

Response to Anonymous reviewer comments

I thank the reviewer for his/her thorough reading of the paper and extensive comments. In particular, I appreciate the many instances where the reviewer pointed out that particular references, methods, or reasoning was unclear, as I expect much of that stemmed from the different perspectives and background of those coming from different disciplines.

Reviewer comments in italics, my replies in regular type.

General comments not also addressed in the specific comments: *A conclusions section is missing. The Methods section should be presented before the Results section.*

Several paragraphs of conclusions were grouped in the Discussion section, and these are now separated into their own Conclusions section.

The literature has many examples of papers where the Methods precede the Results section, and many where the Methods are given at the end (many journals have specific requirements for one or the other). In this case, since there are multiple impacts calculated and each requires a description of the technical details, the original Methods was ~10 pages long and I expect provided more detail that would be of interest to most Economics readers (but is nevertheless important to include to fully document this work). Thus I have followed the reviewer's suggestion to describe the Methods prior to the results by moving the primary description to a new Methods section preceding the Results section (containing about half the material in the previous Methods section) while keeping the remaining more technical material in a renamed "Methods: Technical Details" section at the end.

Specific comments

Introduction p.2: The first paragraph requires references. There are a number of papers that analyse "...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." You could elaborate more on the debate in the literature.

I have added a number of references here. As reviewer 1 pointed out, discussion of basic topics such as which impacts to internalize can be found in any textbook on environmental economics, and hence the debates about these concepts are likely familiar to most readers. As this is simply the introduction to the detailed analysis that follows, its purpose is simply to introduce several issues that will arise later on rather than to review the literature on these topics. More discussion on each topic follows later when I discuss which impacts are internalized, discount rates, and comparison across pollutants.

Introduction p.2: "Prior studies have provided compelling demonstrations of the importance of linkages between climate change and air quality valuation ... but have typically not fully represented the climate impact of short-lived emissions, especially aerosols and methane." You could support the last statement providing references. Why

is this the case? What are the problems representing the climate impact of short lived emissions?

I have added a number of references here. I suspect that the climate impact of short-lived pollutants was not included in most prior analyses because authoritative assessments by the climate science community (e.g. IPCC) did not include metric values for most of these until this year. There may have also been a reluctance to include the climate impact of compounds that are not formally part of the current policies formulated by the United Nations Framework Convention on Climate Change, which includes only methane among the shorter-lived emissions. I do not see a good reason for having neglected well-mixed greenhouse gases other than CO₂ (including methane, N₂O, etc.).

Introduction p.3: "While many uncertainties remain in this type of analysis..." You could discuss such uncertainties here.

The uncertainties and limitations in analysis of environmental damages due to atmospheric release are the primary topic of the Discussion section, so I have added a pointer to that section here.

Approach p.3: "Thus social costs for emissions of other pollutants should at minimum include their impacts on these same quantities." Which quantities? This is not clear.

This referred to the quantities in the previous sentence, but as this sentence begins a new paragraph I've added a parenthetical comment listing several of these impacts: "health, agriculture, property damage, etc".

Approach p.4: "I evaluate a broad Social Cost of Atmospheric Release (SCAR) for emissions of CO₂, CH₄, carbon monoxide (CO), SO₂, BC, organic carbon (OC), nitrous oxide (N₂O) and the exemplar hydrofluorocarbon HFC-134a" What exactly was the criteria used to select these pollutants?

See reply to next comment.

Approach p.4: "The pollutants emphasized here are the major drivers of global mean climate ...and the global health burden from poor air quality." OK, but what is the evidence? You could discuss this.

The reviewer notes that the end of this paragraph gave the criteria used to select the pollutants that he/she asked about in the previous comment. However, I agree it wasn't obvious at the start of the paragraph, so have rearranged the sentences to give the motivation for choosing these specific pollutants first, then list the pollutants themselves. While I had cited the studies that provided the evidence for the role of these pollutants, I realize that many Economics readers may not be familiar with these documents so have now spelled out that these are authoritative international assessments of climate change (by the IPCC) and of public health (by universities and the WHO).

Approach p.4: “This analysis is primarily concerned with pollutants that have multiple impacts (e.g. health and climate).” You could provide a table describing the exact impacts on health and climate of each of the selected pollutants.

I have added such a Table, and thank the reviewer for this useful suggestion.

Approach p.4: “Most of these substances are now controlled and decreasing” what is the evidence?

The most up-to-date and comprehensive review of the evidence on the changing concentration of the ozone-depleting substances is given in the new IPCC Fifth Assessment Report, so I’ve added a reference to the relevant chapter here.

Approach p.4: “A few other pollutants” examples?

Two examples (volatile organic compounds and ammonia) were given later in that same sentence, but I’ve moved those to just after the phrase ‘A few other pollutants’ for clarity.

Approach p.4: “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.” Economic valuation has been conducted, see for example:

*Swain, E. B., Jakus, P. M., Rice, G., Lupi, F., Maxson, P. A., Pacyna, J. M., ... & Veiga, M. M. (2007). Socioeconomic consequences of mercury use and pollution. *AMBIO: A Journal of the Human Environment*, 36(1), 45-61.*

*Spadaro, J. V., & Rabl, A. (2008). Global health impacts and costs due to mercury emissions. *Risk Analysis*, 28(3), 603-613.*

*Sundseth, K., Pacyna, J. M., Pacyna, E. G., Munthe, J., Belhaj, M., & Astrom, S. (2010). Economic benefits from decreased mercury emissions: Projections for 2020. *Journal of Cleaner Production*, 18(4), 386-394.*

The reviewer is correct in pointing out that there are several studies that value damages attributable to mercury, and I thank him/her for pointing out this oversight on my part. I found valuation literature for the US that included all health impacts, but not for the world (global studies covered single effects such as IQ only, for example, as in the 2nd and 3rd references given by the reviewer, whereas premature mortality is the largest component and was not monetized at the global level). Given that the health effects occur via fish consumption, and that there are substantial differences in dietary practices I did not want to apply the US values elsewhere. Hence I have added valuation of mercury emissions to the US sectoral analysis in the Illustrative Applications sections but have not included it in the global valuation, and revised the approach to state this.

Approach p.5: “This analysis facilitates discussion of the relative importance of those emissions with primarily a near-term influence ...and those with effects that are large over long-terms” How exactly? This is not clear

I have clarified this paragraph to compare the SCAR with the SCC, and to state that comparison of the SCAR valuation of different pollutants at a particular discount rate shows the relative importance of short- vs long-lived pollutants, while comparison of SCAR valuations across discount rates shows how the physical timescales interact with

the time-preference for the value of money.

Results p. 5: “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 CO₂ (equivalent to the traditional SCC) are 11-140 \$/ton using constant discounting rates of 5 to 1.4%” Since valuation is highly sensitive to discounting, you should provide a detailed explanation of the reasons to use constant discount rates (of 5 to 1.4%) and the implications for your calculations

The motivation behind the choices of discount rates (both constant and declining) is now discussed in the preceding section (5th paragraph of Methods).

Results p. 5: “integrated assessment model (IAM) estimates” You could discuss this methodology

The methodology used in the IAMs is based on a decrease in GDP that’s proportional to the square of the change in temperature, as now described in some detail in the preceding Methods section (see response to comments on Methods). This damage function includes climate-health impacts, but the various impacts contained within the damage function are for the most part not readily separable in the IAMs.

Results p. 6: “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 or a particular temperature increase” What is the reason to base the valuation on the mean of these two estimates? Are they comparable? Why did you assume 50% uncertainty in climate health impacts?

The two estimates of climate-health impacts each have their own limitations: the IAM climate-health estimates are difficult to apportion as the damage functions include all climate-related impacts and the underlying climate-health linkage is based on very simplified assumptions, while the WHO-based estimate depends on a single study’s result for the number of premature deaths attributable to current warming. Hence there does not seem to be a clear justification for decisively favoring one over the other, and thus I chose the mean of the two along with a 50% range so that the total valuation range for this impact would encompass both the available estimates. This is now described in the preceding Methods section.

Results p. 6: “The use of a declining discount rate” You should explain why do you use a declining discount rate

This is now discussed in the preceding section (5th paragraph of Methods).

Results p. 6: “the relative SCAR valuation per ton is much larger for methane and the aerosols or aerosol precursor species BC, SO₂ and OC than for CO₂, with a ton of

methane causing ~30-90 times more damage than a ton of CO₂ and a ton of the aerosols causing up to ~6000 times more damage.” You should explain why

I’ve added an explanation, as suggested: “The larger valuation on a per ton basis stems primarily from the greater radiative efficiency per molecule of non-CO₂ compounds relative to CO₂ and the additional composition-health impacts.”

Results p. 7: “Uncertainty in the regional aerosol impacts is obviously not systematic across pollutants.” This is not obvious for me. You could explain why.

I have added that this uncertainty is not systematic across pollutants “as it does not apply to non-aerosols”, so uncertainty in this aerosol-related impact has no effect on non-aerosols.

Results p. 7: “Differences may arise from the use of different carbon-cycle models, atmospheric lifetimes and radiative efficiencies.” True, you should discuss the model used in your analysis and how this is different to others.

I have included full details on the values for all these quantities in my modeling setup, and indeed the entire computer code is posted alongside the paper. However, this is not the case for prior publications, so I cannot comment more specifically on the differences with respect to other models as the papers do not include the precise values they used for any of these properties.

Results p. 8: “I present the valuation of 1% of current global anthropogenic emissions” Why 1%?

As stated in that same sentence, 1% is “a level small enough that it can still be considered a marginal change”. This is simply for illustrative purposes.

Results p. 8: “Valuation of HFC-134a is always relatively small despite it having the highest per ton valuation” You should explain why

I have added that this is “due to the small amount that is currently emitted”.

Illustrative applications p.9: It is not clear how did you obtain the valuation of environmental damages presented in table 3

I have added that this valuation is obtained “by simply multiplying the SCAR valuation by the associated emissions”. In the next sentence, I specify that the valuation for US emissions by sector is “obtained by multiplying the SCAR by emissions attributed to those sectors [US EPA, 2012; 2013a; b]”.

Illustrative applications p.9: “much of the uncertainty is systematic across sectors” how did you measured the uncertainty figures?

This is a good point. I have added that “uncertainty comes solely from the SCAR as uncertainty in emissions is assumed to be much less” since this refers to US emissions, which are well known in comparison with the 50-80% uncertainty in valuation.

Illustrative applications p.10: “the latest estimates of the health effects of ambient air pollution are much greater than the previous Global Burden of Disease values.” You should mention them

I have added the two sets of values, stating that they are “3.2 million premature deaths annually due to outdoor PM_{2.5} in the 2010 Burden [Lim et al., 2013] versus 800,000 in the 2000 version that included urban PM_{2.5} only [Cohen et al., 2004]”.

Illustrative applications p.11: “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.” Exactly what damages are considered here? How exactly did you obtain such figures?

I have added the requested explanations: “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.” I believe it is now clear that the damages that are considered are those that are included within the SCAR metric, reinforced by the additional phrase ‘damages related to atmospheric releases’ at the beginning of the sentence.

Illustrative applications p.11: “There is substantial variation across coal-fired power plants, however, with damages typically greater for older plants and less for newer ones.” You could provide some figures about the variance of emissions.

I have revised the subsequent sentence that included the variance in damages to also include the variance in air-quality related emissions: “A coal plant with air-quality related emissions at the 5th 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 95th 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]”.

Illustrative applications p.12: “The total levelized energy costs for new capacity in a recent US government estimate... are about equal for conventional coal and nuclear or renewables, with conventional combined cycle gas costing substantially less.” You could mention the costs here.

The costs are shown in Figure 2, and I have added a reference to that figure here.

Discussion p. 14: “Furthermore, there are multiple benefits that have not been taken into account in this analysis.” Why? You may be underestimating costs and benefits in your valuation exercise

I have revised this sentence to explain that “there are multiple benefits for which valuation methodologies have not yet been as thoroughly developed and hence these have not been taken into account in this analysis”. Indeed the point of this paragraph in the discussion is to say why the damage estimates obtained here may be in fact conservative. See also reply to next comment.

Discussion p. 14: “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.” The valuation is therefore not accurate.

I readily agree that the valuation is incomplete, but that does not mean that it is not useful. The community does not yet, at least to the best of my knowledge, have an agreed methodology to monetize impacts such as the contribution of air pollution to depression or the impact of CO₂ on ocean acidification. The discussion raised here is therefore important, I feel, to make it clear that while these results are a step towards more comprehensive emission metrics, they remain incomplete. Nonetheless, I feel their utility should be measured against the current standard rather than an ideal metric (which may never be achieved). Emission metrics used in the Kyoto protocol or the SCC used by the US government, for example, include an even more limited set of impacts than the SCAR, yet already affect society quite substantially. The point of the SCAR is to address a real-world situation where incomplete metrics are in active use, and to suggest a path forward to making those metrics more complete. Hence even if it does not include all known impacts and remains imperfect, it can still be a step forward and useful.

Note that similar arguments have been made by others. For example, Nordhaus and Boyer wrote of climate-change impacts “ Although the literature in this area is extensive, there are many gaps in coverage of sectors and countries, and many of the most important impacts have not been satisfactorily quantified and monetized. Notwithstanding the imprecision of the estimates, it is essential that impacts be considered in the climate-change debate.”

To clarify some of these issues to readers, I have added just after “suggesting that these damages are conservative” the phrase “and that there are ample opportunities to further improve the comprehensiveness of social cost metrics”.

Discussion p. 16: “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” True, the assumptions on the damage function are very important and should be discussed in detailed

I have included additional discussion of the damage function in the Methods section (where it is first introduced).

Discussion p. 16: “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.” Due to the huge uncertainty associated with the valuation methods, I am not sure that this analysis facilitates the

examination of how society values different impacts occurring over different timescales

It is important to remember that much of the uncertainty is systematic across pollutants. If climate sensitivity is at the high end of its range, then the impacts are towards the upper end of the range for all pollutants, not just one or two. Similarly a higher VSL or population growth rate would affect all pollutants. While some sources of uncertainty are not systematic, this returns us to the point raised two comments earlier about the utility of informing decision-making with imperfect information. Although the concentration-response function quantifying how air pollution leads to premature death has a large uncertainty, air pollution is killing people now, and I would argue that it does not make sense to ignore what information we do have on this function while waiting until the uncertainty is reduced. Best estimates are available within the range, which are used in the SCAR as in most climate and air quality-related policy making, and there is ample literature on decision-making under uncertainty, so I do not believe large uncertainties should be a barrier to using the best available information.

Methods pp. 17-18: The first paragraph requires references. A detailed explanation of the IAM is needed here.

I have added references to several papers describing widely-used IAMs. I have also added a brief discussion of how the IAMs calculate damages to the first paragraph of the Methods section, with more extensive discussion in the fourth paragraph where the damage function from the DICE IAM (as used here) is described in some detail.

Methods p.19: "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." You should elaborate more on the assumptions of this damage function and how realistic it is to assume that the different pollutants will have the same impacts on temperature changes.

As noted in my response to the previous comment, I have elaborated more on the DICE damage function as suggested. I do not, however, assume that different pollutants will have the same impact on temperature changes. Radiative forcing is calculated for each pollutant, and then the temperature response to each individual pollutant's forcing is calculated and used in the SCAR (see Figure 3 for an illustration of this). I have moved the sentence on the temperature response calculation to just after the description of the forcing calculation and before the description of the SCAR's climate damages calculation to ensure this is clear.

Methods p.20: "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." True, and you should explain why this is the case for each pollutant

I have revised to clarify that the increase is due to the dependence of the climate impacts on the square of the temperature change and GDP and the dependence of the health

impacts on increasing population and GDP, and that this applies generally to all pollutants. Differences between pollutants arise due to their differing lifetimes, but that is not the primary point here (as that is true for the present as well).

Methods p.20: “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 CO₂ when using comparable climate-health impacts, and I use the same discount rates” Why? You should provide a detailed explanation to follow this methodology.

I have added discussion of the motivation for both parts of this description: “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 CO₂ 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.”

Methods p.21: “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].” I am not sure that the author understands what a declining discount rate is. Why is an exponential discount rate used?

A declining discount rate is simply one that decreases with time, as the name indicates. To make the description even clearer, I’ve added just after saying that “I use a rate starting at 4% and decreasing exponentially with a 250 year time constant” the phrase “(i.e. the percentage rate is $4 \cdot \exp(-t/250)$ where t is the time in years)”. This seems unambiguous to me.

As stated in the text quoted by the reviewer, the exponential decrease in the rate is used to approximate the mean behavior in several prior studies. To demonstrate this, I have plotted the declining discount rate produced by my formulation below. The curve indeed approximates the mean behavior of the prior studies as shown in the Figure in *Arrow et al., 2013*.

