

# The Social Cost of Atmospheric Release

*Drew T. Shindell*

*NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025 USA*

[drew.t.shindell@nasa.gov](mailto:drew.t.shindell@nasa.gov)

## ***Abstract***

I present a multi-impact economic valuation framework called the Social Cost of Atmospheric Release (SCAR) that extends the Social Cost of Carbon (SCC) used previously for carbon dioxide (CO<sub>2</sub>) to a broader range of pollutants and impacts. Values consistently incorporate health and agricultural impacts of air quality along with climate damages. The latter include damages associated with aerosol-induced hydrologic cycle changes that lead to net climate benefits when reducing cooling aerosols. Evaluating a 1% reduction in current global emissions, benefits with a high discount rate are greatest for reductions of sulfur dioxide (SO<sub>2</sub>), followed by co-emitted products of incomplete combustion (PIC) and then CO<sub>2</sub> and methane. With a low discount rate, benefits are greatest for CO<sub>2</sub> reductions, and those are nearly equal to the total from SO<sub>2</sub>, PIC and methane. These results suggest that efforts to mitigate atmosphere-related environmental damages should target a broad set of emissions including CO<sub>2</sub>, methane and aerosols. Illustrative calculations indicate environmental damages are \$160-620 billion yr<sup>-1</sup> for current US electricity generation (~7-24¢ per kWh for coal, ~2-14¢ for gas) and \$0.87±0.44 per gallon of gasoline (\$1.40±0.80 per gallon for diesel). These results suggest that total atmosphere-related environmental damages plus generation costs are greater for coal-fired power than other sources, and damages associated with gasoline vehicles exceed those for electric vehicles.

**Keywords:** environmental economics; valuation (Q51), air pollution (Q53), climate (Q54), government policy (Q58)

## ***Introduction***

Societal perception of environmental threats depends upon a variety of factors including physical science-based estimates of the risk of various impacts and economic valuation of those impacts. Quantitative estimates of costs and benefits associated with particular policy options can provide powerful evidence to inform responses, but such valuations face a myriad of issues, including the choice of which impacts to ‘internalize’ within the economic valuation, the value of future versus present risk, and how to compare different types of impacts on a common scale (e.g. [*Arrow et al.*, 2013; *European Commission*, 1995; *Johnson and Hope*, 2012; *Muller et al.*, 2011; *National Research Council*, 2010; *Nordhaus and Boyer*, 2000]).

To examine these issues, I explore here the economic damages associated with a marginal change in the release of individual pollutants to the atmosphere owing to their effects on climate and air quality. Prior studies have provided compelling demonstrations of the importance of linkages between climate change and air quality valuation (e.g. [*Caplan and Silva*, 2005; *Nemet et al.*, 2010; *Tollefsen et al.*, 2009]) and of the incorporation of economics into emission metrics (e.g. [*Johansson*, 2012; *Tanaka et al.*, 2013]), but have typically not fully represented the climate impact of short-lived emissions, especially aerosols and methane (e.g. [*International Monetary Fund*, 2013; *Muller et al.*, 2011; *National Research Council*, 2010]). As opposed to previous estimates of damages associated with particular activities (e.g. electricity generation [*European Commission*, 1995; *National Research Council*, 2010]), the general values presented here allow valuation of the impact of any sector or any policy scenario whose emissions are known. While many uncertainties remain in this type of analysis (see Discussion section), and hence caution is advised in using these values in policy decisions, this evaluation of a wide variety of pollutants nevertheless allows exploration of how society values human welfare at different timescales and in response to different environmental threats.

## ***General Approach***

This work builds upon the Social Cost of Carbon (SCC), a widely used methodology for valuation of the estimated damages associated with an incremental increase in carbon dioxide (CO<sub>2</sub>) emissions in a given year. The US Government Interagency Working

Group on SCC describes it as being “intended to include (but not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change.” ([*Interagency Working Group on Social Cost of Carbon*, 2010; 2013]; hereafter IWG2010 and IWG2013; see also Methods: Technical Details).

Thus social costs for emissions of other pollutants should at minimum include their impacts on these same quantities (health, agriculture, property damage, etc.). This applies even in the case where their effects take place via different processes than for CO<sub>2</sub> as it is the impact that is of concern rather than the process bringing it about. For example, pollutants such as black carbon (BC), sulfur dioxide (SO<sub>2</sub>) or methane (CH<sub>4</sub>), affect human health both by altering climate as CO<sub>2</sub> does (hereafter climate-health impacts) but also by more directly degrading air quality (hereafter composition-health impacts). Hence this work assesses impacts of atmospheric pollutants regardless of the route by which they occur, and it thus also builds upon prior valuation of air quality-related health impacts of emissions (e.g. [*Muller et al.*, 2011; *National Research Council*, 2010]). More broadly, the costs to society of emissions to the atmosphere should ideally include all components of environmental response.

Here I evaluate a broad Social Cost of Atmospheric Release (SCAR) for emissions of the pollutants that are the major drivers of global mean climate change, based on comprehensive international assessment of the effect of all factors controlling climate change [*Myhre et al.*, 2013], and of the global health burden from poor air quality, based on a similarly comprehensive assessment of the contribution of particulate matter and ozone to the global burden of disease [*Lim et al.*, 2013]. These pollutants are: CO<sub>2</sub>, CH<sub>4</sub>, carbon monoxide (CO), SO<sub>2</sub>, BC, organic carbon (OC), nitrous oxide (N<sub>2</sub>O) and the exemplar hydrofluorocarbon HFC-134a (Table 1). The composition-health impacts of nitrogen oxide (NO<sub>x</sub>) are also assessed, but impacts of NO<sub>x</sub> on climate are uncertain even as to their sign [*Myhre et al.*, 2013] and so are excluded. Valuation of the multiple health impacts of mercury emissions has been performed for the US (e.g. [*Rice and Hammitt*, 2005; *Swain et al.*, 2007]), so is discussed in the calculations of US sectoral impacts (see Illustrative Applications).

This analysis is primarily concerned with pollutants that have multiple impacts (e.g. health and climate). Ozone-depleting substances affect both climate and health, and could be examined under the SCAR framework (N<sub>2</sub>O is evaluated, and affects stratospheric ozone and hence skin cancer rates, but valuation of that chain of effects has not been performed and so is excluded here). Most of these substances are now controlled and decreasing, however [Myhre *et al.*, 2013]. They are being replaced by ozone-friendly hydrofluorocarbons (HFCs), which influence climate, and so I include the most important to date, the compound HFC-134a. A few other pollutants, including volatile organic compounds and ammonia, also fall squarely within the category of those affecting both air quality and climate but either not enough information is available at present or uncertainties are extremely large, so they are not included. Other emissions also influence health, such as persistent organic pollutants, although these have no effect on climate, but valuation is not readily available in the literature. Similarly, additional gases affect climate but not air quality, and could be added to the SCAR, but the ones included here are the most important for climate change and air pollution thus far.

Unlike the SCC, which has been evaluated for long-lived gases only, this analysis spans a wide range of pollutants, and thus the SCAR metric facilitates discussion of the relative importance of compounds with very different lifetimes. Those emissions with primarily a near-term influence (years to decades; aerosols, ozone precursors, methane and HFC-134a) and those with effects that are large over long-terms (centuries; long-lived greenhouse gases such as CO<sub>2</sub> and N<sub>2</sub>O) can be compared by contrasting their valuation at a particular discount rate. Comparison of the SCAR valuation across discount rates shows how those physical timescales interact with time-preferences for the value of money.

### ***Methods***

The primary components of the SCAR calculations are described here, with additional technical details provided in the “Methods: Technical Details” section at the end of the paper. The first component of the SCAR is damage associated with climate change that is proportional to global mean surface temperature change. Social costs are typically assessed in integrated assessment models (IAMs) using global mean surface

temperature change as a proxy for most damages (e.g. agriculture, health, flooding, ecosystems, etc.), though some costs such as agriculture and forestry can also depend upon CO<sub>2</sub> concentrations and damages associated with sea-level rise are sometimes calculated separately (e.g. [*Hope, 2013; Narita et al., 2010; Nordhaus, 2010; Nordhaus and Boyer, 2000*]). The IAMs contain relatively simple equations relating impacts to temperature changes, typically separated into several major economic sectors and world regions, but these are based on a large volume of primary studies that the IAMs attempt to aggregate into the best available representation of climate damages. The available data on climate impacts is quite limited for many sectors and/or regions, however.

Global mean temperature changes are driven by the global mean radiative forcing (RF) caused by each emitted compound. My RF calculations for long-lived gases are based on a set of simple models. The evolution of CO<sub>2</sub> is based on the four exponential decay timescales given in the IPCC AR4 [*Forster et al., 2007*]. Methane's evolution is calculated using the observationally-constrained perturbation timescale of 12.4 yr [*Prather et al., 2012*] and the equilibrium response per unit methane emissions change calculated with the GISS-PUCCINI model [*Shindell et al., 2009*] (equivalent to a 100yr global warming potential of ~32). RF due to CO<sub>2</sub> and methane is computed using the standard IPCC formulation [*Ramaswamy et al., 2001*]. Forcing by N<sub>2</sub>O and HFC-134a is calculated based on the lifetimes and integrated forcing reported in [*Hodnebrog et al., 2013*].

Radiative forcing due to short-lived species is based on a combination of modeling and literature analysis and includes indirect aerosol forcing [*Shindell et al., 2012a; Shindell et al., 2009; United Nations Environment Programme and World Meteorological Organization, 2011*] (hereafter UNEP/WMO, 2011). For context, the total industrial-era forcings attributed to aerosols are -0.72 W m<sup>-2</sup> for sulfate, -0.19 W m<sup>-2</sup> for OC, and +0.51 W m<sup>-2</sup> for BC. Forcing by non-CO<sub>2</sub> emissions includes a component driven by the response of the carbon-cycle to temperature changes induced by those emissions (as in the four timescales used for CO<sub>2</sub> itself) based on a reduced carbon uptake of 1 GtC per degree warming [*Arora et al., 2013; Collins et al., 2013*]. Temperature responses to forcings by each individual pollutant are calculated using the impulse-response function derived from the Hadley Centre climate model [*Boucher et al., 2009*] which has a climate

sensitivity of 3.75°C for doubled CO<sub>2</sub>, higher than the mean but well within the range in AR4 [Hegerl *et al.*, 2007].

Basic climate damages for all pollutants in the SCAR are then calculated from their impact on global mean temperature as in the SCC for CO<sub>2</sub>. The calculations presented here use a damage function based on that in the DICE IAM [Nordhaus and Boyer, 2000], which has damages proportional to the square of the temperature change and equal to 1.8% of world output at 2.5°C. For comparison, the most recent version of the PAGE IAM finds fairly similar results, with damages of just under 2% of world GDP at 3°C [Hope, 2013] and the DICE result lies well within the range of ~0.5-2.5% of world GDP for 2.5°C warming given in the IPCC AR4 [Yohe *et al.*, 2007] (or a similar range in [Stern, 2006]). The DICE damage function is based on regionally aggregated damages across major economic sectors, especially human health and amenities, agriculture, and forestry, and uses a willingness-to-pay approach to estimate what societies might spend as ‘insurance’ to avoid the climate-related damages. Damages are calculated as a function of temperature change, regional output per capita at present and at the time of the future temperature change, and the authors’ assessment of available data on the monetized impact of a particular amount of warming (and associated climate changes). The latter includes an enormous analysis of the literature, which cannot easily be summarized here for even a single IAM, but an example for the case of climate-health impacts is discussed further below.

In my calculations, valuation for non-CO<sub>2</sub> emissions is increased by 10% relative to CO<sub>2</sub> due to the lack of CO<sub>2</sub> fertilization effects on plants. Reference temperature change follows a business-as-usual trend with a projected increase starting at 0.015°C yr<sup>-1</sup> (as in recent observations) gradually increasing with time but then slowing to 0.008°C yr<sup>-1</sup> after the total increase exceeds 4°C and with a maximum tolerated warming of 4.5°C on the assumption of a substantial societal response to large changes. Reference temperatures are ~3.8°C greater than preindustrial in 2100, in accord with projections for the higher end emissions pathways in recent simulations [Forster *et al.*, 2013]. GDP increases at 2% yr<sup>-1</sup>, giving a 2100 value of \$355 trillion, consistent with that in IWG2010. Values are presented for 2010 emissions in 2007 \$US (as in IWG2013), and an uncertainty range of 50% is assigned to the climate damages (though the distribution is non-Gaussian with a

long tail at high values, and I reiterate that the 1.4% discount rate values are somewhat similar to the 95<sup>th</sup> percentile for the 3% discount rate; see Methods: Technical Details for additional uncertainty and sensitivity discussion).

The discount rate is an important choice in valuation of future damages. An interagency analysis by the US government gives 2010 SCC values using three different constant discount rates, 5, 3 and 2.5%, based on results from several IAMs examining multiple scenarios for emissions, population, GDP, etc. and a broad distribution for climate sensitivity (IWG2010; 2013). I use the same discount rates to facilitate comparison and as these reflect the view of multiple distinct parts of the US government about which values reflect plausible discount rate choices. I selected parameter values in the model to roughly match the average IWG2013 estimates for climate damages from CO<sub>2</sub> when using comparable climate-health impacts in order to calibrate the single SCAR model and scenario used here to the mean obtained across the sampling of model and scenario uncertainties in the IWG study. I also include analysis using a constant discount rate of 1.4%, approximately the value used in [*Stern, 2006*] (as discussed in, e.g., [*Weitzman, 2007*]). This low discount rate gives values for the SCC of CO<sub>2</sub> of about \$140/ton (with conventional climate-health impacts), consistent with the middle of the additional SCC range suggested as plausible in [*Johnson and Hope, 2012*] using similar methodology, though lower than [*Tol, 2008*] or [*Ackerman and Stanton, 2012*]. Note that the US government analysis also reports the 95% percentile value for the 3% discount rate and describes the use of that high-end value as important to account for the risk of higher than expected damages. The use here of the lower 1.4% discount rate in effect accomplishes roughly the same thing. Finally, several authors have argued for the use of a discount rate that declines over time as this better represents the mid-range of uncertainties at long time scales since those are dominated by the low end of the plausible range (e.g. [*Arrow et al., 2013*]). To examine the influence of a declining discount rate (DDR), I use a rate starting at 4% and decreasing exponentially with a 250 year time constant (i.e. the percentage rate is  $4 \cdot \exp(-t/250)$  where  $t$  is the time in years) which approximates the mean behavior seen in several prior studies [*Freeman et al., 2013*; *Groom et al., 2007*; *Newell and Pizer, 2003*]. Note that the framework employed here

does not directly include any economic response to environmental damages (though such responses were included in the DICE IAM used to derive the damage function).

The SCC includes damages driven by the effects of climate change on human health. Premature mortality and morbidity was associated with ~10-50% of total damages in the IAM studies summarized in [Nordhaus and Boyer, 2000]. The DICE model damage function used here includes climate-health impacts based on the 1996 Global Burden of Disease assessment of tropical disease burdens and some simple assumptions: (1) climate change affects health via tropical diseases only, and (2) climate change reduces projected reductions in tropical diseases by half, or the response can be estimated using the regression between current tropical disease burdens and mean regional temperatures [Nordhaus and Boyer, 2000]. These assumptions are clearly quite simplistic (e.g. impacts via malnutrition or heatwaves are ignored), and serve as a reminder of how the data that the IAM creators rely on to define regional and sectoral damage functions is often quite limited or unavailable. Recent estimates of climate-health impacts by the World Health Organization (WHO) [Campbell-Lendrum and Woodruff, 2007] find large impacts, however, with 150,000 premature deaths attributed to the current warming (~0.8°C). I thus perform an additional set of climate-health valuation calculations using this estimate, assuming these effects are also proportional to the temperature change squared. Both the magnitude and long-term trend of climate-health impacts clearly merit further study, however.

A consistent valuation methodology is used for climate-health and composition-health impact calculations. Both changes in population and baseline mortality affect the health-related damages, especially for climate-health (they have less impact on composition-health impacts as those are almost all very near term). I assume that population grows by 0.4% yr<sup>-1</sup>, leading to a worldwide population of 9 billion in 2100, and that baseline mortality decreases by 0.9% yr<sup>-1</sup> based on the hypothesis that human health is so paramount to society that continued public health efforts would lead to a net reduction in vulnerability with time.

All health calculations use a current Value of a Statistical Life (VSL) of \$1.7 million, which is the nominal US-based VSL of \$7.5 million adjusted to account for country-specific income differences and the relative magnitude of carbonaceous aerosols and

population density in various regions based on prior study [UNEP/WMO, 2011]. Thus this analysis implicitly assumes that the occurrence of climate-health damages, like composition-health damages, is weighted towards areas with high current carbonaceous aerosols, consistent with the general pattern of baseline mortality and susceptibility to climate-health impacts (such as malnutrition and tropical disease spread) being greater in developing nations where carbonaceous emissions are currently high. The prior work used an elasticity of 0.40 between the per capita income in each country and the ‘willingness-to-pay’ and examined the effects of emissions changes on 210 countries using country specific incomes and pollutant levels. Note that health literature often uses disability adjusted life years, which are arguably more informative since they incorporate the age of the affected individuals, but VSL is a better established metric in the economics literature (e.g [Viscusi and Aldy, 2003]). The VSL increases along with the per capita growth in GDP ( $1.6\% \text{ yr}^{-1}$ ) since it is associated with the willingness-to-pay.

In addition to the climate damages associated with global mean temperature change, I include impacts stemming from regional disruption of the hydrologic cycle due to aerosols. Multiple climate modeling studies have shown that both scattering and absorbing aerosols induce strong regional hydrologic cycle changes (e.g. [Levy *et al.*, 2013; Ramanathan and Carmichael, 2008; Wang *et al.*, 2009]), and that there is typically a substantially greater precipitation response per unit RF than for long-lived greenhouse gases (LLGHGs) [Shindell *et al.*, 2012a; Shindell *et al.*, 2012b]. I assume all precipitation changes lead to net damages as they cause shifts relative to traditional patterns to which human systems are aligned. These shifts can also alter the intensity distribution (e.g. wet areas getting wetter and dry areas drier (e.g. [Held and Soden, 2006])), potentially leading to more extremes either directly [Portmann *et al.*, 2009] or indirectly via teleconnections [Kenyon and Hegerl, 2010], which would again lead to damages even in cases where changes in mean precipitation could be beneficial. Hence I assign damages to both scattering aerosols and absorbing BC even though the sign of their impact is sometimes opposite. It is difficult to estimate precisely how much of the climate-related damages are due to precipitation changes. Even for a particular impact such as human health, temperature and precipitation both play important roles by influencing malnutrition, vector borne diseases, etc [Campbell-Lendrum and Woodruff, 2007]. I

attribute 50% of the climate-related damages to precipitation changes, and increase these by a factor of 4.2 for aerosols based on the mean ratio in the prior modeling (see Technical Details).

Damages attributable to atmospheric composition changes are based upon prior modeling of the response of surface pollutants to emissions. Adverse health impacts of PM<sub>2.5</sub> (particulate matter with a diameter less than 2.5 microns) are attributed using the total current outdoor PM<sub>2.5</sub> impact on human health (3.2 million premature deaths annually [Lim *et al.*, 2013]) and total current emissions, with the fractional contribution of each individual aerosol type given by the fractional contribution of each to surface PM<sub>2.5</sub> [UNEP/WMO, 2011]. Total valuation is again based on country-specific VSLs for globally distributed carbonaceous aerosols as in [Shindell *et al.*, 2012a], with VSL again increasing along with per capita GDP. Using results based on the impact of all current emissions gives air quality damages that are representative of the global mean impact, but values would differ for particular locations.

The impacts are based on population aged 25 and older for most health effects, as in the epidemiological literature (e.g. [Cohen *et al.*, 2004]), which is a potential source of low bias. Values might, however, be biased high for marginal changes as the concentration-response function (CRF) may saturate at very high exposure levels (which was not assumed to happen in the prior work underlying these results). Hence there are potential biases in either direction in these results. Similarly for ozone, only premature death associated with respiratory disease related to long-term exposure is included [Smith *et al.*, 2009]. Despite the possibility of biases in these analyses, the assumed uncertainty in the CRF is very large, so that the overall uncertainty (~80%; including differences in the modeled concentration response to emissions changes [UNEP/WMO, 2011]) is dominated by the CRF and likely encompasses most of the potential biases discussed here. Note that impacts on indoor health have not been included here, as these depend strongly on the exposure pattern and are thus not well-suited to generalized emission metrics, but these may be quite large [Lim *et al.*, 2013] and have consequently large valuation [Mehta and Shahpar, 2004].

Impacts of methane on human health (via ozone) are drawn from results of two global composition-climate models [Shindell *et al.*, 2012a]. Impacts again use country-

specific VSL based on the \$ per ton reported previously, adjusted to current population and VSL and accounting for the time-dependence of the ozone response to methane emissions (hence these impacts are affected by the choice of discount rate).

Impacts of methane on agriculture via the induced change in surface ozone are also included. These are again based upon prior valuation using results from two global composition-climate models and incorporating the impact of ozone on four staple crops: wheat, maize, soy and rice [*Shindell et al.*, 2012a].

### **Results**

Valuation of climate damages is highly sensitive to discounting, reflecting the relative value of money over time, and estimated climate-health impacts. The basic climate damages attributable to CO<sub>2</sub> (equivalent to the traditional SCC) are 11-140 \$/ton using constant discounting rates of 5 to 1.4% and conventional climate-health impacts from IAM estimates (Table 2).

SCAR values for CO<sub>2</sub> increase to 27-277 \$/ton using the larger health impacts of climate change based upon the recent estimates of the WHO [*Campbell-Lendrum and Woodruff*, 2007]. In fact, this valuation of the climate-health impact alone gives values that are comparable to the total climate valuation following the traditional SCC methods (Table 2). Note that the climate damages alone are consistent with those in many prior studies (e.g. IWG2013), with the values including the updated climate-health damages more consistent with the higher range in the literature [*Ackerman and Stanton*, 2012; *Johnson and Hope*, 2012; *Kopp et al.*, 2012] (though these do not necessarily find higher values for the same reasons). As the new WHO-based climate-health impacts rely on a single study, of course with its own limitations, while the underlying information on climate-health impacts used in the IAMs is also quite limited, I use half the new WHO-based impacts for the mean additional climate-health valuation (added to the basic climate damages in the SCAR) with an uncertainty also equal to half the WHO-based climate-health impacts as this provides a best estimate that encompasses the IAM-based impacts at the low end and the full WHO-based values at the high end. All other climate-related impacts are assumed to have an uncertainty of 50%. The climate-related uncertainties are assumed to be entirely systematic (though not all of it in fact is), and the

resulting total climate-related uncertainty spans the bulk of published damage estimates for a particular temperature increase [Yohe *et al.*, 2007].

SCAR valuation for long-lived N<sub>2</sub>O is much larger than for CO<sub>2</sub> due to its far greater radiative efficiency, but shows broadly similar sensitivity to the choice of discount rate (Table 2). In contrast, valuation for the shorter-lived pollutants is much less sensitive to the choice of discounting rate, especially for the aerosols. This is in part because the contribution of their composition-health impacts, which are unaffected by discounting, tends to dominate their valuation even though the regional hydrologic cycle response makes the net climate damages of even cooling aerosols positive (see also Methods: Technical Details section). The use of a DDR produces values generally similar to the constant 3% case with the decline rate used here (Table 2). Regardless of the discounting, the relative SCAR valuation per ton is much larger for methane and the aerosols or aerosol precursor species BC, SO<sub>2</sub> and OC than for CO<sub>2</sub>, with a ton of methane causing ~25-85 times more damage than a ton of CO<sub>2</sub> and a ton of the aerosols causing up to ~5000 times more damage. The larger valuation on a per ton basis stems primarily from the greater radiative efficiency per molecule of non-CO<sub>2</sub> compounds relative to CO<sub>2</sub> and the additional composition-health impacts. For comparison, the valuation of the composition-health impacts of NO<sub>x</sub> emissions is \$2600 ton<sup>-1</sup> N.

Uncertainties in the valuation are often systematic across pollutants, so do not affect their relative importance. For example, the bulk of the uncertainty in damages associated with emissions of SO<sub>2</sub> and OC comes from the 80% range in the effect of particulate matter on human health, and hence the relative importance of these pollutants is robust despite the large range for each. Similarly, the largest contributor to uncertainties in the valuation of CO<sub>2</sub>, CH<sub>4</sub>, BC, CO, N<sub>2</sub>O and HFC-134a comes from the estimate of basic climate plus additional climate-health impacts, which is systematic across these pollutants. Uncertainty in the regional aerosol impacts is obviously not systematic across all pollutants (as it does not apply to non-aerosols). These lead to a substantial fraction of the total aerosol valuation, especially at low discount rates.

The ratios of the SCAR values for CH<sub>4</sub> and N<sub>2</sub>O to CO<sub>2</sub> using 5% discounting are 51 and 302, respectively, with only the traditional IAM-based climate-health impact and no additional composition-health impact for methane (or 44 and 267 without the carbon-

cycle response to non-CO<sub>2</sub> emissions). These are fairly similar to the values of 39 and 372 for the social costs calculated by [Marten and Newbold, 2012] using comparable assumptions (earlier work, summarized in [Marten and Newbold, 2012], used older, incompatible assumptions). Differences may arise from the use of different carbon-cycle models, atmospheric lifetimes and radiative efficiencies. Inclusion of the additional effects considered here, however, brings the ratio to 83 for methane while leaving the ratio at 295 for N<sub>2</sub>O. The ratio increases for methane in part due to use of the higher estimated climate-health impact along with a slow decrease in baseline health vulnerability, as that effect is weighted towards the near-term for methane relative to N<sub>2</sub>O or CO<sub>2</sub> due to the shorter methane lifetime. Note that for methane, the climate-health and composition-health impacts are more similar in magnitude than for any other pollutant. Interestingly, the ratio decreases from 83 to 24 for methane going from 5% to 1.4% discounting, similar to the change in the widely used global warming potential (GWP) emission metric for methane going from a time horizon of 20 to 100 years (consistent with similarities between methane's GWP and global damages noted previously [Boucher, 2012]). The ratio for N<sub>2</sub>O is also always similar to its 20- or 100-year GWPs of ~265. SCAR values are not closely related to GWPs for other species, however.

Another useful perspective can be gained by incorporating the relative magnitude of emissions of each compound as these vary enormously. I present the valuation of 1% of current global anthropogenic emissions (2010 values from [Thomson *et al.*, 2011], open biomass burning emissions are not included), a level small enough that it can still be considered a marginal change (Figure 1). With a high (5%) discounting rate, placing a greater weight on near-term impacts, the valuation of 1% of current SO<sub>2</sub> emissions is much larger than the valuation of any other pollutant. Carbon dioxide is valued at about 30% of the value of SO<sub>2</sub>, and 50% of the sum of products of incomplete combustion (PIC; OC, BC and CO) that are usually co-emitted. Towards the other end of the discounting rate spectrum, a rate of 1.4% leads to a larger impact at long timescales, enhancing the valuation of CO<sub>2</sub> more than ten-fold and increasing the valuation of methane, BC and CO by factors of two to four while having less impact on reflective aerosols. Valuation of CO<sub>2</sub> is by far the greatest with 1.4% discounting, followed by PIC,

SO<sub>2</sub>, and methane (Figure 1). Valuation of HFC-134a is always relatively small despite it having the highest per ton valuation (Table 3) due to the small amount currently emitted.

Of course the relative ease of reducing emissions is not equivalent across pollutants. The SCAR metric provides a simple way to compare the impacts of aggregate reductions once achievable values have been estimated, however. For example, the valuation of reducing products of incomplete combustion by only ~5% would be comparable to that of reducing CO<sub>2</sub> by 10% with a near-term focus (5% discounting), while reductions would have to be ~25% to be as valuable as CO<sub>2</sub> reductions of 10% using a long-term perspective (1.4% discounting). Similarly, reducing CH<sub>4</sub> emissions by ~13% provides as much benefit as reducing CO<sub>2</sub> emissions by 10% with a near-term perspective, while reductions need to be 47% with a long-term view.

### ***Illustrative Applications***

The SCAR can be used to explore the societal impacts of emissions attributable to particular activities and locations by simply multiplying the SCAR valuation by the associated emissions. For example, valuation of environmental damages due to US emissions from electricity generation and transportation, obtained by multiplying the SCAR by emissions attributed to those sectors [*US EPA*, 2012; 2013a; b], are very large (Table 4). These damages, by virtue of their not being internalized within the economic system, are effectively subsidies [*International Monetary Fund*, 2013], and regardless of the discount rate, for electricity generation these dwarf the direct US government subsidies (primarily via tax expenditures and research and development credits) which were \$1.4 billion for coal and \$2.8 billion for natural gas in 2010 [*Energy Information Administration*, 2011]. These damages are comparable to or even exceed the total value added to the economy from these sectors, which are \$184 billion (electricity generation) and \$232 billion (transportation) [*Muller et al.*, 2011]. Note that much of the uncertainty is systematic across sectors, so despite large ranges, differences can be significant (e.g. valuation of coal-related damages is \$160±80 billion greater than gas at 3% discounting; uncertainty comes solely from the SCAR as uncertainty in emissions is assumed to be much smaller).

Additional damages due to atmospheric emissions of mercury have been assessed for the US [*Rice and Hammitt, 2005; Swain et al., 2007*]. Based on the valuation per ton attributable to all health impacts (IQ reduction, cardiovascular effects and premature mortality) [*Rice and Hammitt, 2005*], adjusted to account for the later and hence larger VSL used here, and the 2008 US emissions of 29.5 tons from coal-fired power and 9.2 tons from industry [*US EPA, 2013a*], mercury emissions lead to human health damages of \$5.4 and \$1.7 billion for coal-fired power and industry, respectively. Hence these contributions are not insignificant, but are relatively small compared to the estimated environmental damages associated with other emissions.

Within the transportation sector, the environmental damages per unit of fuel consumption are  $\$0.87 \pm 0.44$  per gallon of gasoline using a 3% discount rate, much larger than the current federal tax of \$0.184 per gallon and roughly 75% greater than the typical combined local, state and federal gasoline tax. Damages are substantially larger for diesel fuel,  $\$1.40 \pm 0.80$  per gallon, owing to the greater BC emissions from diesel engines.

Unsurprisingly, the SCAR-based values are generally larger than prior estimates of environmental damages by sector. I also calculate a “limited-SCAR” including only those impacts included in previous studies: composition-health impacts of all pollutants, but climate impacts for CO<sub>2</sub> only and based on IAM climate-health effects (Table 4). The limited-SCAR values are typically comparable to prior estimates when using a similar discount rate (3%) and taking into account that the latest estimates of the health effects of ambient air pollution are much greater than the previous Global Burden of Disease values (3.2 million premature deaths annually due to outdoor PM<sub>2.5</sub> in the 2010 Burden [*Lim et al., 2013*] versus 800,000 in the 2000 version that included urban PM<sub>2.5</sub> only [*Cohen et al., 2004*]). For example, previous estimates of environmental damages due to emissions from US coal-burning power plants with a limited-SCAR-like method reported values of \$95 billion ([*International Monetary Fund, 2013*]; using composition-health valuation from [*National Research Council, 2010*]) and \$53 billion [*Muller et al., 2011*]. These are comparable to the limited-SCAR valuation of  $\$140 \pm 80$  billion (using the comparable IWG2010 SCC for CO<sub>2</sub>), as the limited-SCAR is reduced to ~\$100 billion using older composition-health estimates. Likewise for the US transportation sector, valuation for composition-health only of ~\$23 billion is reported by [*International Monetary Fund,*

2013], while the SCAR composition-health component is ~\$20 billion using the older estimates. Another study [Muller *et al.*, 2011] reported a limited-SCAR-like valuation of \$23 billion for transportation, while the limited-SCAR gives ~\$57 billion (using IWG2010 SCC and older health estimates).

In general, the values found here are larger than those of [Muller *et al.*, 2011] and very similar to those of [International Monetary Fund, 2013] using the same subset of impacts. The full SCAR-based valuations are substantially larger, as a result of including the additional climate-health impacts (by using the mean of IAM- and WHO-based values) and including the climate impacts of non-CO<sub>2</sub> emissions. The latter can be quite important, with methane's effect on climate contributing 29% of the SCAR valuation of gas-related electricity generation damages (using 3% discount rate), for example. The shares of damages from CO<sub>2</sub> are 48%, 46% and 62%, for the electricity, transportation and industrial combustion sectors, respectively, for the SCAR-based analysis of current US emissions with 3% discounting.

The flexibility of the SCAR, as a general emission metric, readily allows comparison of the environmental damages associated with different fuel types or technology choices as well. I present two examples here, for power generation and vehicles. Mean US damages related to atmospheric releases for power generation are calculated on a per kWh basis by multiplying the SCAR by the emissions associated with a given fuel type [US EPA, 2012; 2013a; b], then dividing by the kWh generated using that fuel type. Environmental damages from the US average coal-fired power plant are  $6.7 \pm 3.6\text{¢}$ ,  $10 \pm 5\text{¢}$ , and  $24 \pm 13\text{¢}$  per kWh with 5, 3 and 1.4% discounting, respectively. Comparable values for gas-fired plants are  $2.5 \pm 1.2\text{¢}$ ,  $5.0 \pm 2.7\text{¢}$ ,  $14 \pm 8\text{¢}$ . Total damages from coal are greater than from gas regardless of the discount rate, as the uncertainties are partially systematic and so differences are significant despite the large ranges (e.g. damages from coal are  $5.1 \pm 3.0\text{¢}$  per kWh greater than from gas for 3% discounting). There is substantial variation across coal-fired power plants, however, with damages typically greater for older plants and less for newer ones. A coal plant with air-quality related emissions at the 5<sup>th</sup> lowest percentile (about 5% of the average) would have damages close to those for gas (~4-5¢ per kWh for either; 3% discounting) while one at the 95<sup>th</sup> percentile (emissions about 360% of the average) would have far greater damages (~21¢ per kWh;

3% discounting) based on emissions in [*National Research Council, 2010*]. Damages from mercury emissions are less than 1¢ per kWh, so are not included here.

Similarly, one can easily compute how much methane releases would have to be from the gas sub-sector (e.g. due to greater leakage associated with unconventional extraction) to produce damages as large as those from coal. Using a discount rate of 1.4%, fugitive (leaked) methane emissions from natural gas systems would have to be 4.8% for the average gas-fired power plant to produce damages as large as the average coal-fired power plant on a per kWh basis, while with a high discount rate of 5% emissions would need to be 6.1%. The value increases with the near-term focus inherent in the high discount rate due to the very large damages associated with SO<sub>2</sub> emissions. In comparison with coal plants with ultra-efficient flue gas scrubbers (i.e. assuming no SO<sub>2</sub> or NO<sub>x</sub> emissions), the leak rate for the natural gas sector has to be only 2.9%, 1.6% or 0.8% for 1.4, 3 and 5% discounting, respectively, to match the damages from coal (for the aforementioned plant at the 5<sup>th</sup> percentile of current air quality emissions, the respective values are 3.0%, 1.7% and 1.1%). Hence in this latter comparison, which primarily compares the effect of the CO<sub>2</sub> and CH<sub>4</sub> emitted by these two sectors (and hence the leak rate threshold decreases with a nearer-term perspective), even very small leak rates would make natural gas as environmentally damaging as coal. Current estimates of methane leakage associated with natural gas extraction, transport and storage have substantial uncertainties, with some estimates yielding lower methane emissions than the 1.4% used in current EPA inventories (e.g. [*Cathles et al., 2012*]), and seeming to be supported by measurements at many surface locations ([*Allen et al., 2013*]; though note that these measurements were only taken where industry permitted access), while other estimates are much larger (e.g. [*Howarth et al., 2011*]) and seem to be supported by at least some atmospheric measurements ([*Karion et al., 2013*; *Miller et al., 2013*]). Hence these gas versus coal tradeoffs merit further consideration as better emission data becomes available.

The total levelized energy costs for new capacity in a recent US government estimate [*Energy Information Administration, 2012*] are about equal for conventional coal and nuclear or renewables, with conventional combined cycle gas costing substantially less (Figure 2). Including atmospheric environmental damages, however, coal-fired power is

substantially more expensive than nuclear or renewables, while gas becomes comparable to nuclear or solar but more expensive than wind (Figure 2). Estimated generation costs for advanced fossil-fuel with carbon capture and sequestration are similar to the totals from conventional fossil-fuel plus environmental damages found here. The SCAR can also be used to assess variations between nations. For example, the environmental damages for the mean coal-fired power plant in China are valued at  $15 \pm 9\text{¢}$  per kWh with 5% discounting and  $38 \pm 18\text{¢}$  per kWh with 1.4% discounting, ~160-230% more than the mean for US coal-fired power plants due to the greater levels of non-CO<sub>2</sub> pollutants.

For vehicles, emissions from a typical midsize US gasoline powered vehicle (26 miles gallon<sup>-1</sup>, 12000 miles yr<sup>-1</sup>) lead to environmental damages valued at \$400 yr<sup>-1</sup> using the SCAR with 3% discounting. In comparison, analogous damages associated with the generation of electricity to power a midsize electric vehicle (EV; 2013 Nissan Leaf, 0.29 kWh mile<sup>-1</sup> (fueleconomy.gov)) are \$350 yr<sup>-1</sup> for electricity from coal, \$180 yr<sup>-1</sup> for electricity from natural gas and miniscule for nuclear or renewables. Hence environmental damages are only slightly reduced if an EV is powered from coal-fired electricity, while they are substantially lower for other electricity sources or for the mean US electricity mix. Clearly, a switch to less polluting electricity combined with vehicle electrification would be needed to greatly reduce the large environmental damages associated with emissions from transportation.

Finally, valuation of the total anthropogenic emissions of the compounds examined here is \$7.3 trillion using 3% discounting. Thus the effective subsidy of environmental damages attributable to these emissions is more than an order of magnitude larger than the worldwide pre-tax subsidy of \$480 billion for electricity and fossil fuels [International Monetary Fund, 2013]. Damages attributable to SO<sub>2</sub> and CO<sub>2</sub> total \$4.2 trillion, consistent with values calculated by the International Monetary Fund [International Monetary Fund, 2013] based largely on the impact of these two pollutants (\$1.9 trillion) once the higher SCC for CO<sub>2</sub> and the newer health impacts used here are accounted for. The increase when other components are included is dominated by the impact of methane (\$0.8 trillion) and PIC (\$1.8 trillion).

## ***Discussion***

Society's will to mitigate emissions is influenced by the costs as well as the benefits. Prior analyses have suggested the potential to achieve large reductions in emissions of all the compounds examined here at relatively low cost [Enkvist *et al.*, 2007; Rypdal *et al.*, 2009; Shindell *et al.*, 2012a; UNEP, 2011]. Including the larger SCAR valuation would make the economics even more favorable from the perspective of a social planner considering broad societal costs. Market barriers are important, however, and the common 'split incentives' mismatch between those incurring costs and those accruing benefits can be particularly important for planet-wide benefits such as reduced climate damages.

Furthermore, there are multiple benefits for which valuation methodologies have not yet been as thoroughly developed and hence which have not been taken into account in this analysis. For example, I include only valuation of premature deaths from outdoor PM<sub>2.5</sub> and ozone exposure, while there are also chronic physical health issues, and studies have demonstrated that exposure to PM<sub>2.5</sub> contributes to cognitive decline in older people [Weuve *et al.*, 2012] and to decreases in memory and IQ in children [Calderon-Garciduenas *et al.*, 2011; Suglia *et al.*, 2008]. Exposure to air pollution has also been shown to contribute to anxiety and depression [Marques and Lima, 2011], with attendant economic impacts. Effects of indoor air pollution are also neglected, though these are important especially for household solid fuel use [Lim *et al.*, 2013]. Beyond health, additional impacts of emissions such as ocean acidification, biodiversity loss, ecosystem impacts of nitrogen deposition, and changes in visibility are not included in the valuation, suggesting that these damages are conservative and that there are ample opportunities to further improve the comprehensiveness of social cost metrics. Societal decisions will also be influenced by effects other than atmospheric release, such as impacts on fresh water, waste products (e.g. coal ash ponds, spent nuclear fuel) and national or energy security (e.g. reliance on imported fossil fuels, nuclear proliferation), which are not readily incorporated into an emission metric but can be studied with broader life-cycle analyses.

While valuation allows the various impacts of long-lived and short-lived species to be placed on a common scale, and the choice of discount rate allows one to weight the relative importance of the very different timescales on which these pollutant classes

operate, the SCAR does not fully account for the different geographical distribution of impacts caused by long- versus short-lived pollutants. In particular, the impacts of short-lived pollutants will be localized more closely to the region where emissions changes take place, especially for composition-health. Not only would this lead to differences between valuation across nations, but even within small areas (e.g. urban versus rural) based on population density, country-specific income and local physical conditions affecting the lifetime of compounds in the atmosphere. In addition, even the global mean climate impact for short-lived species depends somewhat on the location of emissions, with, for example, greater impact from BC emitted near snow and ice covered regions. Prior analyses using global climate metrics suggest that global impacts typically vary by a factor of up to 3 for emissions from different regions (e.g. [Fuglestedt *et al.*, 2010]), less than the effect of the choice of discount rate on valuation of climate damages. Composition-health impacts would depend more strongly on emission location, but are less sensitive to the choice of discount rate. Hence the values given here, being averages from worldwide changes in emissions, provide only a rough guide to the impacts due to emissions changes for any particular location. For example, the damages associated with US gasoline vehicles might be considerably higher taking into account that most are operated in areas with high population density. Hence accounting for emission location could increase the ratio of gasoline to EV damages further. Thus further analysis could explore the effect of including regional variation in the SCAR based on the emission location, though given the desire for metrics to be transparent as well as comprehensive it may in the end be better to maintain a single globally representative value.

The SCAR, like the SCC, values benefits worldwide. For CO<sub>2</sub>, N<sub>2</sub>O or methane, emissions from any location have the same effect, so one could argue that although damages occur globally from local emissions, there is a need to account for the global damages since local damages also result from the emissions of others. Adopting a purely local perspective in which only local damages from local emissions are accounted for would greatly increase the relative valuation of short-lived versus long-lived compounds, but seems unlikely to lead to appropriate valuation for the globally-influential long-lived pollutants.

Finally, it is interesting to note that the interplay between the rather uncertain damage function and the discounting rate depends on the timescale over which impacts take place. This timescale varies greatly across the pollutants examined here according to their atmospheric residence time (Figure 3). For CO<sub>2</sub>, if damages have a weaker dependence on temperature change than assumed here (e.g. linear instead of the square of the temperature change; maintaining the same valuation at 2.5°C), valuation would be greater for high discounting rates and less for low rates and overall less sensitive to the discounting rate. Conversely, if damages accelerate more rapidly as temperature changes increase, perhaps as catastrophic shifts take place at high temperature changes, valuations would be even more sensitive to the choice of discount rate. For a short-lived forcing agent such as methane or aerosols, a weaker damage function (e.g. linear in temperature change; maintaining the same valuation at 2.5°C) again would lead to a reduced sensitivity to changes in the discount rate, but with most of the impacts felt at short timescales the weaker damage function with the same 2.5°C damages would increase the valuation at all discount rates examined here (by a factor of 50-500%). A substantial part of the methane and aerosol valuation is from climate-health effects with short timescales, which is part of the reason that their valuation is more sensitive to this hypothetical change in assumptions, and grows more slowly with decreasing discount rate than CO<sub>2</sub>. This example is illustrative of the sensitivity of the long- versus short-lived comparison to the damage function, but it may be that no IAM would produce damages of 1.8% of GDP at 2.5°C using a damage function linear in temperature.

### ***Conclusion***

Although much further work is required to fully characterize benefits and compare with costs, this extension of SCC-type analyses to encompass a broader range of pollutants and impacts facilitates examination of how society values different impacts occurring over different timescales. When near-term impacts are deemed most important, as reflected in the use of a high discounting rate of ~5% comparable to those used in current investment decisions, the results indicate that society can reap the greatest benefits by targeting emissions reductions at sulfur dioxide and PIC. This reflects the large impact of PM<sub>2.5</sub> on near-term human health via air quality and the substantial

impact of BC on climate. If instead longer-term impacts are given more weight, as reflected in use of a low discounting rate that arguably better captures multi-generational impacts, reductions of carbon dioxide provide the greatest benefit, but the sum of benefits from reductions of SO<sub>2</sub>, PIC and methane is roughly equal to that from CO<sub>2</sub> reductions.

The large impacts of aerosols and methane, especially at high discount rates, reflect the high values placed upon human lives by society. They appear to capture the reality that near-term health impacts seem to typically be considered more important to citizens than longer-term impacts of any sort, consistent with the vastly greater sums spent on medical care and research than on long-term environmental protection, and within the realm of air quality consistent with a societal emphasis on SO<sub>2</sub> reductions. Such a strategy has been fairly well aligned with the optimal path suggested by this analysis given a preference for avoiding near-term impacts. However, even with such a preference, greater efforts to reduce PIC and methane emissions appear warranted due to their large impacts. To avoid longer-term damages, society clearly will have to greatly reduce CO<sub>2</sub> emissions given their dominance in total emission valuation at low discount rates. A narrow focus on CO<sub>2</sub> alone or even on the Kyoto gases would neglect pollutants contributing approximately one-third of environmental damages even at low discount rates, however. Hence these results suggest that irrespective of time preference, society should pursue a multi-pollutant emissions reduction strategy that includes multiple greenhouse gases and aerosols in order to obtain maximum socioeconomic benefits. Use of the SCAR metric, as in the illustrative applications presented here, can help society determine the optimal pathways to achieve such reductions.

***Acknowledgements.*** This work does not represent the official views of the US Government or NASA, and was performed on the author's own time. The author's affiliation is given for identification purposes only.

## ***Methods: Technical Details***

### ***SCAR methodology and context with the SCC***

SCC results are based on IAMs that estimate damages to agriculture, human health, coastal areas (due to sea-level rise), outdoor recreation, forestry, water, energy, human settlements, and ecosystems in a warming climate. These damages are generally based on global mean temperatures, and either scale with roughly the square of temperature change (typical powers range from 1 to 3) or depend upon both the magnitude and rate of temperature change. The IAMs also include some estimate for the occurrence of ‘catastrophic’ changes. Impacts such as biodiversity loss and ocean acidification are not accounted for in these models. Human health impacts may include changes in vector-borne diseases such as malaria and dengue, as well as responses to changes in air quality due to climate change, the sum of which is referred to here as climate-health impacts (as distinct from composition-health impacts).

IPCC AR4 WGII [Yohe *et al.*, 2007] indicates the impact affecting the largest number of people by far is exposure to increases in water resources stress, followed by increased risk of hunger (especially when CO<sub>2</sub> fertilization is not included, as would be the case for warming induced by non-CO<sub>2</sub> forcing) and lastly increased risk of coastal flooding. Hence a large portion of impacts may be related more closely to regional changes in precipitation (directly affecting water and food) than global mean temperature (affecting sea-level rise due to thermal expansion, as well as more indirectly health and food). A recent review paper on agriculture and climate suggests that changes in both temperature and precipitation means and extremes, as well as in CO<sub>2</sub>, are important but they highlight the many uncertainties involved that implicitly prevent determination of the relative impact of each factor [Gornall *et al.*, 2010].

In the main text, values are presented for 2010 emissions in 2007 \$US (as in IWG2013). SCAR values in future years are substantially larger, though the increase is uneven across pollutants (Table 5). Values increase substantially over time for all pollutants due to the dependence of the climate impacts on the square of the temperature change and GDP (as both temperature and GDP are increasing) and the dependence of the health impacts on increasing population and GDP.

The average values for the SCC of CO<sub>2</sub> found by the IWG2013, in 2007 \$US per metric ton of CO<sub>2</sub> emission, are \$11 for a 5% discount rate, \$33 for a 3% discount rate, and \$52 for a 2.5% discount rate. The 95<sup>th</sup> percentile value for the mid-range 3% discount rate is \$90. These values are quite consistent with those shown in the analogous basic ‘climate’ valuation in Table 2 (my value with a 2.5% discount rate is \$52), in accord with the aforementioned selection of parameters to roughly reproduce the IWG2013 mean values. Selection of alternative parameters (reduced climate sensitivity and damage function) is used to give values similar to the IWG2010 and earlier literature (e.g. \$21 per ton CO<sub>2</sub> with 3% discounting) for some Limited-SCAR calculations discussed in the Illustrative Applications section. Note that as these are mean probabilities, they are risk-neutral and so on the low side relative to valuation reflecting risk-averse costs. Other research [*Johnson and Hope, 2012*] suggests that the discount rate range should encompass substantially smaller values than in the US government analysis, with correspondingly greater SCC (which is further increased accounting for equity weighting in that study). Another study [*Ackerman and Stanton, 2012*] also argues for a higher SCC based on the possibility of higher climate sensitivity and high-damage impacts. The review of [*Tol, 2008*] found \$265 per ton over a range of studies with near zero discount rate while the analysis in [*Ackerman and Stanton, 2012*] found values up to an order of magnitude greater than the IWG. Hence substantial uncertainties remain in the choice of discount rate and thus in the SCC.

Agreement with the IWG2013 mean values along with the assignment of 50% uncertainty to represent the range incorporates much of the uncertainty due to the underlying assumptions regarding climate damages. For example, the IPCC AR4 [*Yohe et al., 2007*] gives damages at 2.5°C ranging from ~0.5% to 2.5% of world economic output. While the 1.8% value used here lies well within this range, another value could also match the IWG2013 mean with alternate values of related parameters (e.g. climate sensitivity). The range cited by IPCC gives an idea of the uncertainty associated with valuation of climate damages, taken here as 50% for a given discount rate and added to the additional uncertainty associated with the valuation of climate-health damages as described previously. For CO<sub>2</sub>, this leads to an overall uncertainty of ~55-65%, which is judged to roughly correspond to the 90% confidence interval.

Uncertainties attributable to the additional components included here are obviously not represented in the IWG2013 ranges. I performed sensitivity studies of these factors. The climate-health valuation of the shorter-lived emissions is mildly sensitive to the assumption that baseline mortality decreases by  $0.9\% \text{ yr}^{-1}$ , increasing by  $\sim 7\text{-}30\%$  if the baseline mortality is instead assumed to decrease at only  $0.4\% \text{ yr}^{-1}$ , though the climate-health valuation for the longer-lived gases such as  $\text{CO}_2$  increases more strongly (by 25-55%). Using half the enhanced hydrologic cycle response to aerosols reduces their total SCAR by  $\sim 10\text{-}25\%$  at 3% discounting. The inclusion of the response of the carbon-cycle to temperature changes induced by non- $\text{CO}_2$  emissions increased their total valuation by 5-8%, 13-21% and 19-48% for 5%, 3% and 1.4% discounting, respectively (except for  $\text{SO}_2$  and OC, for which it had weaker impacts of 1-12%). This range is also a reasonable estimate of the total uncertainty associated with this process [Arora *et al.*, 2013; Collins *et al.*, 2013]. The uncertainty for all of the additional processes incorporated into the SCAR is within the overall bounds used here, and is generally small compared with the influence of the discount rate choice, though it may nevertheless be important as uncertainties in some of the processes can be reduced with improved understanding of physical science while others, like projected baseline mortality or the choice of discount rate, cannot. It's also worth noting that uncertainties in various parameters affect different parts of SCAR. For example, the climate valuation scales with the reference rate of temperature change (e.g. a 33% slower rate leads to roughly 17% less climate valuation), but the reference temperature trend has no effect on the composition-related impacts.

### Regional Precipitation Changes due to Aerosols

As noted in the main text, impacts stemming from regional disruption of the hydrologic cycle due to aerosols are included in the SCAR. The response to scenarios reducing emissions of BC and co-emitted pollutants shows that the spatial pattern of July-September precipitation changes is in general similar to that seen in response to LLGHG forcing, but with a substantially stronger magnitude [Shindell *et al.*, 2012a]. The mean response for those reductions compared with equivalent forcing reductions in LLGHGs (and hence equal global mean temperature changes in this methodology) is 4.2 times greater (median 6.2), and 2/3 of locations show a response more than double that for

LLGHGs (Figure 4). There is a substantial area of negative response ratios, nearly all of which are located in the Amazon, where BC causes increased precipitation while LLGHGs cause drying. In contrast, in most parts of the globe the responses are similar in sign, with both LLGHGs and BC leading to increased precipitation over India and decreases in the Sahel, in Southern Africa, and around the Mediterranean. Excluding the Amazon locations brings the mean response ratio up to 6.6 (median 7.8), and then ~80% of locations experience more than twice the LLGHG response, which corresponds to the relative impact that would be felt in most of the world, offset by the opposing response in the Amazon. While this analysis includes only points with precipitation changes that are significant at the 1.6 sigma level (95% confidence), using all land points give the same mean while using all land and ocean points the mean is only slightly different at 4.0. In addition, analysis of multiple experiments with an earlier version of the same climate model also showed that both scattering and absorbing aerosols typically induce a substantially greater precipitation response per unit RF than LLGHGs [*Shindell et al.*, 2012b]. I do not include an enhanced regional precipitation response to ozone as the prior modeling did not clearly indicate a distinctly different response relative to CO<sub>2</sub> [*Shindell et al.*, 2012b]. Though not dependent on the sampling used in this analysis, the results may be model dependent.

In the SCAR valuation of damages owing to regional hydrological cycle disruption, the portion of the global climate response attributable to carbon-cycle feedbacks is excluded. The WHO-based climate-health estimates for aerosols are scaled by the ratio of their net global+regional to global damages to account for the full climate impact, with again the mean of the WHO- and IAM-based values used in the totals.

The assumption that regional aerosol impacts can be represented by assigning precipitation impacts to be ~4× greater and assuming precipitation changes account for half of climate damages are clearly first order assumptions meriting further refinement. Aerosols, being primarily in the Northern extratropics, would also have a greater impact on Arctic/Greenland melting, for example, than LLGHGs. As noted, using half the aerosol enhancement (equivalent to attributing 25% of climate-related damages to precipitation changes maintaining the 4.2× enhancement) has a fairly small effect on the total SCAR for SO<sub>2</sub> and OC, though it alters the BC value by 20%.

While this valuation of the hydrologic cycle response to aerosols represents only an initial attempt to include climate responses that are not simply proportional to the global mean temperature change, it leads to two key conclusions. First, although uncertainties are large for both the fraction of damages due to precipitation changes and for the precipitation response to aerosols, including disruption to the hydrologic cycle can lead to net climate benefit for reflective aerosol reductions. Second, for scattering aerosols, climate impacts either based on global mean temperature change alone or including precipitation changes are small compared with health impacts (Table 2). Hence even if reductions in scattering aerosol emissions have a net beneficial impact via climate, the health benefits are dominant based on valuation. Reduced disruption of regional precipitation can contribute up to half the total estimated benefits from BC, however.

#### *Composition-Health and Climate-Health Valuation*

Epidemiological data to separate the effects of individual PM<sub>2.5</sub> components is minimal, and so impacts are typically calculated for aggregate PM<sub>2.5</sub>. For the aerosol and aerosol precursor emissions included here, the relative contributions to population weighted PM<sub>2.5</sub> are: BC 5.5%, OC 32%, SO<sub>2</sub> 37% [Shindell *et al.*, 2012a]. Composition-health impacts for nitrate and secondary organics were not included as they are not a result of a single precursor emission (mineral dust was also excluded). Composition-health impacts of CO were not included as these have not yet been sufficiently characterized. The health response to emissions of NO<sub>x</sub> alone had not been assessed in the models that provided output for other pollutions, so a simplified approach based on other published analyses is used to include these impacts. The valuation of SO<sub>2</sub> emissions found here is multiplied by the ratio of composition-health damages due to US coal-related emissions of NO<sub>x</sub> versus SO<sub>2</sub> [National Research Council, 2010] divided by the ratio of their emissions [US EPA, 2013a]. This yields a valuation of \$2645 per ton N.

While the valuation for climate-health impacts is tied to temperature change, this is used as a proxy for all climate impacts. In the case of cooling aerosols (SO<sub>2</sub> and OC), the global mean temperature change is negative, and hence the traditional IAM-like basic climate damages are also negative. The net climate-related damages are positive, however, once the regional disruption of the hydrologic cycle is accounted for, and hence

in this study the climate-health damages are also taken to have positive values. I find that simply using the temperature squared for cooling aerosols produces climate-health values that have a similar ratio to the net climate-related damages to that found for BC (a simpler case as all damages have positive values). Hence I use the positive climate-health damages for cooling aerosols that stem from the temperature squared calculation, although clearly further work is needed to better understand the net impact of cooler temperatures along with disruptions to precipitation patterns on human health.

#### *Methane emissions in the Illustrative Applications*

Emissions of methane from the US EPA inventory [US EPA, 2013b] are assigned to sectors differently here than in that inventory's aggregate results. Emissions from petroleum systems are assumed to have gasoline as their primary end-use, and hence are assigned to transportation. Emissions from coal mining and natural gas systems are assigned to electricity generation (rather than to industry, as in the EPA aggregation), with the former included in the coal-fired and the latter in the gas-fired power generation analyses. Emissions from iron, coke and steel production are assigned to the industry sector.

Table 1. Pollutants examined here and their major impacts

	Global mean surface temperature impact <sup>1</sup>	Enhanced regional hydrologic cycle impact	Pathway to composition-health impacts
Carbon dioxide (CO <sub>2</sub> )	warming		none
Methane (CH <sub>4</sub> )	warming		surface ozone
Carbon monoxide (CO)	warming		surface ozone
Sulfur dioxide (SO <sub>2</sub> )	cooling	X	surface PM <sub>2.5</sub>
Black Carbon (BC)	warming	X	surface PM <sub>2.5</sub>
Organic Carbon (OC)	cooling	X	surface PM <sub>2.5</sub>
Nitrous oxide (N <sub>2</sub> O)	warming		none
HFC-134a	warming		none
Nitrogen oxides (NO <sub>x</sub> )	neutral		surface ozone
Mercury (Hg)	neutral		bioaccumulation in fish

<sup>1</sup>The global mean surface temperature impact is also a proxy for the many additional climate impacts that occur alongside global mean temperature change, including changes in sea-level, rainfall, heatwaves, etc.

Table 2. Valuation of 2010 emissions (damages per ton in \$2007 US)

Valuation; discount rate	CO <sub>2</sub>	CH <sub>4</sub>	BC	SO <sub>2</sub>	CO	OC	N <sub>2</sub> O	HFC- 134a
Climate <sup>1</sup> ; 5%	11	560	15000	-1000	270	-2100	3300	22000
Climate <sup>1</sup> ; 3%	35	1100	24000	-1700	490	-3300	11000	43000
Climate <sup>1</sup> ; 1.4%	140	2700	57000	-3900	1200	-7800	44000	110000
Regional climate, aerosols; 5%	0	0	22000	2600	0	5100	0	0
Regional climate, aerosols; 3%	0	0	31000	3800	0	7600	0	0
Regional climate, aerosols; 1.4%	0	0	55000	7700	0	15000	0	0
Climate-Health <sup>2</sup> ; 5%	16	940	67000	2700	450	5500	4600	37000
Climate-Health <sup>2</sup> ; 3%	43	1600	86000	3300	720	6600	12000	62000
Climate-Health <sup>2</sup> ; 1.4%	140	3100	132000	4500	1400	9000	39000	120000
Composition- Health; 5%	0	550	34000	17000	*	27000	0	0
Composition- Health; 1.4%	0	810	34000	17000	*	27000	0	0
Composition- Agricultural; 5%	**	22						
Composition- Agricultural; 1.4%	**	30						
Sum; 5% discounting <sup>3</sup>	19 ±14	1600 ±900	100000 ±60000	20000 ±14000	490 ±360	33000 ±22000	5600 ±3900	41000 ±29000
Sum; 3% discounting <sup>3</sup>	56 ±39	2500 ±1400	130000 ±80000	21000 ±14000	850 ±610	35000 ±23000	17000 ±12000	74000 ±52000
Sum; 1.4% discounting <sup>3</sup>	210 ±140	5100 ±3000	210000 ±130000	23000 ±14000	1900 ±1300	40000 ±23000	63000 ±41000	170000 ±120000
Sum; declining discounting <sup>3</sup>	72 ±48	2500 ±1400	130000 ±80000	21000 ±14000	890 ±620	35000 ±23000	22000 ±14000	77000 ±54000

<sup>1</sup>This basic climate valuation includes IAM-based climate-health impacts.

<sup>2</sup>This valuation of climate-health impacts is based on WHO analyses as described in the text.

<sup>3</sup>The sum uses half the WHO-based climate-health impacts, with uncertainty based on the range between the WHO-based and IAM-based analyses (and 50% on basic climate valuation) and the 80% uncertainty on composition-health impacts reported in [*D Shindell et al.*, 2012a].

\* health damages resulting from ozone formation induced by CO are not included here.

\*\* net agricultural valuation of CO<sub>2</sub> is negative (beneficial) and included in the Climate damages.

Table 3. Valuation of 1% of 2010 anthropogenic emissions (billions \$2007 US)

	CO <sub>2</sub>	CH <sub>4</sub>	BC	SO <sub>2</sub>	CO	OC	N <sub>2</sub> O	HFC-134a
5% discounting	6.6	4.9	5.6	22	3.3	4.6	0.7	0.06
3% discounting	20	7.8	7.0	22	5.6	4.9	2.1	0.11
1.4% discounting	73	16	11	25	13	5.5	7.8	0.24
Declining discounting	25	7.9	7.1	22	5.9	4.8	2.7	0.11

Values use the mean of the WHO-based and IAM health impacts of climate change.

Table 4. Valuation of environmental damages (billions \$2007 US) by sector, 2011 US emissions

Sector \ Discount rate	Full SCAR			Limited SCAR	Composition-health only
	5%	3%	1.4%	3%	3%
Electricity	160±80	250±120	620±330	170±90	91±73
coal-fired	130±70	200±100	480±250	140±80	84±67
gas-fired	22±11	44±24	130±70	20±11	6±5
Transportation	120±60	210±110	560±310	100±50	40±32
Industrial combustion	36±18	65±34	180±110	43±23	18±14

SCAR calculations using emissions data from [US EPA, 2012; 2013a; b]. Coal- and gas-fired are subsets of the electricity generation sector. Transportation emissions include those associated with petroleum extraction and refining as well as direct vehicle emissions. Health damages from mercury emissions contribute an additional ~\$5 billion to damages due to coal-fired power plants and \$2 billion to industrial combustion (see text).

Table 5. Valuation of anthropogenic emissions at different times (damages per ton in \$2007 US)

Year/discount rate	CO <sub>2</sub>	CH <sub>4</sub>	BC	SO <sub>2</sub>	CO	OC	N <sub>2</sub> O	HFC-134a
2010 / 5%	19	1600	100000	20000	490	33000	5600	40000
2030 / 5%	31	2600	160000	22000	860	38000	9200	70000
2050 / 5%	50	4000	250000	26000	1400	45000	15000	120000
2010 / 1.4%	210	5100	210000	23000	1900	40000	63000	170000
2030 / 1.4%	310	7800	320000	26000	3000	47000	94000	270000
2050 / 1.4%	440	12000	470000	32000	4600	57000	130000	410000

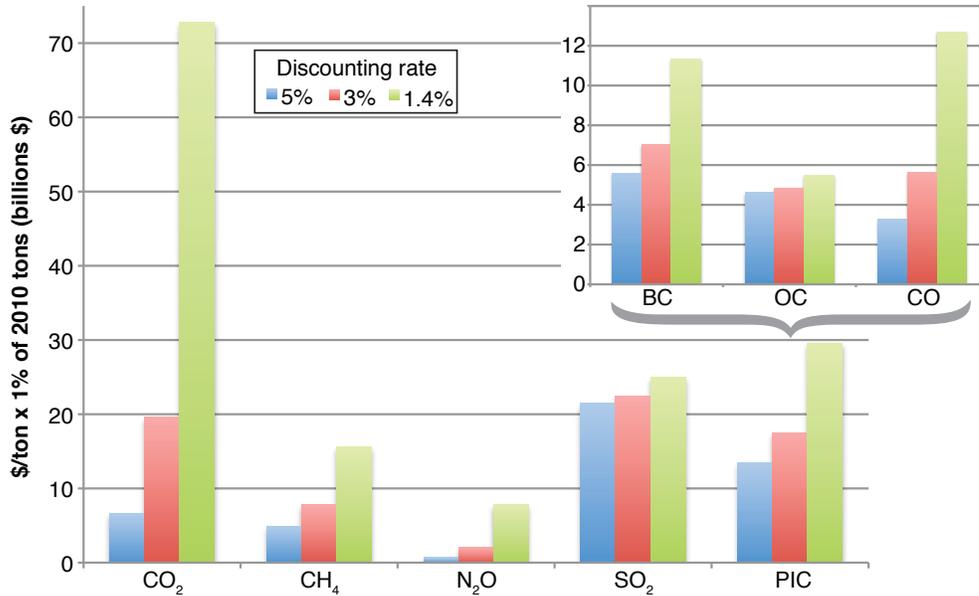


Figure 1. SCAR valuation of 1% of current global anthropogenic emissions (to illustrate the relative benefits of a marginal change in emissions) using the indicated discount rates. Products of incomplete combustion (PIC) is the sum of BC, OC and CO (inset). Numerical values are in Table 3. Relative uncertainties for each component are given in Table 2. Note that values with the declining discount rate used in this study are very similar to the 3% discounting results in this figure (Table 3).

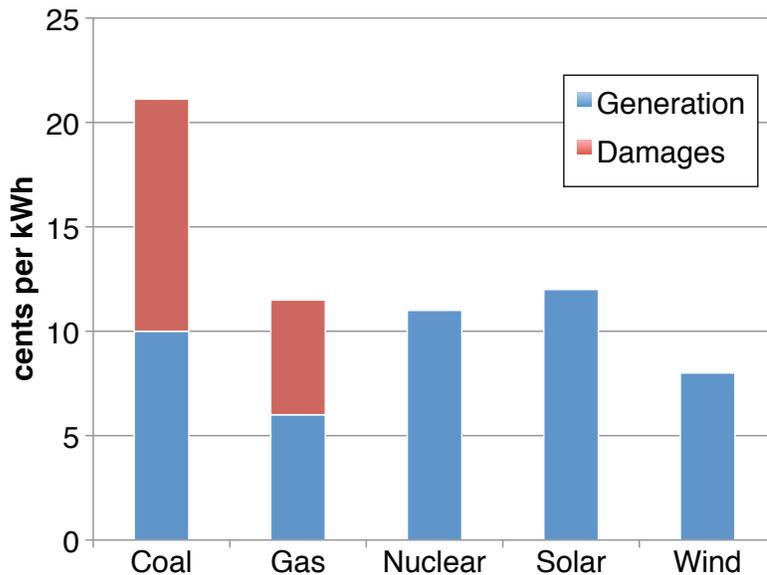


Figure 2. Levelized generation costs for new electricity generation and SCAR-based environmental damages by type (using 3% discounting). Damages are inflated to 2010 \$US to match generation costs.

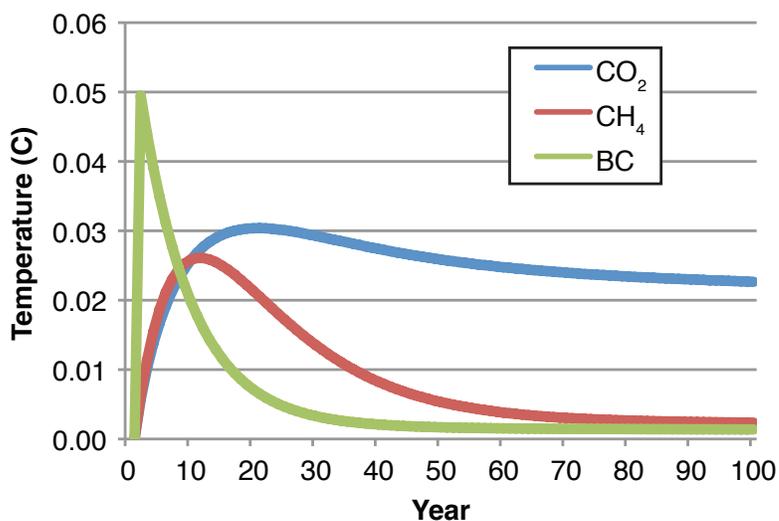


Figure 3. Timescales of temperature response to different forcings ( $^{\circ}\text{C}$  per  $\text{kg} \times 1 \text{ year's}$  worth of current global anthropogenic emissions (excluding open biomass burning)).

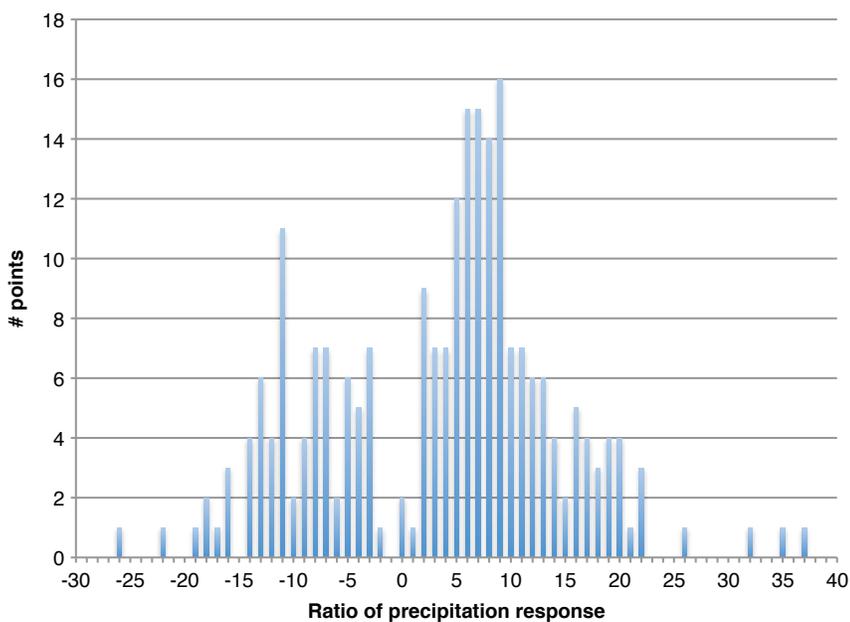


Figure 4. The ratio of precipitation changes in response to forcing by BC and co-emitted species relative to equal global mean LLGHG forcing. Values are from analysis of  $\sim 250$  land locations from  $60^{\circ}\text{S}$ – $60^{\circ}\text{N}$  where responses were statistically significant in both sets of simulations [Shindell *et al.*, 2012a].



## References

- Ackerman, F., and E. Stanton (2012), Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, *Economics-the Open Access Open-Assessment E-Journal*, 6, doi:10.5018/economics-ejournal.ja.2012-10.
- Allen, D., et al. (2013), Measurements of methane emissions at natural gas production sites in the United States (vol 110, pg 17768, 2013), *Proceedings of the National Academy of Sciences of the United States of America*, 110(44), 18023-18023, doi:10.1073/pnas.1318658110.
- Arora, V. K., et al. (2013), Carbon-concentration and carbon-climate feedbacks in CMIP5 Earth system models, *Journal of Climate*, doi:10.1175/JCLI-D-12-00494.1.
- Arrow, K., et al. (2013), Determining Benefits and Costs for Future Generations, *Science*, 341, 349-350.
- Boucher, O. (2012), Comparison of physically- and economically-based CO<sub>2</sub>-equivalences for methane, *Earth Syst. Dynam.*, 3(1), 49-61, doi:10.5194/esd-3-49-2012.
- Boucher, O., P. Friedlingstein, B. Collins, and K. P. Shine (2009), The indirect global warming potential and global temperature change potential due to methane oxidation, *Environ. Res. Lett.*, 4, doi:10.1088/1748-9326/1084/1084/044007.
- Calderon-Garciduenas, L., et al. (2011), Exposure to severe urban air pollution influences cognitive outcomes, brain volume and systemic inflammation in clinically healthy children, *Brain and Cognition*, 77(3), 345-355, doi:10.1016/j.bandc.2011.09.006.
- Campbell-Lendrum, D., and R. Woodruff (2007), Climate change: Quantifying the health impact at national and local levels, in *Environmental Burden of Disease Series, No. 14*, edited by A. Pruss-Üstun and C. Corvalán, World Health Organization.
- Caplan, A., and E. Silva (2005), An efficient mechanism to control correlated externalities: redistributive transfers and the coexistence of regional and global pollution permit markets, *Journal of Environmental Economics and Management*, 49(1), 68-82, doi:10.1016/j.jeem.2004.03.004.
- Cathles, L., L. Brown, M. Taam, and A. Hunter (2012), A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by RW Howarth, R. Santoro, and Anthony Ingraffea, *Climatic Change*, 113(2), 525-535, doi:10.1007/s10584-011-0333-0.
- Cohen, A. J., et al. (2004), Urban air pollution, in *Comparative quantification of health risks*, edited, World Health Organization, Geneva.
- Collins, W. J., M. M. Fry, H. Yu, J. S. Fuglestedt, D. T. Shindell, and J. J. West (2013), Global and regional temperature-change potentials for near-term climate forcers, *Atmos. Chem. Phys.*, 13(5), 2471-2485, doi:10.5194/acp-13-2471-2013.
- Energy Information Administration (2011), *Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2010*, US Dept. of Energy, Washington D.C.
- Energy Information Administration (2012), *Annual Energy Outlook 2012*, US Dept. of Energy, Washington DC.
- Enkvist, P.-A., T. Nauclér, and J. Rosander (2007), A cost curve for greenhouse gas reduction, *The McKinsey Quarterly*.
- European Commission (1995), *ExternE: Externalities of Energy*, Office for Official Publications of the European Communities, Luxembourg.

- Forster, P., et al. (2007), Changes in Atmospheric Constituents and in Radiative Forcing, in *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon, Cambridge University Press, New York.
- Forster, P. M., T. Andrews, P. Good, J. M. Gregory, L. S. Jackson, and M. Zelinka (2013), Evaluating adjusted forcing and model spread for historical and future scenarios in the CMIP5 generation of climate models, *Journal of Geophysical Research: Atmospheres*, 118(3), 1139-1150, doi:10.1002/jgrd.50174.
- Freeman, M., B. Groom, K. Panopoulou, and T. Pantelidis (2013), Declining discount rates and the Fisher effect: Inflated past, discounted future, edited, Centre for Climate Change Economics and Policy Working Paper No. 129, Grantham Research Institute on Climate Change and the Environment, Working Paper No. 109, London School of Economics, London.
- Fuglestedt, J. S., K. P. Shine, T. Berntsen, J. Cook, D. S. Lee, A. Stenke, R. B. Skeie, G. J. M. Velders, and I. A. Waitz (2010), Transport impacts on atmosphere and climate: Metrics, *Atmos. Env.*, 44, 4648-4677.
- Gornall, J., R. Betts, E. Burke, R. Clark, J. Camp, K. Willett, and A. Wiltshire (2010), Implications of climate change for agricultural productivity in the early twenty-first century, *Philosophical Transactions of the Royal Society B-Biological Sciences*, 365(1554), 2973-2989, doi:10.1098/rstb.2010.0158.
- Groom, B., P. Koundouri, E. Panopoulou, and T. Pantelidis (2007), Discounting the distant future: How much does model selection affect the certainty equivalent rate?, *Journal of Applied Econometrics*, 22(3), 641-656, doi:10.1002/jae.937.
- Hegerl, G. C., F. W. Zwiers, P. Braconnot, N. P. Gillett, Y. Luo, J. A. Marengo-Orsini, N. Nicholls, J. E. Penner, and P. A. Stott (2007), Understanding and Attributing Climate Change, in *Intergovernmental Panel on Climate Change Fourth Assessment Report*, edited by S. Solomon, Cambridge, New York.
- Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global warming, *J. Clim.*, 19, 5686-5699.
- Hodnebrog, Ø., M. Etminan, J. Fuglestedt, G. Marston, G. Myhre, K. P. Shine, and T. J. Wallington (2013), Global Warming Potentials and Radiative Efficiencies of Halocarbons and Related Compounds: A Comprehensive Review, *Reviews of Geophysics*, 51, DOI:10.1002/rog.20013.
- Hope, C. (2013), Critical issues for the calculation of the social cost of CO<sub>2</sub>: why the estimates from PAGE09 are higher than those from PAGE2002, *Climatic Change*, 117(3), 531-543, doi:10.1007/s10584-012-0633-z.
- Howarth, R., R. Santoro, and A. Ingraffea (2011), Methane and the greenhouse-gas footprint of natural gas from shale formations, *Climatic Change*, 106(4), 679-690, doi:10.1007/s10584-011-0061-5.
- Interagency Working Group on Social Cost of Carbon (2010), Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, United States Government.
- Interagency Working Group on Social Cost of Carbon (2013), Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, United States Government.
- International Monetary Fund (2013), *Energy Subsidy Reform: Lessons and Implications*, International Monetary Fund, Washington D.C.

- Johansson, D. (2012), Economics- and physical-based metrics for comparing greenhouse gases, *Climatic Change*, 110(1-2), 123-141, doi:10.1007/s10584-011-0072-2.
- Johnson, L. T., and C. Hope (2012), The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, *J. Environ. Stud. Sci.*, DOI 10.1007/s13412-012-0087-7.
- Karion, A., et al. (2013), Methane emissions estimate from airborne measurements over a western United States natural gas field, *Geophysical Research Letters*, 40(16), 4393-4397, doi:10.1002/grl.50811.
- Kenyon, J., and G. Hegerl (2010), Influence of Modes of Climate Variability on Global Precipitation Extremes, *Journal of Climate*, 23(23), 6248-6262, doi:10.1175/2010JCLI3617.1.
- Kopp, R., A. Golub, N. Keohane, and C. Onda (2012), The Influence of the Specification of Climate Change Damages on the Social Cost of Carbon, *Economics-the Open Access Open-Assessment E-Journal*, 6, doi:10.5018/economics-ejournal.ja.2012-13.
- Levy, H., L. Horowitz, M. Schwarzkopf, Y. Ming, J. Golaz, V. Naik, and V. Ramaswamy (2013), The roles of aerosol direct and indirect effects in past and future climate change, *Journal of Geophysical Research-Atmospheres*, 118(10), 4521-4532, doi:10.1002/jgrd.50192.
- Lim, S., T. Vos, and A. Flaxman (2013), A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010 (vol 380, pg 2224, 2012), *Lancet*, 381(9874), 1276-1276.
- Marques, S., and M. Lima (2011), Living in grey areas: Industrial activity and psychological health, *Journal of Environmental Psychology*, 31(4), 314-322, doi:10.1016/j.jenvp.2010.12.002.
- Marten, A. L., and S. C. Newbold (2012), Estimating the social cost of non-CO2 GHG emissions: Methane and nitrous oxide, *Energy Policy*, 51(0), 957-972.
- Mehta, S., and C. Shahpar (2004), The health benefits of interventions to reduce indoor air pollution from solid fuel use: a cost-effectiveness analysis, *Energy for Sustainable Development*, 8, 53-59.
- Miller, S. M., et al. (2013), Anthropogenic emissions of methane in the United States, *Proc. Natl. Acad. Sci.*, 110(50), 20018-20022.
- Muller, N., R. Mendelsohn, and W. Nordhaus (2011), Environmental Accounting for Pollution in the United States Economy, *American Economic Review*, 101(5), 1649-1675, doi:10.1257/aer.101.5.1649.
- Myhre, G., et al. (2013), Anthropogenic and Natural Radiative Forcing, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Narita, D., R. Tol, and D. Anthoff (2010), Economic costs of extratropical storms under climate change: an application of FUND, *Journal of Environmental Planning and Management*, 53(3), 371-384, doi:10.1080/09640561003613138.
- National Research Council (2010), *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, The National Academies Press, Washington D.C.

- Nemet, G., T. Holloway, and P. Meier (2010), Implications of incorporating air-quality co-benefits into climate change policymaking, *Environmental Research Letters*, 5(1), doi:10.1088/1748-9326/5/1/014007.
- Newell, R., and W. Pizer (2003), Discounting the distant future: how much do uncertain rates increase valuations?, *Journal of Environmental Economics and Management*, 46(1), 52-71, doi:10.1016/S0095-0696(02)00031-1.
- Nordhaus, W. (2010), Economic aspects of global warming in a post-Copenhagen environment, *Proceedings of the National Academy of Sciences of the United States of America*, 107(26), 11721-11726, doi:10.1073/pnas.1005985107.
- Nordhaus, W., and J. Boyer (2000), *Warming the world: Economic models of global warming*, The MIT Press, Cambridge, MA.
- Portmann, R., S. Solomon, and G. Hegerl (2009), Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States, *Proceedings of the National Academy of Sciences of the United States of America*, 106(18), 7324-7329, doi:10.1073/pnas.0808533106.
- Prather, M. J., C. D. Holmes, and J. Hsu (2012), Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry, *Geophysical Research Letters*, 39, L09803, doi:10.1029/2012gl051440.
- Ramanathan, V., and G. Carmichael (2008), Global and regional climate changes due to black carbon, *Nature Geosci.*, 1, 221-227.
- Ramaswamy, V., O. Boucher, J. D. Haigh, D. A. Hauglustaine, J. Haywood, G. Myhre, T. Nakajima, G. Y. Shi, and S. Solomon (2001), Radiative forcing of climate change, in *Climate Change 2001*, edited by J. T. Houghton, pp. 349-416, Cambridge Univ. Press, Cambridge.
- Rice, G., and J. K. Hammitt (2005), Economic Valuation of Human Health Benefits of Controlling Mercury Emissions from U.S. Coal-Fired Power Plants, Report for NESCAUM, Northeast States for Coordinated Air Use Management.
- Rypdal, K., N. Rive, T. Berntsen, Z. Klimont, T. Mideksa, G. Myhre, and R. Skeie (2009), Costs and global impacts of black carbon abatement strategies, *Tellus Series B-Chemical and Physical Meteorology*, 625-641, doi:DOI 10.1111/j.1600-0889.2009.00430.x.
- Shindell, D., et al. (2012a), Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security, *Science*, 335(6065), 183-189, doi:10.1126/science.1210026.
- Shindell, D. T., G. Faluvegi, D. M. Koch, G. A. Schmidt, N. Unger, and S. E. Bauer (2009), Improved Attribution of Climate Forcing to Emissions, *Science*, 326, 716-718.
- Shindell, D. T., A. Voulgarakis, G. Faluvegi, and G. Milly (2012b), Precipitation response to regional radiative forcing, *Atmos. Chem. Phys.*, 12, 6969-6982.
- Smith, K. R., et al. (2009), Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants, *The Lancet*, 374, 2091-2103.
- Stern, N. (2006), *Stern review on the economics of climate change*, UK Treasury, London.

- Suglia, S., A. Gryparis, R. Wright, J. Schwartz, and R. Wright (2008), Association of black carbon with cognition among children in a prospective birth cohort study, *American Journal of Epidemiology*, 167(3), 280-286, doi:10.1093/aje/kwm308.
- Swain, E., P. Jakus, G. Rice, F. Lupi, P. Maxson, J. Pacyna, A. Penn, S. Spiegel, and M. Veiga (2007), Socioeconomic consequences of mercury use and pollution, *Ambio*, 36(1), 45-61.
- Tanaka, K., D. Johansson, B. O'Neill, and J. Fuglestvedt (2013), Emission metrics under the 2°C climate stabilization, *Climatic Change Letters*, 9 pp, doi:10.1007/s10584-013-0693-8.
- Thomson, A., et al. (2011), RCP4.5: a pathway for stabilization of radiative forcing by 2100, *Climatic Change*, 109(1-2), 77-94, doi:10.1007/s10584-011-0151-4.
- Tol, R. S. J. (2008), The social cost of carbon: trends, outliers and catastrophes, *Economics the Open Access, Open Assessment E-Journal*, 2(25), 1-24.
- Tollefsen, P., K. Rypdal, A. Torvanger, and N. Rive (2009), Air pollution policies in Europe: efficiency gains from integrating climate effects with damage costs to health and crops, *Environmental Science & Policy*, 12(7), 870-881, doi:10.1016/j.envsci.2009.08.006.
- UNEP (2011), Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers, 78 pp, United Nations Environment Programme (UNEP), Nairobi, Kenya.
- United Nations Environment Programme and World Meteorological Organization (2011), Integrated Assessment of Black Carbon and Tropospheric Ozone, Nairobi, Kenya.
- US EPA (2012), *Report to Congress on Black Carbon*, Washington D.C.
- US EPA (2013a), *2008 National Emissions Inventory: Review, Analysis and Highlights*, US Environmental Protection Agency, Research Triangle Park, North Carolina.
- US EPA (2013b), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011*, Washington D.C.
- Viscusi, W. K., and J. E. Aldy (2003), The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World, *J. Risk Uncert.*, 27(1), 5-76.
- Wang, C., D. Kim, A. M. L. Ekman, M. C. Barth, and P. J. Rasch (2009), Impact of anthropogenic aerosols on Indian summer monsoon, *Geophys. Res. Lett.*, 36, L21704, doi:10.1029/2009GL040114.
- Weitzman, M. L. (2007), A Review of The Stern Review on the Economics of Climate Change, *J. Econ. Lit.*, 45, 703-724.
- Weuve, J., R. Puett, J. Schwartz, J. Yanosky, F. Laden, and F. Grodstein (2012), Exposure to Particulate Air Pollution and Cognitive Decline in Older Women, *Archives of Internal Medicine*, 172(3), 219-227.
- Yohe, G. W., R. D. Lasco, Q. K. Ahmad, N. W. Arnell, S. J. Cohen, C. Hope, A. C. Janetos, and R. T. Perez (2007), Perspectives on climate change and sustainability, in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson, pp. 811-841, Cambridge University Press, Cambridge, UK.