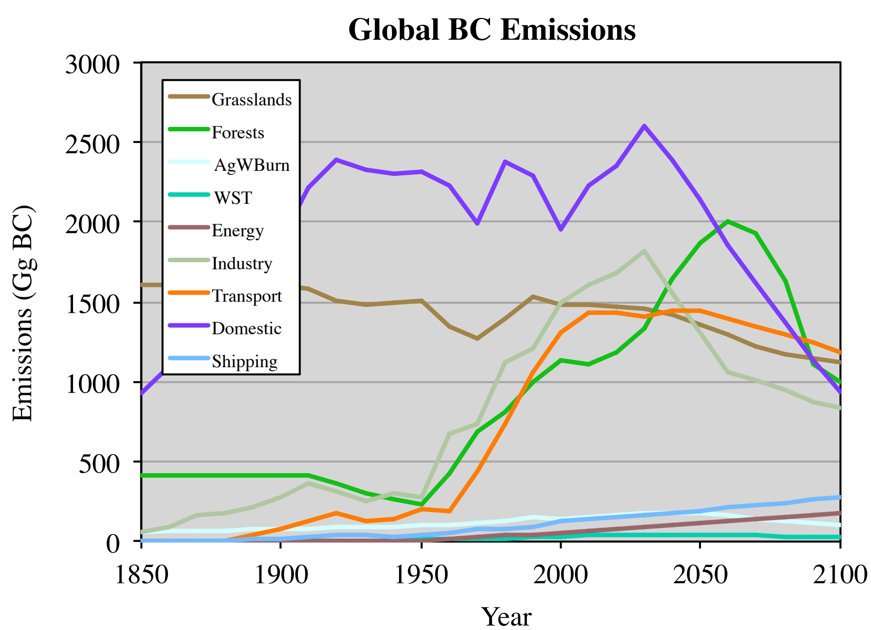
The GCAM RCP4.5 scenario (Thomson et al. 2011) is a climate policy scenario where a global carbon price is applied in order to reduce global radiative forcing to a specified target level. The carbon price is applied to all net carbon emissions and also to all carbon in terrestrial carbon stocks. The RCP4.5 scenario was designed to stabilize radiative forcing at 4.5 W/m^2 in 2100. In the RCP4.5 scenario the carbon price carbon price increases at an annual rate of 5% per year and is approximately constant once stabilization is achieved.

Note that the 4.5 W/m^2 radiative forcing target in the RCP process was defined as total anthropogenic forcing not including forcing from nitrate aerosols, mineral dust, and land-use change. These sum of these forcings are assumed to be constant in the future at -0.4

W/m^2. Total forcing at the end of the 21st century, including these forcings is, therefore, 4.1 W/m^2.

D. Global Emissions Detail





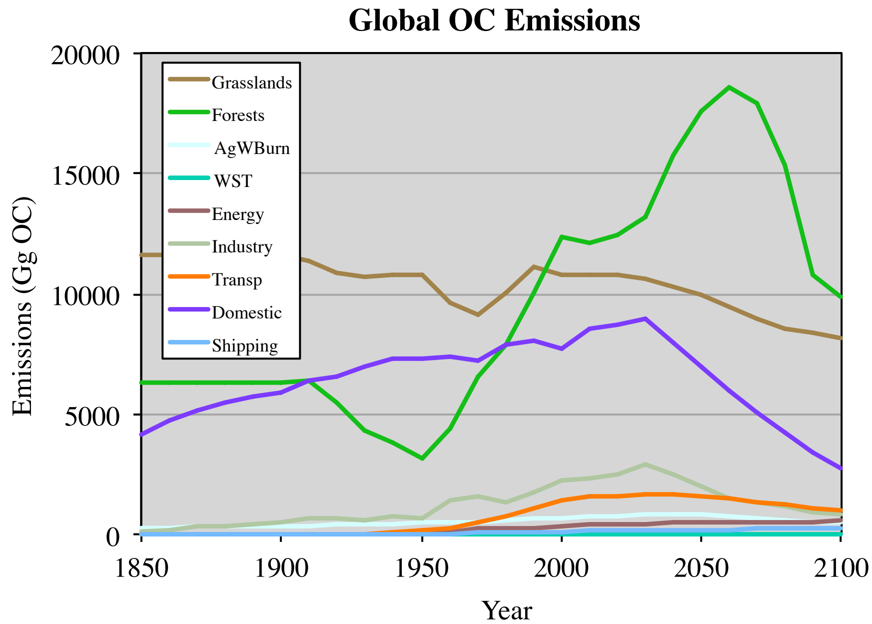
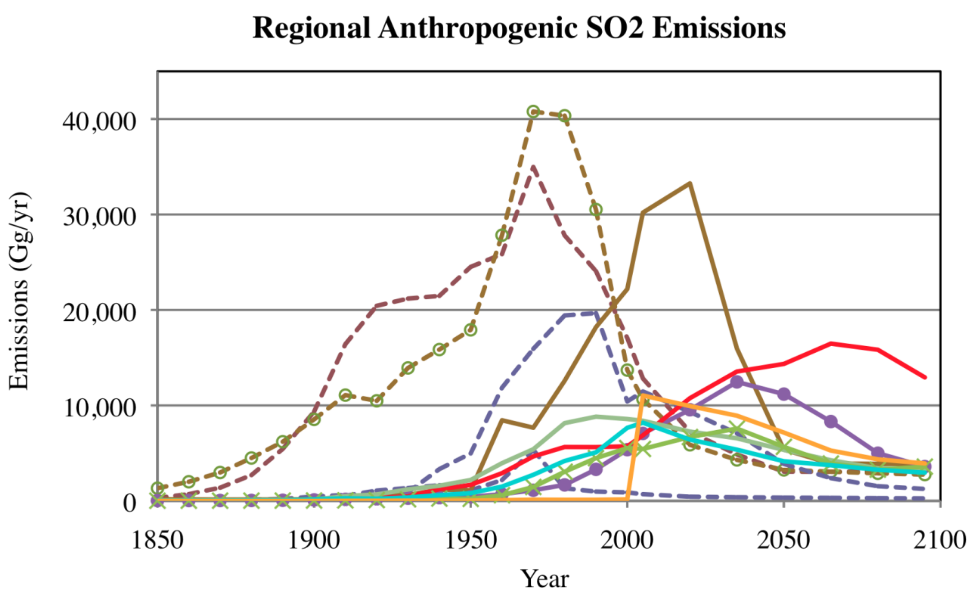


Figure S-2 – Historical and future sulfur dioxide, black carbon, and organic carbon emissions by sector for the reference scenario (as in Figure 1 main text, but as time series to show trends by sector).



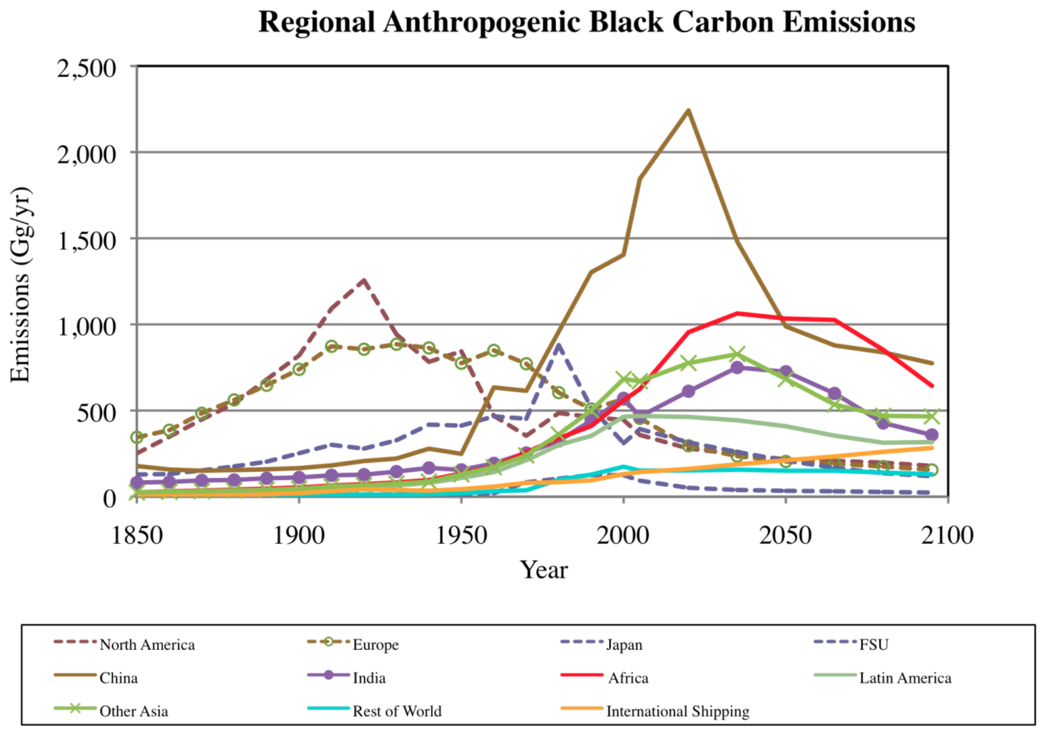


Figure S-3 – Historical and future sulfur dioxide and black carbon emissions by region under a reference case. Emissions from open burning (deforestation, grassland fires, and forest fires) are not included.

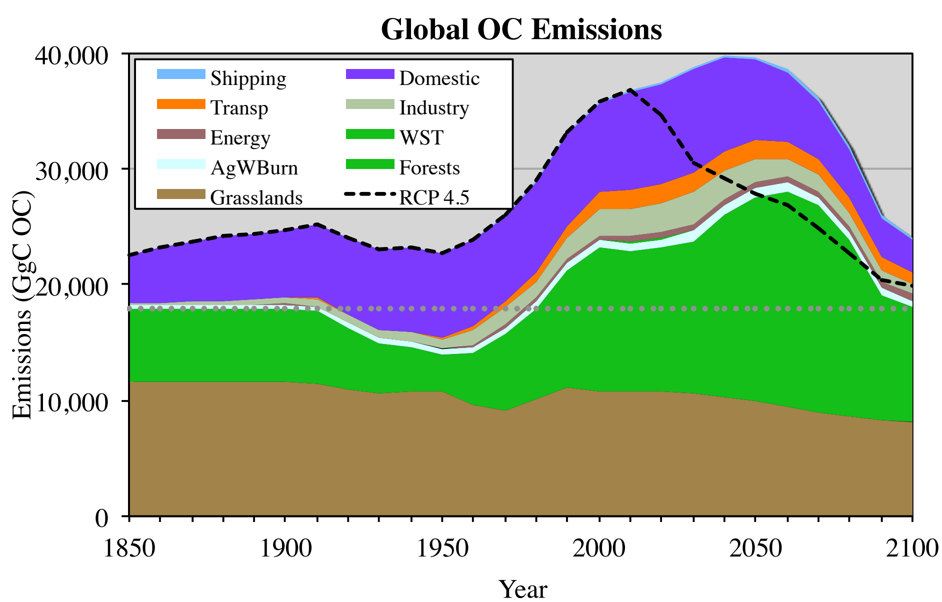
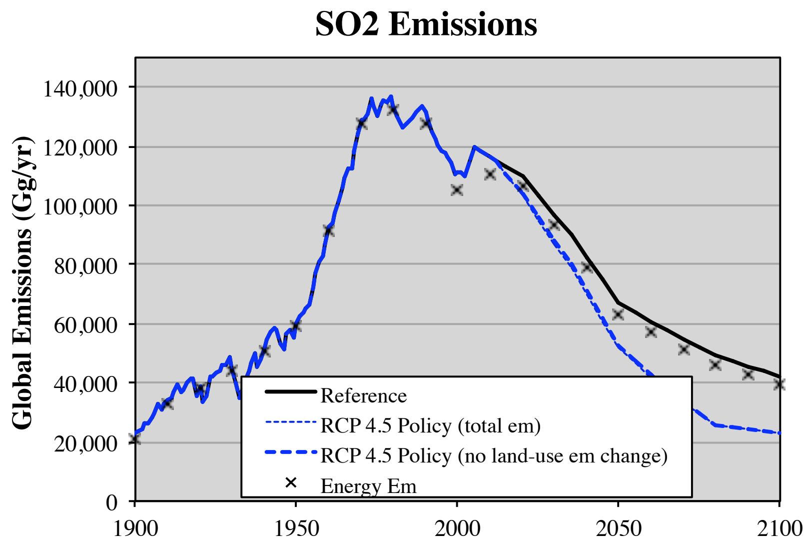
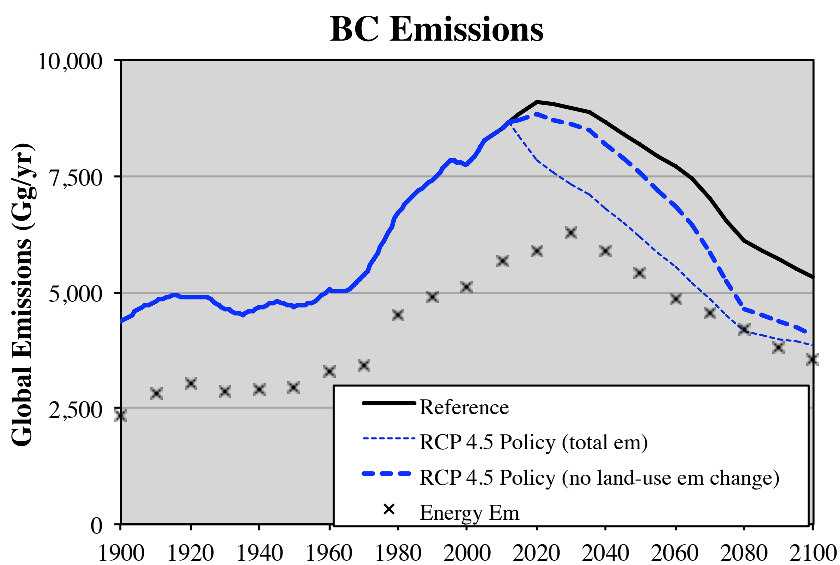


Figure S-4 – Historical and future organic carbon emissions. Future emissions under the GCAM reference climate policy scenario are shown in the shaded region. Total emissions under the RCP 4.5 climate policy scenario are shown in the black dashed line. See also caption to Figure 1.



SO2 Emissions
Global Emissions (Gg/yr)
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1900
1950
2000
2050
2100
Reference
RCP 4.5 Policy (total em)
RCP 4.5 Policy (no land-use em change)
Energy Em



BC Emissions
Global Emissions (Gg/yr)
10,000
7,500
5,000
2,500
0
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
Reference
RCP 4.5 Policy (total em)
RCP 4.5 Policy (no land-use em change)
Energy Em

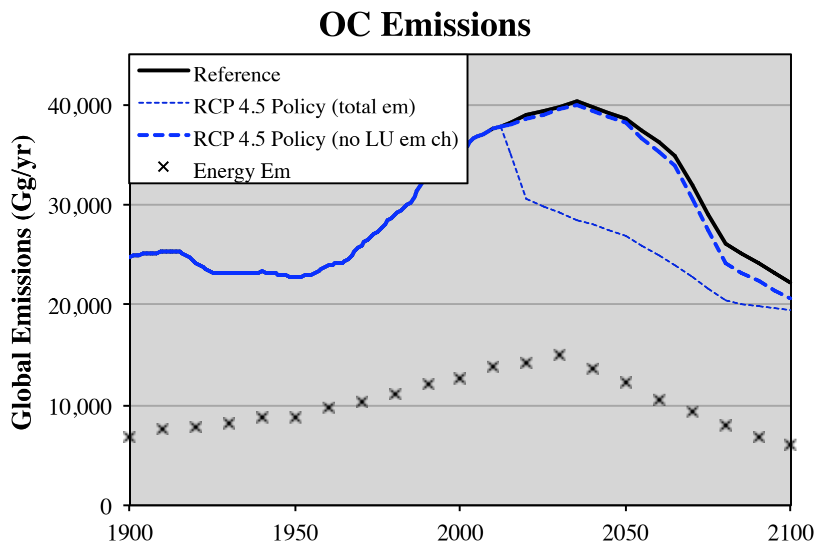
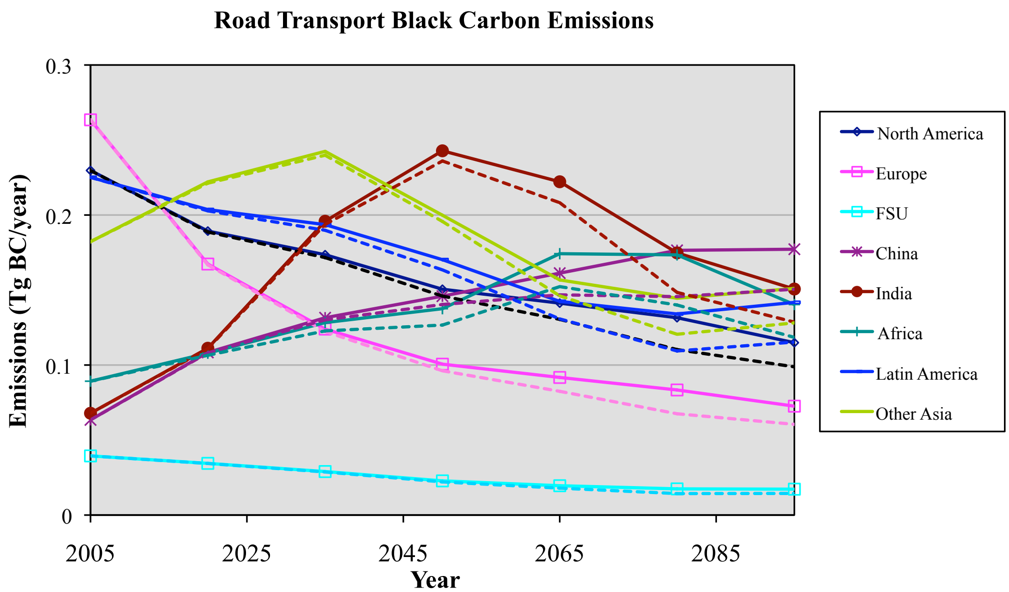
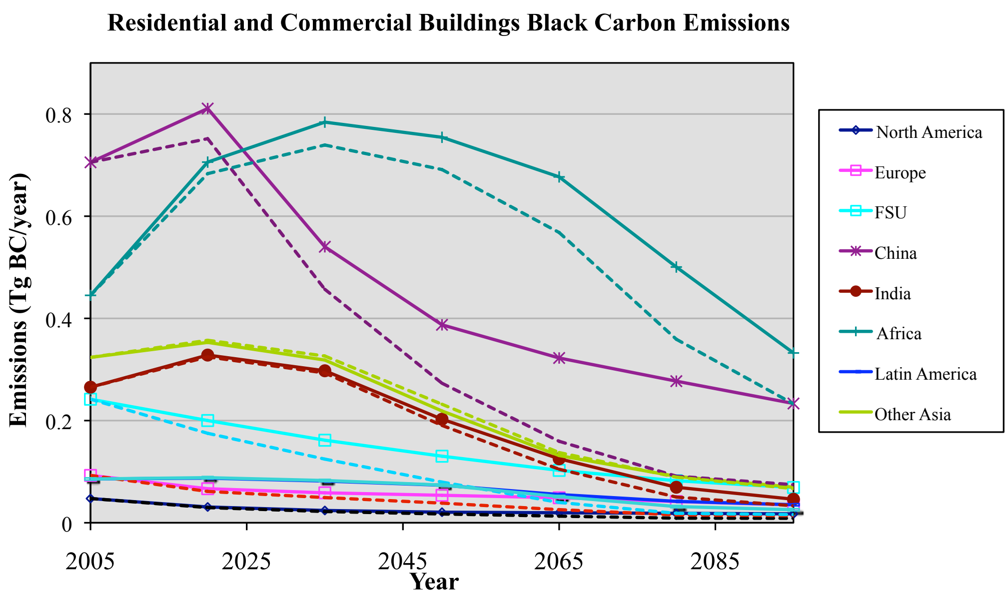


Figure S-5 – Global emissions of sulfur dioxide, black carbon, and organic carbon under a reference case (solid black lines) and RCP 4.5 policy scenario (dotted blue lines). The emissions changes under the policy scenario excluding changes in forest and grassland burning are also shown, labeled "no land-use em change" (blue dashed lines). Symbols show energy-related emissions only for the reference case.

As shown in Figures 1–4 (main text), Figure S-2, and Figure S-5, the sectoral distribution of emissions, and also of climate-policy related reductions, differ substantially for the three substances considered here. Organic carbon emissions are largely from land-use and the buildings sector, sulfur dioxide emissions are largely from energy combustion and industrial process sectors, and black carbon emissions have large components from both land-use and energy sectors. The climate consequences of changes in land-use emissions are quite different from changes in energy sectors due to the difference in BC/OC emissions ratio. While the global average BC/OC emissions ratio for open burning emissions is 0.1, this ratio for fossil plus biofuel emissions ranges from 0.4 – 0.6 over the 21^{st} century.

E. Sectoral Emissions Detail





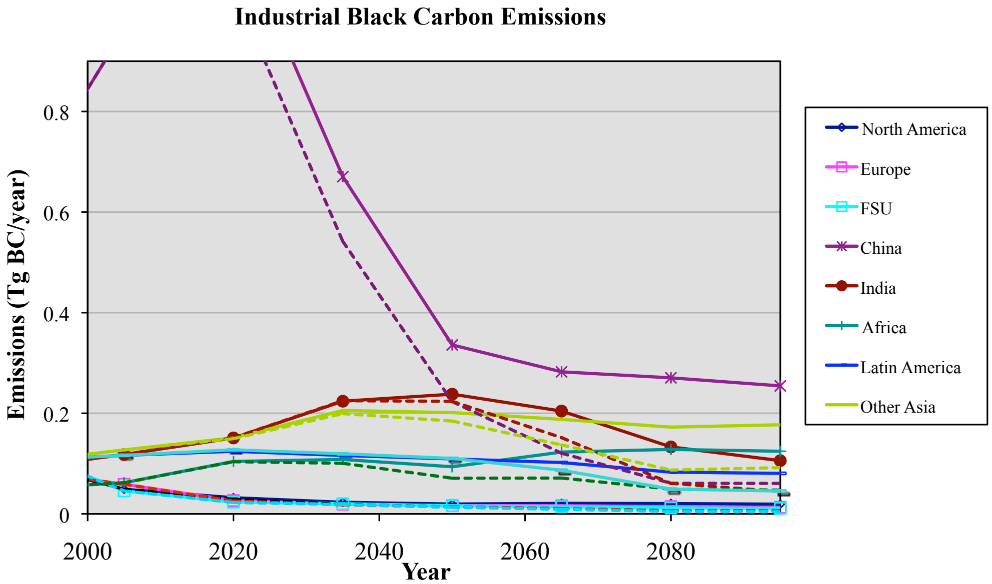


Figure S-6 – Black carbon emissions from road transportation, residential and commercial buildings, and industrial sector for various world regions for the reference case (solid lines) and RCP 4.5 policy scenario (dashed lines).

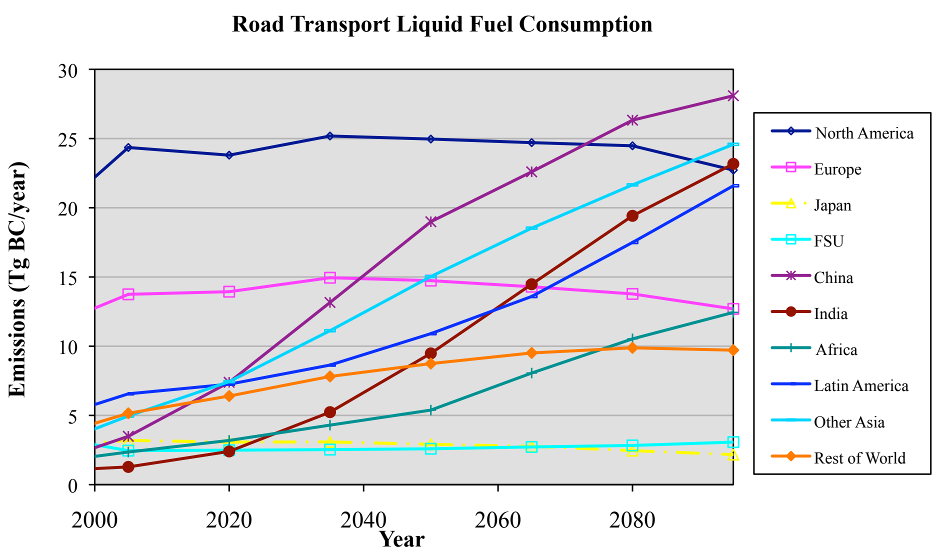


Figure S-7 – Liquid fuel consumption for road transport by region in the reference case (solid lines) and RCP 4.5 policy scenario (dashed lines).

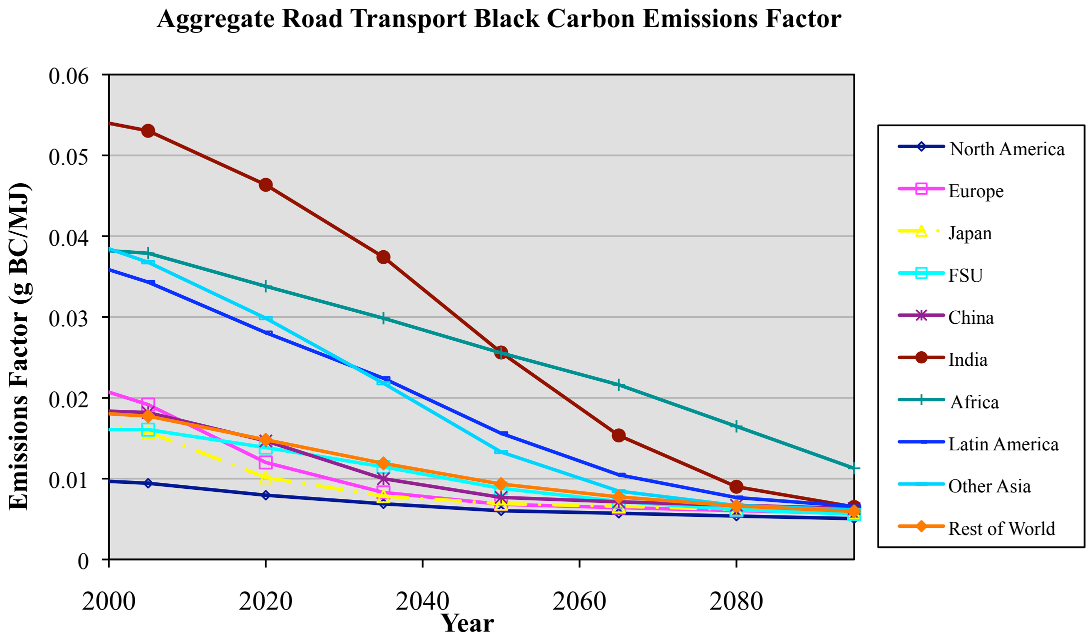


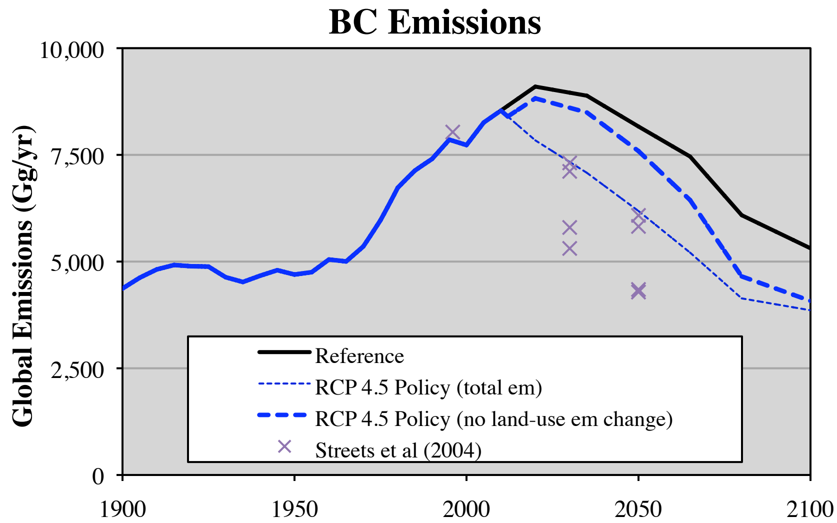
Figure S-8 – Aggregate emission factor for black carbon emissions from liquid fuel consumption for road transportation for various world regions.

F. Global Emission Comparisons

D1. Comparison to Streets et al. (2004)

Table S-2 – Numerical values for global emissions from the current study as compared to those of Streets et al. (2004).

	1996	A1B 2030	A2 2030	B1 2030	B2 2030	A1B 2050	A2 2050	B1 2050	B2 2050
Streets et al (2004)									
BC	8,035	7,113	7,311	5,308	5,799	6,082	5,823	4,346	4,286
OC	34,305	28,737	30,069	24,166	26,048	28,103	24,584	22,340	21,094
GCAM Ref									
BC	7,831	8,957				8,164			
OC	35,966	39,783				38,605			
Diff									
BC	*-204*	*1,844*	*1,646*	*3,649*	*3,158*	*2,082*	*2,341*	*3,818*	*3,878*
OC	*1,661*	*11,046*	*9,714*	*15,617*	*13,735*	*10,502*	*14,021*	*16,265*	*17,511*
GCAM RCP 4.5									
BC	7,831	7,333				6,184			
OC	35,966	29,179				26,866			



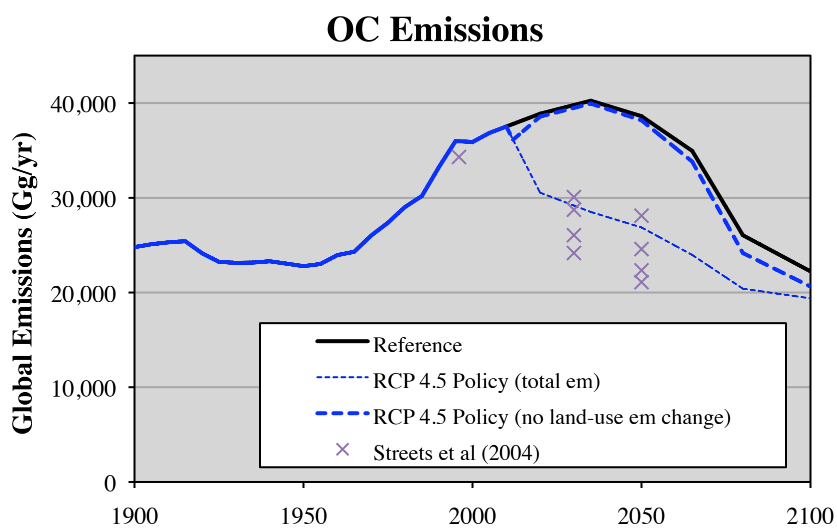


Figure S-9 – Emissions as in Figure S-3 above, with the addition of the global emissions estimates from Streets et al. (2004).

Note that the lower emissions in Streets et al. (2004) may be due to lower coal and biofuel use in the SRES scenarios on which these projections were based (Streets et al. 2010).

D2. Comparison to Yan et al. (2011)

Table S-3 – Global emissions and fuel consumption from road transportation from the current study as compared to those of Yan et al. (2011).

	Fuel Consumption			Emissions Factor			BC (or PM) Emissions		
	GCAM	Yan et al.		GCAM	Yan et al.		GCAM	Yan et al.	
		B1	B2		B1	B2		B1	B2
2030/2005 ratio	1.3	1.4	1.3	0.76	0.49	0.50	1.0	0.69	0.63
2050/2030 ratio	1.3	0.91	0.81	0.76	1.00	0.92	0.97	0.91	0.74
2050/2005 ratio	1.7	1.3	1.0	0.58	0.49	0.46	0.98	0.63	0.47

The table above shows the change, relative to 2005 or 2030, in global liquid fuel consumption, global BC emissions (or Yan et al PM emissions), and implied aggregate global emission factor (emissions divided by fuel consumption) from the GCAM reference scenario and the Yan et al. B1 and B2 scenarios. The socio-economic assumptions in the B2 scenario, used to drive the projections in Yan et al., are most similar to the socio-economic assumptions in the GCAM reference scenarios. This simple global comparison is presented in order to illustrate the reasons for different results in these two scenarios.

Global PM emissions in Yan et al. are lower in 2050 than in 2005 in both of the scenarios shown while global GCAM BC emissions are relatively constant. Differences in fuel consumption and in implied emission factor both contribute to this difference in emissions over time.

The increase in assumed fuel use between 2005 and 2030 is similar in the two studies. There is a large difference between these two studies in terms of fuel consumption increase from 2030 to 2050. There is a continued increase in the GCAM scenario, as compared to a decrease in fuel consumption in Yan et al. scenarios over this period. Scenarios in the literature show a wide range of behavior over this period (Uhereka et al. 2010; Figure 24), with some showing flat or decreasing road transport fuel consumption from 2030 to 2050, and others showing a continued increase in fuel consumption past 2030. In aggregate from 2005 to 2050, the Yan et al. scenarios have global fuel consumption that has either decreased back to the 2005 value (B2 scenario) or increased by 30% from the 2005 value, as compared to GCAM, where global road transport liquid fuel consumption has increased to 70% above the 2005 value.

A second factor contributing to the difference in emissions is a lower assumed decrease in aggregate emission factor over time in the GCAM scenario. The aggregate global emission factor in the Yan et al. scenarios decreases by about 50% over 2005-2030, a rapid decrease due to implementation of standards requiring end-of-pipe particle filters, while in the GCAM the decrease over this period is much smaller, only 25%. The Yan et al. global aggregate emission factor is relatively constant past 2030, while the GCAM emission factor continues to decrease. By 2050, the aggregate emission factor in the Yan et al. scenarios are 10-15% smaller than the GCAM value.

The Yan et al. scenarios assume that countries around the world enact vehicle emissions standards in accordance with announced plans, albeit with a delay for countries in Africa. Yan et al. account for the presence of “super-emitters”, a fraction of the vehicle population that have emissions well in excess of the average. This accounting for these super-emitters results in emissions that are higher than values from previous estimates that did not account for these vehicles. The GCAM scenario, in contrast, does not directly include this level of detail, but instead exogenously specifies the rate that emission factors decline as a regionally-varying function of regional GDP per capita (see also Smith, West, and Kyle 2011). The aggregate emission factor decrease in the GCAM scenario, therefore, has implicitly assumed a slower overall adoption of emissions controls over the next two decades, and a slightly lower level of controls by 2050 for road transport vehicles than the Yan et al. scenarios.

G. Removed Forcing Cases

The bounding scenarios that were not within the 1970-2000 forcing bound as discussed in the text are:

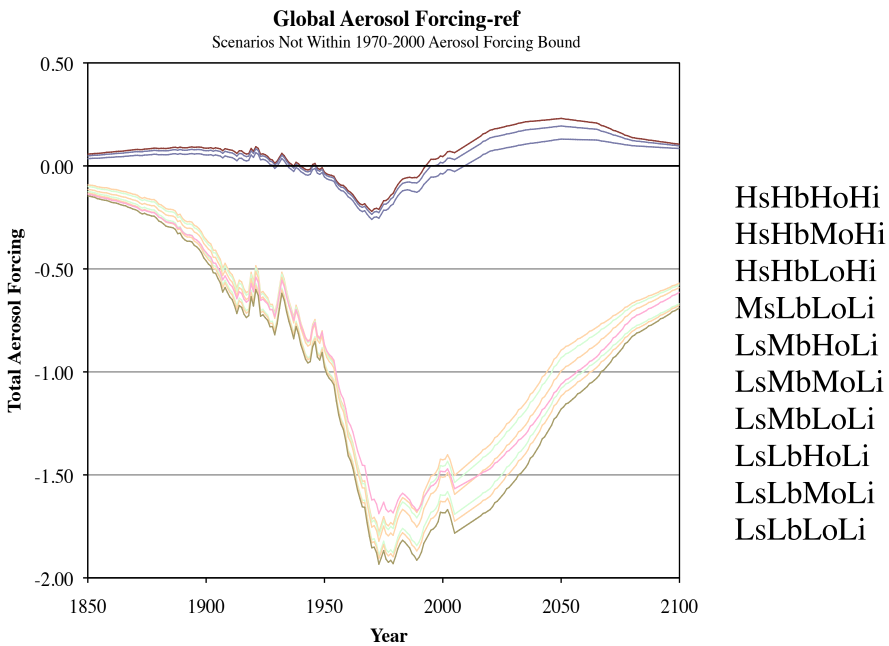


Figure S-10 – Scenarios removed from the analysis due to forcing that exceeds the estimated observational bound. The scenarios remove are listed at right. The upper-case H, M, L represent high, medium, or low forcing assumptions and the lower-case s, b, o, and i represent sulfate, black carbon, organic carbon, and cloud indirect forcings.

H. Forcing Relative To Well-Mixed Greenhouse Gases

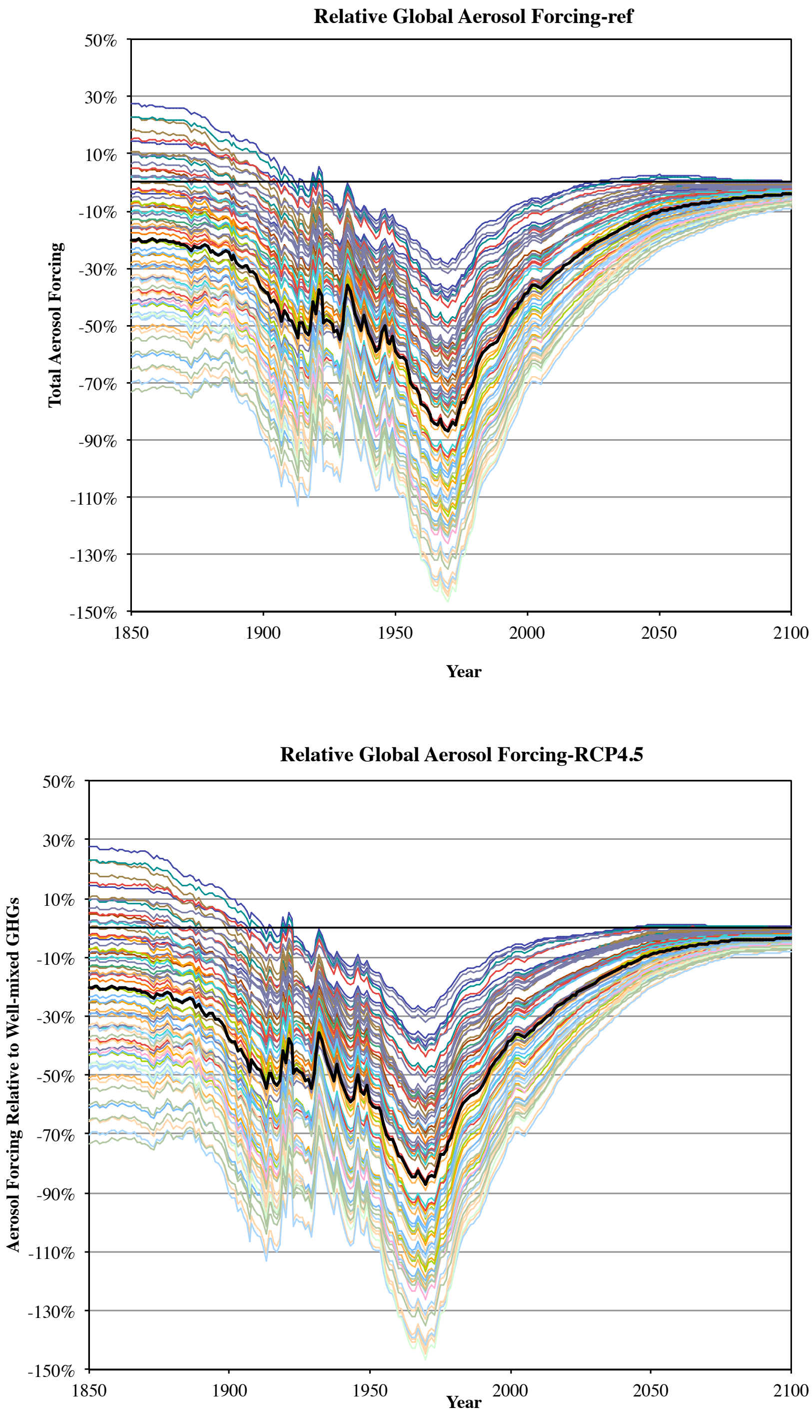


Figure S-11 Total aerosol forcing relative to that of greenhouse gases for the reference and RCP4.5 scenarios.

I. FORCING CHANGE DUE TO CLIMATE POLICY

Figure S-12 shows the change in aerosol forcing (RCP4.5 – reference) divided by the greenhouse gas forcing reduction. A positive value means that the net effect of the change in aerosols is a warming. Out of the 71 scenarios, 22 initially show a net cooling due to aerosol forcing changes (Table S-4), where decreases in BC emissions outweigh the impact of decreases in negative forcing from aerosols. This number decreases to 9 by 2050 and, by 2100, only three of the cases result in a net reduction in climate forcing.

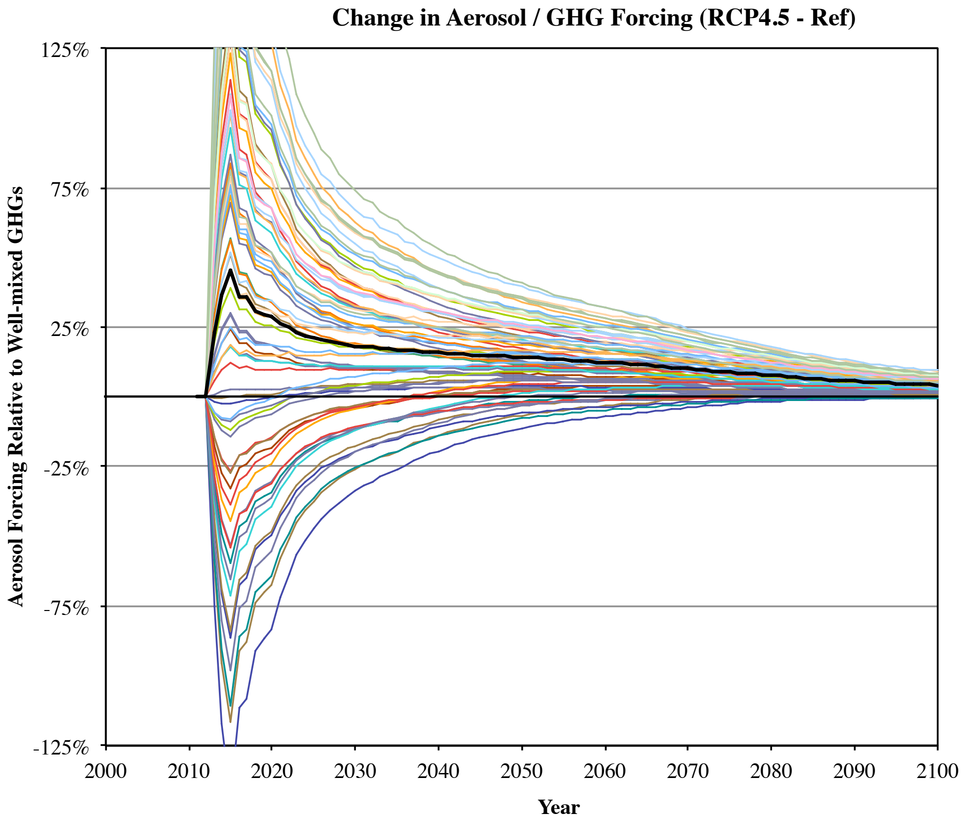


Figure S-12 Ratio of the change in aerosol forcing (as in Figures 4 and 5, main text) over the change in greenhouse gas forcing between the RCP4.5 and reference case scenario. A positive value indicates a net positive change in forcing in the RCP4.5 scenario (e.g., a net warming due to aerosols) as compared to the reference case scenario. The ratio is initially large because aerosol changes, although small, impact forcing immediately while changes in greenhouse gas emissions impact concentrations, and hence, forcing over a longer period.

Table S-4 – Number of scenarios with negative change in aerosol forcing.

Aerosol Forcing (RCP4.5 - Reference)										
	2015	2020	2030	2040	2050	2060	2070	2080	2090	2100
Number	22	21	16	11	9	8	6	5	3	3

J. Aerosol Forcing Relative To 1970-2000

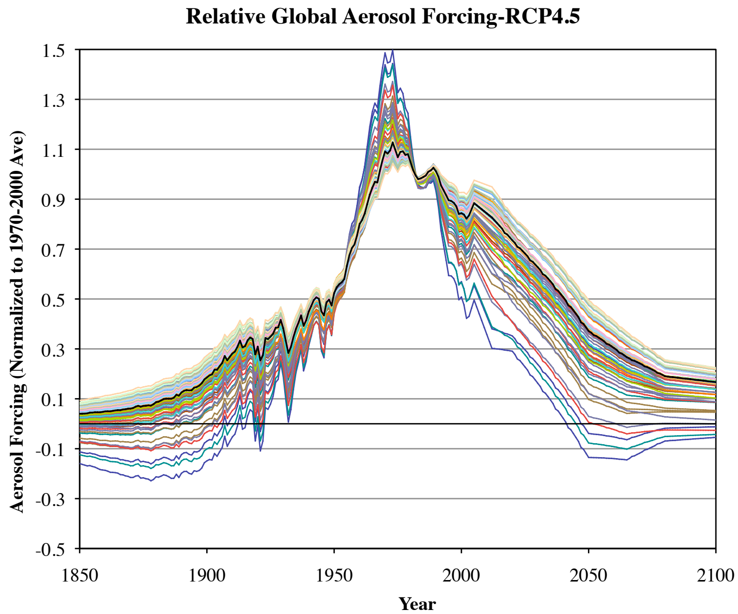


Figure S-13 – Total aerosol forcing (as in Figure 4, main text) relative to the 1970-2000 average for each case.

K. Supplemental References

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