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The Social Cost of Atmospheric Release

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Abstract
The author presents 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 (CO2) 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 (SO2), followed by co-emitted products of incomplete combustion (PIC) and then CO2 and methane. With a low discount rate, benefits are greatest for CO2 reductions, and are nearly equal to the total from SO2, PIC and methane. These results suggest that efforts to mitigate atmosphere-related environmental damages should target a broad set of emissions including CO2, methane and aerosols. Illustrative calculations indicate environmental damages are $150-510 billion per year for current US electricity generation (~6-20¢ per kWh for coal, ~2-11¢ for gas) and $0.73±0.34 per gallon of gasoline ($1.20±0.70 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.

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Keywords Environmental economics; valuation; air pollution; climate; government policy

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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.

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. As opposed to previous estimates of damages associated with particular activities (e.g. electricity generation [*European Commission*, 1995; *National Research Council*, 2010]), the basic 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, and hence it may be premature to use 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.

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_2) 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).

Thus social costs for emissions of other pollutants should at minimum include their impacts on these same quantities. This applies even in the case where their effects take place via different processes than for CO_2 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_2) or methane (CH_4), affect human health both by altering climate as CO_2 does (hereafter climate-health impacts) but also by more directly degrading air quality (hereafter composition-health impacts). Hence this work also builds upon prior valuation of air quality-related 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 CO_2, CH_4, carbon monoxide (CO), SO_2, BC, organic carbon (OC), nitrous oxide (N_2O) and the exemplar hydrofluorocarbon HFC-134a. The composition-health impacts of nitrogen oxide (NO_x) emissions are also assessed, but impacts of NO_x on climate are uncertain even as to their sign [*Forster et al.*, 2007] and so are excluded. The pollutants emphasized here are the major drivers of global mean climate change [*Forster et al.*, 2007] and the global health burden from poor air quality [*Lim et al.*, 2013].

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_2O is evaluated, and affects stratospheric ozone and hence skin cancer rates, but valuation of that effect has not been performed and so is excluded here). Most of these substances are now controlled and decreasing, however. 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 also fall squarely within the category of those affecting both air quality and climate, including volatile organic compounds and ammonia, but either not enough information is available at present or uncertainties are extremely large, so analysis of their effects is not included. Other emissions also influence health, such as mercury and 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.

This analysis facilitates discussion of the relative importance of 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_2 and N_2O) and how those physical timescales interact with time-preferences for the value of money.

Results

Valuation is performed encompassing the climate, health and agricultural impacts resulting from release of each of these pollutants, including health and agricultural impacts occurring via both air quality and climate changes. Valuation of climate damages includes both a component related to the global mean change and an additional component associated with aerosol-driven changes to the hydrologic cycle (see Methods). Air quality impacts are globally representative values (see Discussion). Valuation of climate damages is highly sensitive to discounting, reflecting the relative value of money over time, and estimated climate-health impacts. The climate damages attributable to CO_2 (equivalent to the traditional SCC) are 11-140 $/ton using constant discounting rates of 5 to 1.4% and conventional climate-health impacts from integrated assessment model (IAM) estimates (Table 1). SCAR values for CO_2 increase to 21-182 $/ton using the larger recent health impacts of climate change estimated by the World Health Organization (WHO) [*Campbell-Lendrum and Woodruff*, 2007]. The first range is consistent with those in many prior studies (e.g. IWG2013), with the latter 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). I hereafter base the valuation on the mean of these two climate-health estimates, with an assumption of 50% uncertainty in both the climate-health impacts (e.g. spanning the range of these two estimates) and other climate impacts. 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_2O is much larger than for CO_2 due to its far greater radiative efficiency, but shows broadly similar sensitivity to the choice of discount rate (Table 1). In contrast, valuation for the shorter-lived pollutants is much less sensitive to the choice of discounting rate, especially for the aerosols (in part because of the contribution of their composition-health impacts, which are unaffected by discounting). The use of a declining discount rate (DDR; see Methods) produces values generally similar to the constant 3% case with the DDR used here (Table 1). Regardless of the discounting, the relative SCAR valuation per ton is much larger for methane and the aerosols or aerosol precursor species BC, SO_2 and OC than for CO_2, with a ton of methane causing ~30-90 times more damage than a ton of CO_2 and a ton of the aerosols causing up to ~6000 times more damage. For comparison, the valuation of the composition-health impacts of NO_x emissions is \$2600 ton^{-1}.

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_2 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_2, CH_4, BC, CO, N_2O and HFC-134a comes from the estimate of climate plus climate-health impacts, which is systematic across these pollutants. Uncertainty in the regional aerosol impacts is obviously not systematic across pollutants. These lead to a substantial fraction of the total aerosol valuation, especially at low discount rates.

The ratios of the SCAR values for CH_4 and N_2O to CO_2 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 47 and 279 without the carbon-cycle response to non-CO_2 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 87 for methane while leaving the ratio at 290 for N_2O. The ratio increases for methane in part due to use of the higher estimated climate-health impact along with a slow decrease in baseline vulnerability, as that effect is weighted towards the near-term for methane relative to N_2O or CO_2 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 87 to 26 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_2O is also always similar to it's 20- or 100-year GWPs of ~265. SCAR values are not closely related to GWPs for shorter-lived 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_2 emissions is much larger than the valuation of any other pollutant. Carbon dioxide is valued at about 26% of the value of SO_2, and 43% 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_2 roughly ten-fold and increasing the valuation of methane, BC and CO by roughly a factor of two or more while having less impact on reflective aerosols. Valuation of CO_2 is by far the greatest with 1.4% discounting, followed by PIC, SO_2, and methane (Figure 1). Valuation of HFC-134a is always relatively small despite it having the highest per ton valuation (Table 2).

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. For example, the valuation of reducing products of incomplete combustion by only ~4% would be comparable to that of reducing CO_2 by 10% with a near-term focus (5% discounting), while reductions would have to be ~22% to be as valuable as CO_2 reductions of 10% using a long-term perspective (1.4% discounting). Similarly, reducing CH_4 emissions by ~13% provides as much benefit as reducing CO_2 emissions by 10% with a near-term perspective, while reductions need to be 44% 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. For example, US emissions from electricity generation and transportation lead to very large environmental damages (Table 3). These values 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 $140±70 billion greater than gas at 3% discounting). Within the transportation sector, the environmental damages are $0.73±0.34 per gallon using a 3% discount rate, much larger than the current federal tax of $0.184 per gallon and roughly 35% greater than the typical combined local, state and federal gasoline tax. Damages are substantially larger for diesel, $1.20±0.70 per gallon, owing to the greater BC emissions.

Unsurprisingly, the SCAR-based values are generally larger than prior estimates of environmental damages by sector. They are comparable, however, when a "limited-SCAR" is calculated including only those impacts included in previous studies (composition-health impacts of all pollutants, climate impacts for CO_2 only based on IAM climate-health effects) and using a similar discount rate (3%), 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. 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], consistent with the limited-SCAR valuation of \$140±80 billion (using the comparable IWG2010 SCC for CO_2); this 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 using the mean of IAM- and WHO-based climate-health impacts and including the climate impacts of non-CO_2 emissions. The latter can be quite important, with methane's effect on climate contributing 30% of the SCAR valuation of gas-related electricity generation damages (using 3% discount rate), for example. The shares of damages from CO_2 are 43%, 42% and 57%, 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. Environmental damages from the US average coal-fired power plant are 6.3±3.5¢, 9.0±4.2¢, and 20±9¢ per kWh with 5, 3 and 1.4% discounting, respectively. Comparable values for gas-fired plants are 2.2±1.0¢, 4.2±2.0¢, 11±6¢. 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 4.9±3.0¢ 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 emissions at the 5th lowest percentile would have damages close to those for gas (~4-5¢ per kWh for either; 3% discounting) while one at the 95th percentile would have far greater damages (~20¢ per kWh; 3% discounting) based on emissions in [*National Research Council*, 2010]. Similarly, one can easily compute how much higher 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%, emissions would have to be 5 times greater to produce damages as large as coal on a per kWh basis, while with a high discount rate of 5% emissions would need to be 2.5 times greater than the methane emissions from gas in current inventories. As the valuation of damages from the cleanest coal plants is roughly equal to gas, clearly only marginally larger increases in estimated methane releases would tip that balance. Some estimates of the additional methane resulting from hydraulic fracturing are much larger than estimates in current inventories (e.g. [*Howarth et al.*, 2011]), although other studies estimate lower methane emissions (e.g. [*Cathles et al.*, 2012]), so such 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. 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 found here. The SCAR can also be used to assess variations between nations, which can be large. For example, the environmental damages for the mean coal-fired power plant in China are valued at 15±9¢ per kWh with 5% discounting and 32±14¢ per kWh with 1.4% discounting, ~160-230% more than the mean for US emissions due to the greater levels of non-CO_2 pollutants.

For vehicles, emissions from a typical midsize US gasoline vehicle (26 miles gallon^{-1}, 12000 miles yr^{-1}) lead to environmental damages valued at \$340 yr^{-1} 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^{-1} (fueleconomy.gov)) are \$310 yr^{-1} for electricity from coal, \$140 yr^{-1} 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 and 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 $6.5 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 pre-tax subsidy of $480 billion for electricity and fossil fuels [*International Monetary Fund*, 2013]. Damages attributable to SO_2 and CO_2 total $3.7 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_2 and the newer health impacts used here are accounted for. The increase when other components are included is dominated by the impact of methane ($0.7 trillion) and PIC ($1.6 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 mismatch between those incurring costs and those accruing benefits exists and can be particularly important for planet-wide benefits such as reduced climate damages. Furthermore, there are multiple benefits that have not been taken into account in this analysis. For example, I include only valuation of premature deaths from outdoor particulate matter (PM) and ozone exposure, while there are also chronic physical health issues, and studies have demonstrated that exposure to PM 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. 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 or spent nuclear fuel) and national or energy security (e.g. reliance on fossil fuels, nuclear proliferation), which are not readily incorporated into an emission metric but can be studied with even 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. 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 3 or less for emissions from different regions (e.g. [*Fuglestvedt 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. Thus accounting for emission location could increase the ratio of gasoline to EV damages further.

The interplay between the rather uncertain damage function and the discounting rate depends on the timescale over which impacts take place. This timscale varies greatly across the pollutants examined here according to their atmospheric residence time (Figure 3). For CO_2, 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 kick in 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 composition-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_2. 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.

Although much further work is required to fully characterize benefits and compare with costs, this initial 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 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_2, PIC and methane is roughly equal. Hence even in this case, these results suggest that society should pursue a multi-pollutant emissions reduction strategy that includes multiple greenhouse gases and aerosols in order to obtain maximum benefits.

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_2 reductions. Such a strategy has been fairly well aligned with the optimal path suggested by this analysis given a preference for avoiding near-term over longer-term impacts. However, even with such a preference, a greater focus on reductions in PIC and methane emissions appears warranted due to their large impacts. To avoid longer-term damages, society must greatly reduce CO_2 emissions given their dominance in total emission valuation, but a narrow focus on CO_2 alone or even on the Kyoto gases would neglect pollutants contributing the majority of environmental damages.

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Methods

SCAR methodology and context with the SCC

SCC results are based on IAMs that estimated 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, though typical powers range from 1 to 3, or depend upon both the magnitude and rate of temperature change. Some damages (e.g. agriculture and forestry) can also depend upon CO_2 concentrations. 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 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_2 fertilization is not included, as would be the case for warming induced by non-CO_2 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_2, are important but they highlight the many uncertainties involved that implicitly prevent determination of the relative impact of each factor [*Gornall et al.*, 2010].

The damages attributable to climate change in the SCC are based upon temperature changes that are in turn driven by the global mean radiative forcing caused by each emitted compound. Forcing calculations performed here are based on a set of simple and complex models. The evolution of CO_2 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 GWP of ~32). RF due to CO_2 and methane is computed using the standard IPCC formulation [*Ramaswamy et al.*, 2001]. Forcing by N_2O 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]. For context, the total industrial-era forcings attributed to aerosols are -0.72 W m^{-2} for sulfate, -0.19 W m^{-2} for OC, and +0.51 W m^{-2} for BC. Forcing by non-CO_2 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_2 itself) based on a reduced carbon uptake of 1 GtC per degree warming [*Arora et al.*, 2013; *Collins et al.*, 2013].

Basic climate damages for all pollutants in the SCAR are then based on their impact on global mean temperature as in the SCC for CO_2. The calculations presented here use the damage function of the DICE model [*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. Valuation for non-CO_2 emissions is increased by 10% relative to CO_2 due to the lack of CO_2 fertilization effects on plants. Reference temperature change follows a business-as-usual trend with a projected increase starting at 0.015°C yr^{-1} (as in recent observations) gradually increasing with time but then slowing to 0.008°C yr^{-1} 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]. Temperature responses to forcings 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_2, higher than the mean but well within the range in AR4 [*Hegerl et al.*, 2007]. GDP increases at 2% yr^{-1}, giving a 2100 value of $355 trillion, consistent with that in IWG2010. 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 4). Values increase substantially over time due to their dependence on the square of the temperature change as well as increasing population and GDP.

An interagency analysis by the US government gives 2010 SCC values for discount rates of 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 therefore selected parameter values in the model to roughly match the average IWG2013 estimates for climate damages from CO_2 when using comparable climate-health impacts, and I use the same discount rates. I also include analysis using a discount rate of 1.4%, as in [*Stern*, 2006]. This low discount rate gives values for the SCC of CO_2 of about $140/ton (without an enhanced health impact), consistent with the middle of the additional SCC range suggested as plausible in [2012] using similar methodology, though lower than [2008] or [2012]. 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 possibility 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 (e.g. [*Arrow et al.*, 2013]). To examine the influence of a declining discount rate, I use a rate starting at 4% and decreasing exponentially with a 250 year time constant which roughly 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 include any economic response to environmental damages.

The average values for the SCC of CO_2 found by the IWG (2013), in 2007 $US per metric ton of CO_2 emission, are $11 for a 5% discount rate, $33 for a 3% discount rate, and $52 for a 2.5% discount rate. The 95th percentile value for the mid-range 3% discount rate is $90. These values are quite consistent with those shown in the analogous ‘climate’ valuation in Table 1 (my value with a 2.5% discount rate is $52), in accord with the aforementioned selection of parameters to roughly reproduce the IWG2013 means. 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_2

with 3% discounting) for some Limited-SCAR calculations discussed here. 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 [2012] found values up to an order of magnitude greater than the IWG. Hence substantial uncertainties remain in the SCC.

Agreement with the IWG2013 mean 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_2, 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 only weakly sensitive to the assumption that baseline mortality decreases by 0.9% yr^{-1}, increasing by ~4-15% if the baseline mortality is instead assumed to decrease at only 0.4% yr^{-1}, though the climate-health valuation for the longer-lived gases such as CO_2 increases by 10-40%. Using half the enhanced hydrologic cycle response to aerosols reduces their total SCAR by ~10-25% at 3% discounting. The inclusion of the response of the carbon-cycle to temperature changes induced by non-CO_2 emissions increased their total valuation by 1-7%, 3-19% and 11-44% for 5%, 3% and

1.4% discounting, respectively (except for SO_2 and OC, for which it had little impact). 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.

The SCAR, like the SCC, values benefits worldwide. For CO_2, N_2O or methane, emissions from any location have the same impact, 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 seems unlikely to lead to valuation appropriate to these globally-influential pollutants. For the shorter-lived compounds, however, the damages will be weighted towards the location where the emissions take place. 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. Thus an important area for further analysis is 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.

Climate-Health

The conventional SCC includes damages driven by the effects of climate change on human health. Recent estimates of the climate-health impact by the World Health Organization [*Campbell-Lendrum and Woodruff*, 2007] find larger impacts than prior estimates, however, with 150,000 premature deaths attributed to the current warming (~0.8°C). I perform an additional set of climate-health valuation calculations using this estimate, assuming the effects are also proportional to the temperature change squared. Both changes in population and baseline mortality affect the climate-health damages (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^{-1}, leading to a worldwide population of 9 billion in 2100, and that baseline mortality decreases by 0.9% yr^{-1} based on the hypothesis that human health is so important to society that mitigation and adaptation efforts would be greater than for other aspects of climate change and that these would lead to a net reduction in vulnerability with time. Along with the magnitude of current climate-health impacts, their long-term trend clearly merits further study, however.

All health calculations use a 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 [*United Nations Environment Programme and World Meteorological Organization*, 2011]. Thus this analysis implicitly assumes that climate-health damages, like composition-health damages, are greater in areas with high current carbonaceous aerosols, consistent with the general pattern of baseline mortality and susceptibility to climate-health impacts being greater in developing nations where such emissions are currently high. That 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]).

This valuation of the climate-health impact alone gives values that are comparable to the total climate valuation following the traditional SCC methods (Table 1). Hence I use half the WHO-based climate-health impacts for the mean additional climate-health valuation with an uncertainty also equal to half the WHO-based climate-health impacts (thus encompassing the IAM-based impacts at the low end and the full WHO-based values at the high end). All other climate-related impacts are also assumed to have an uncertainty of 50% (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 95th percentile for the 3% discount rate).

Regional Precipitation Changes due to Aerosols

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. 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 2x 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 than for CO_2 [*Shindell et al.*, 2012b].

Though not dependent on the sampling used in this analysis, the results may be model dependent.

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 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 above modeling. 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 ~4x 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 WMGHGs. As noted, using half the aerosol enhancement (equivalent to attributing 25% of climate-related damages to precipitation changes maintaining the 4.2x enhancement) has a fairly small effect on the total SCAR for SO_2 and OC, though it alter the BC value by 25%.

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 1). 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 Composition-Agriculture

Damages attributable to atmospheric composition changes are based upon prior modeling of the response of surface pollutants to emissions. Impacts of $PM_{2.5}$ are attributed using the total current outdoor $PM_{2.5}$ impact on human health (3.2 million premature deaths annually [*Lim et al.*, 2013]), with the fractional contribution of each individual aerosol type given by the fractional contribution of each to surface $PM_{2.5}$ [*United Nations Environment Programme and World Meteorological Organization*, 2011]. Total valuation is again based on country-specific VSLs for globally distributed carbonaceous aerosols as in [*Shindell et al.*, 2012a]. Using results based on the impact of all current emissions is representative of the global mean impact, but values would differ for particular location of emissions.

Epidemiological data to separate the effects of individual $PM_{2.5}$ components is minimal, and so impacts are typically calculated for aggregate $PM_{2.5}$. For the aerosol and aerosol precursor emissions included here, the relative contributions to population weighted $PM_{2.5}$ are: BC 5.5%, OC 32%, SO_2 37% [*Shindell et al.*, 2012a]. Composition-health impacts for nitrate and SOA were not included as they are not a result of a single precursor emission (dust was also excluded). Composition-health impacts of CO were not included as these have not been sufficiently characterized. The health response to emissions of NO_x alone had not been assessed in these models, so a simplified approach based on other published analyses is used to include these impacts. The valuation of SO_2 emissions found here is multiplied by the ratio of composition-health damages due to US coal-related emissions of NO_x versus SO_2 [*National Research Council*, 2010] divided by the ratio of their emissions [*US EPA*, 2013a]. This yields a valuation of $2645 per ton N.

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. 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 [*United Nations Environment Programme and World Meteorological Organization*, 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 source activity 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 using country-specific VSL, as in the climate-health valuation, are used, 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).

The 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].

Table 1. Valuation of 2010 emissions (damages per ton in $2007 US)

Valuation; discount rate	CO_2	CH_4	BC	SO_2	CO	OC	N_2O	HFC-134a
Climate[1]; 5%	11	560	15000	-1000	270	-2100	3300	22000
Climate[1]; 3%	35	1100	24000	-1700	490	-3300	11000	43000
Climate[1]; 1.4%	140	2700	57000	-3900	1200	-7800	44000	108000
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[2]; 5%	10	700	57000	2300	340	4600	2600	27000
Climate-Health[2]; 3%	19	1000	65000	2500	480	5000	5200	40000
Climate-Health[2]; 1.4%	42	1500	74000	2500	720	5100	12000	61000
Composition-Health; 5%	0	490	34000	17000	*	27000	0	0
Composition-Health; 1.4%	0	680	34000	17000	*	27000	0	0
Composition-Agricultural; 5%	**	22						
Composition-Agricultural; 1.4%	**	30						
Sum; 5% discounting[3]	16 ±10	1400 ±700	100000 ±50000	20000 ±14000	440 ±310	33000 ±22000	4600 ±3000	36000 ±25000
Sum; 3% discounting[3]	44 ±27	2200 ±1100	120000 ±70000	20000 ±14000	730 ±490	34000 ±22000	14000 ±8000	63000 ±41000
Sum; 1.4% discounting[3]	160 ±90	4100 ±2200	180000 ±100000	22000 ±14000	1600 ±1000	38000 ±23000	50000 ±28000	140000 ±80000
Sum; declining discounting[3]	56 ±33	2200 ±1100	120000 ±60000	20000 ±14000	760 ±490	34000 ±22000	17000 ±10000	64000 ±41000

[1]Climate valuation uses IAM-based climate-health impacts.
[2]This valuation of climate-health impacts is based on WHO analysis and UNEP Assessment VSL.
[3]Sum uses the mean of the WHO-based and IAM climate-health impacts, with uncertainty based on the range between those studies (and similarly 50% on 'climate' valuation) and the 80% uncertainty on composition-health impacts reported in [*Shindell et al.*, 2012a].
[*] health damages resulting from ozone formation induced by CO are not included here.
[**] net agricultural valuation of CO_2 is negative (beneficial) and included in the Climate damages.

Table 2. Valuation of 1% of 2010 anthropogenic emissions (billions $2007 US)

	CO_2	CH_4	BC	SO_2	CO	OC	N_2O	HFC-134a
5% discounting	5.4	4.3	5.3	21	2.9	4.6	0.6	0.05
1.4% discounting	56	13	10	24	10	5.2	6.1	0.20
Declining discounting	20	6.7	6.5	22	5.0	4.7	2.1	0.09

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

Table 3. Valuation of environmental damages (billions $2007 US) by sector, 2011 US emissions

Discount rate / Sector	Full SCAR			Limited SCAR	Composition-health only
	5%	3%	1.4%	3%	3%
Electricity	150±80	220±100	500±230	170±90	90±72
coal-fired	130±70	180±80	390±170	140±80	84±67
gas-fired	19±8	36±17	100±50	20±11	5±4
Transportation	110±50	180±80	450±210	100±50	40±32
Industrial combustion	34±17	56±26	150±70	43±23	18±14

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.

Table 4. Valuation of anthropogenic emissions at different times (damages per ton in $2007 US)

Year/discount rate	CO_2	CH_4	BC	SO_2	CO	OC	N_2O	HFC-134a
2010 / 5%	16	1400	100000	20000	440	33000	4600	36000
2030 / 5%	24	1900	140000	21000	700	36000	7300	57000
2050 / 5%	38	2800	200000	24000	1100	41000	12000	91000
2010 / 1.4%	160	4100	180000	22000	1600	38000	50000	140000
2030 / 1.4%	240	6100	260000	25000	2400	43000	75000	210000
2050 / 1.4%	370	9100	380000	29000	3800	51000	120000	340000

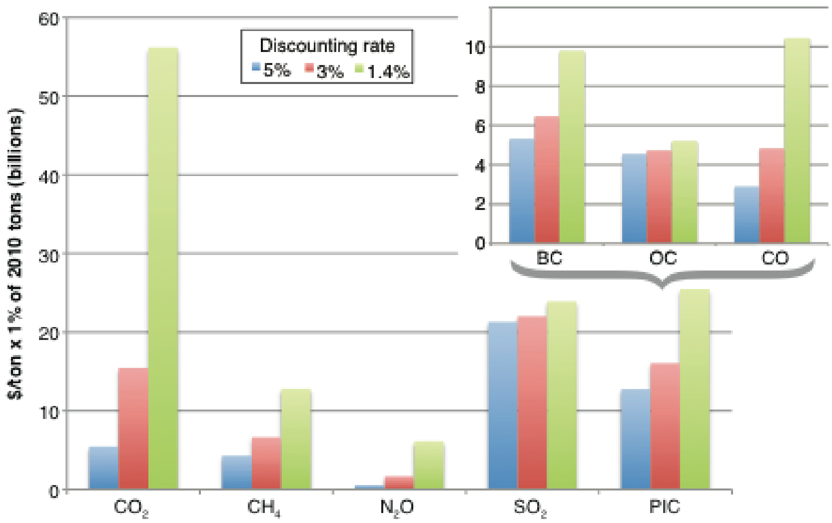

Figure 1. SCAR valuation of 1% of current global anthropogenic emissions (to illustrate the relative benefits of marginal change in emissions) using the indicated discount rates. Products of incomplete combustion (PIC) is the sum of BC, OC and CO (inset). Relative uncertainties for each component are given in Table 1. Numerical values are in Table 2.

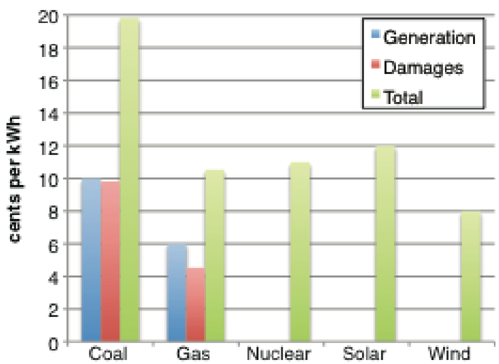

Figure 2. Levelized generation costs for new electricity generation and SCAR-based environmental damages by type (using 3% discounting). Damages are inflated to 2010 $US to match generation costs. Totals are equal to generation costs for nuclear and renewables.

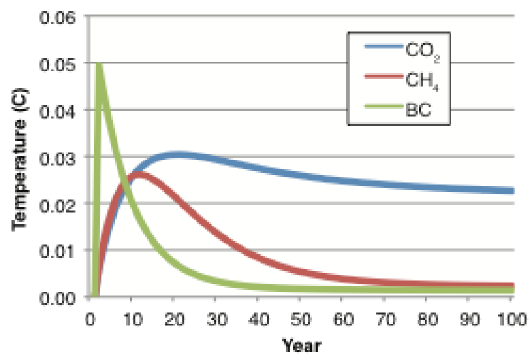

Figure 3. Timescales of temperature response to different forcers (°C per kg x 1 year's worth of current global anthropogenic emissions (excluding open biomass burning)).

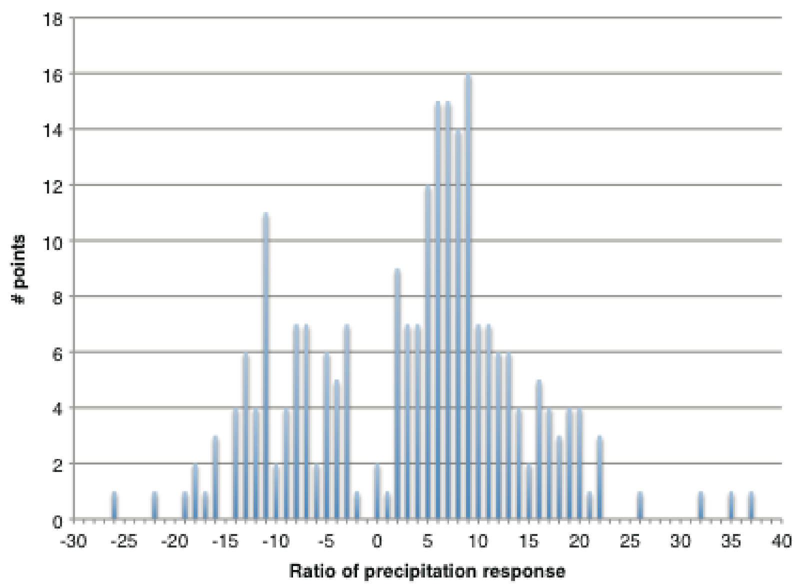

Figure 4. The ratio of precipitation changes in response to forcing by BC and co-emitted species relative to equal global mean LLGHG forcing. Values are from analysis of ~250 land locations from 60°S–60°N where responses were statistically significant in both sets of simulations [*Shindell et al.*, 2012a].

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*, Vol. 6, 2012-10. http://dx.doi.org/10.5018/economics-ejournal.ja.2012-10

Arora, V. K., et al. (2013), Carbon-concentration and carbon-climate feedbacks in CMIP5 Earth system models, *Journal of Climate*. http://dx.doi.org/10.1175/JCLI-D-12-00494.1

Arrow, K., et al. (2013), Determining Benefits and Costs for Future Generations, *Science*, *341*, 349-350. http://emf.stanford.edu/files/docs/340/Science-2013-Arrow-349-50.pdf

Boucher, O. (2012), Comparison of physically- and economically-based CO2-equivalences for methane, *Earth Syst. Dynam.*, *3*(1), 49-61. http://dx.doi.org/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*. http://dx.doi.org/10.1088/1748-9326/4/4/044007

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,. http://dx.doi.org/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. Prüss-Üstün and C. Corvalán, World Health Organization. http://www.unscn.org/layout/modules/resources/files/Climate_change_quantifying_the_impacts.pdf

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. http://ideas.repec.org/a/eee/jeeman/v49y2005i1p68-82.html

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. http://ideas.repec.org/a/spr/climat/v113y2012i2p525-535.html

Cohen, A. J., et al. (2004), Urban air pollution, in *Comparative quantification of health risks*, edited, World Health Organization, Geneva. http://www.healthinternetwork.com/publications/cra/chapters/volume2/1353-1434.pdf

Collins, W. J., M. M. Fry, H. Yu, J. S. Fuglestvedt, 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. http://dx.doi.org/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*Rep.*, 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*. http://facultypages.morris.umn.edu/~kildegac/Courses/Enviro/papers/A%20Cost%20Curve%20for%20Greenhouse%20Gas%20Reduction%20-%20McKinsey.pdf

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. http://hero.epa.gov/index.cfm?action=reference.details&reference_id=92936

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. http://dx.doi.org/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. http://www.lse.ac.uk/GranthamInstitute/publications/WorkingPapers/Papers/100-109/WP109-discount-rates-fisher-effect.pdf

Fuglestvedt, 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. http://dx.doi.org/10.1016/j.atmosenv.2009.04.044

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. http://dx.doi.org/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. http://ideas.repec.org/a/jae/japmet/v22y2007i3p641-656.html

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. http://www.ak-geomorphologie.de/data/Ipccreport_text_9.pdf

Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global warming, *J. Clim.*, *19*, 5686-5699. http://journals.ametsoc.org/doi/abs/10.1175/JCLI3990.1

Hodnebrog, Ø., M. Etminan, J. Fuglestvedt, 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*. http://dx.doi.org/10.1002/rog.20013

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. http://dx.doi.org/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*Rep.*, 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*Rep.*, 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. http://ideas.repec.org/a/spr/climat/v110y2012i1p123-141.html

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.*, 2(3), 205-221. *DOI 10.1007/s13412-012-0087-7*. http://ideas.repec.org/a/spr/jenvss/v2y2012i3p205-221.html

Kenyon, J., and G. Hegerl (2010), Influence of Modes of Climate Variability on Global Precipitation Extremes, *Journal of Climate*, *23*(23), 6248-6262. http://dx.doi.org/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*, Vol. 6, 2012-13. http://dx.doi.org/10.5018/economics-ejournal.ja.2012-13

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), *The Lancet*, *381*(9874), 1276-1276. http://dx.doi.org/10.1016/S0140-6736(12)61766-8 http://www.sciencedirect.com/science/article/pii/S0140673612617668

Marques, S., and M. Lima (2011), Living in grey areas: Industrial activity and psychological health, *Journal of Environmental Psychology*, *31*(4), 314-322, http://dx.doi.org/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. http://dx.doi.org/10.1016/j.enpol.2012.09.073

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. http://dx.doi.org/10.1016/S0973-0826(08)60466-4

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. http://ideas.repec.org/a/aea/aecrev/v101y2011i5p1649-75.html

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). http://dx.doi.org/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. http://dx.doi.org/10.1016/S0095-0696(02)00031-1

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. http://dx.doi.org/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. http://dx.doi.org/10.1029/2012gl051440.

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.

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, http://dx.doi.org/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. http://dx.doi.org/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. http://www.sciencemag.org/content/326/5953/716.short

Shindell, D. T., A. Voulgarakis, G. Faluvegi, and G. Milly (2012b), Precipitation response to regional radiative forcing, *Atmos. Chem. Phys.*, *12*, 6969-6982. http://www.sciencemag.org/content/326/5953/716.short

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. http://dx.doi.org/10.1016/S0140-6736(09)61716-5
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. http://dx.doi.org/10.1093/aje/kwm308
Tanaka, K., D. Johansson, B. O'Neill, and J. Fuglestvedt (2013), Emission metrics under the 2°C climate stabilization, *Climatic Change Letters*, 9 pp. http://dx.doi.org/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. http://dx.doi.org/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*, Vol. 2, 2008-25. http://dx.doi.org/10.5018/economics-ejournal.ja.2008-25
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, http://dx.doi.org/10.1016/j.envsci.2009.08.006.
UNEP (2011), Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers*Rep.*, 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*Rep.*, Nairobi.
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. http://ideas.repec.org/a/kap/jrisku/v27y2003i1p5-76.html
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. http://archinte.jamanetwork.com/article.aspx?articleid=1108716

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.