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Perspective has a strong effect on the calculation of historical contributions to global warming

Ragnhild B Skeie[1], Jan Fuglestvedt[1], Terje Berntsen[1], Glen P Peters[1], Robbie Andrew[1], Myles Allen[2,3] and Steffen Kallbekken[1]

[1] Center for International Climate and Environmental Research—Oslo (CICERO), PO Box 1129 Box 1129 Blindern, 0318 Oslo, Norway
[2] Environmental Change Institute, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, United Kingdom
[3] Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

E-mail: j.s.fuglestvedt@cicero.oslo.no

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Abstract

The politically contentious issue of calculating countries' contributions to climate change is strongly dependent on methodological choices. Different principles can be applied for distributing efforts for reducing human-induced global warming. According to the 'Brazilian Proposal', industrialized countries would reduce emissions proportional to their historical contributions to warming. This proposal was based on the assumption that the political process would lead to a global top-down agreement. The Paris Agreement changed the role of historical responsibilities. Whereas the agreement refers to equity principles, differentiation of mitigation efforts is delegated to each country, as countries will submit new national contributions every five years without any international negotiation. It is likely that considerations of historical contributions and distributive fairness will continue to play a key role, but increasingly so in a national setting. Contributions to warming can be used as a background for negotiations to inform and justify positions, and may also be useful for countries' own assessment of what constitutes reasonable and fair contributions to limiting warming. Despite the fact that the decision from COP21 explicitly rules out compensation in the context of loss and damage, it is likely that considerations of historical responsibility will also play a role in future discussions. However, methodological choices have substantial impacts on calculated contributions to warming, including rank-ordering of contributions, and thus support the view that there is no single correct answer to the question of how much each country has contributed. There are fundamental value-related and ethical questions that cannot be answered through a single set of calculated contributions. Thus, analyses of historical contributions should not present just one set of results, but rather present a spectrum of results showing how the calculated contributions vary with a broad set of choices. Our results clearly expose some of the core issues related to climate responsibility.

1. Introduction

Emissions driving climate change occur in a highly heterogeneous world. There are vast differences in income, population, resources, technologies and capacity across countries. In light of these stark differences, notions of distributive fairness have played a crucial role in the international climate policy debate. Whereas there is a multitude of alternative fairness concepts (Klinsky and Dowlatabadi 2009), the policy debate has largely centered on the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC), which was established by the 1992 UN Framework Convention on Climate Change (UNFCCC). In particular, a proposal by Brazil in 1997 to set mitigation targets according to the impact of countries' historical emissions on global warming spurred academic efforts to quantify the historical contributions of different countries to warming (e.g. den Elzen *et al* 2005, Höhne *et al* 2011, Rive and Fuglestvedt 2008, Matthews 2016, Matthews *et al* 2014, Ward and Mahowald 2014, Prather *et al* 2009, den Elzen *et al* 2013, Müller *et al* 2009, Rosa *et al* 2004).

Research on historical contributions to climate change developed in tandem with the political process. The Brazilian proposal, and the research that followed, was based on the assumption that the political process would lead to a global top-down agreement. The idea of using an agreed formula to distribute countries' mitigation efforts is part of such an approach. The Copenhagen Accord in 2009 marked a shift away from this approach, and the Paris Agreement cemented a new bottom-up approach. This has fundamental implications for the role of historical responsibility in policy debates.

Searching for the one consensual common formula, which policymakers could use to determine the distribution of efforts in a climate agreement, was never likely to succeed. Underdal and Wei (2015) even argue that 'intensive search for a single authoritative "fairness-optimizing" formula may well *increase* the risk of deadlock'. The research on historical contributions to climate change needs to embrace the new political realities, and accept that the role is not to help identify the 'single authoritative fairness-optimizing formula'. The political process leading up to the Paris Agreement acknowledged what has always been true: 'Individual countries can decide, largely on their own, what is in their interest' (Victor 2014). This was made explicit in the 'Lima call for climate action' (UNFCCC 2014) from COP20, which states that when countries submit their contributions they may provide information on 'how the Party considers that its intended nationally determined contribution is fair'.

Whereas the Paris Agreement makes reference to equity principles, differentiation is in practice left up to each country to decide for itself, as countries will submit new national contributions every five years without any international negotiation over the contributions. Civil society, politicians and other actors will use all relevant information (to further their own causes) in these national debates. It is very likely that considerations of distributive fairness will continue to play a key role (see e.g. the recent contribution by Robiou du Pont *et al* (2017)), but that it will do so increasingly in a national setting. What is considered fair in India may be widely different from what is considered fair in the USA. Interpretations of fairness concepts are likely to diverge, and this divergence will tend to reflect conflicts of interest (Kallbekken *et al* 2014). Attempts to find a single authoritative and consensual formula are therefore unlikely to be of broad interest.

What is much more likely to be of interest are comprehensive assessments of contributions to climate change: What is for example Canada's contribution to climate change, viewed from a plurality of perspectives? Are the results robust? Do they depend critically on certain key choices, or do they more or less hold under a range of different interpretations? Would including a perspective on historical responsibility tend to require more or less of a country than their current ambition? Furthermore, the link between contribution to and responsibility for climate change is far from clear (Müller *et al* 2009, Gardiner 2004).

The Paris Agreement also added a new element to the debate. Loss and damage was for the first time included in an agreement as a separate issue (until then it was incorporated into the adaptation agenda). Despite the fact that the decision from COP21 explicitly rules out compensation in the context of loss and damage, it is quite likely that considerations of historical responsibility for causing loss and damage will play a key role in future discussions under this agenda item (Mechler and Schinko 2016, James *et al* 2014, Thompson and Otto 2015, Mace and Verheyen 2016).

This paper contributes to the renewed debate by presenting a broad and systematic analysis of how various scientific and policy-related choices influence the calculations of historical contributions for individual countries. While many earlier papers adopt one or a small set of choices, we expand this view and analyze in a broad and systematic way the impacts of different perspectives.

2. Method

To calculate the relative contribution from countries/regions to global mean surface temperature (GMST) change, we construct time series of emissions of GHGs, aerosols and their precursors for each country/region, and use a simple climate model (an Energy-Balance/Upwelling-diffusion model) to calculate the temperature response (Skeie *et al* 2014, Olivié and Stuber 2010). The model and sources of emissions data and albedo changes are described in the supplementary material. We define contribution in counterfactual terms: how would the change in GMST be different if a particular subset of emissions were absent? In a non-linear model, the sum of calculated contributions to GMST change may be different from the calculated response to total emissions, but different non-linearities, such as the logarithmic relationship between CO_2 concentrations and radiative forcing and the increase in CO_2 airborne fraction with emissions, work in opposite directions. Given these complexities, the counterfactual approach is the simplest way of framing the contribution question, and that which is most relevant to observed climate change. We calculate the historical contribution to global warming for all dimensions shown in figure 1 for which we have

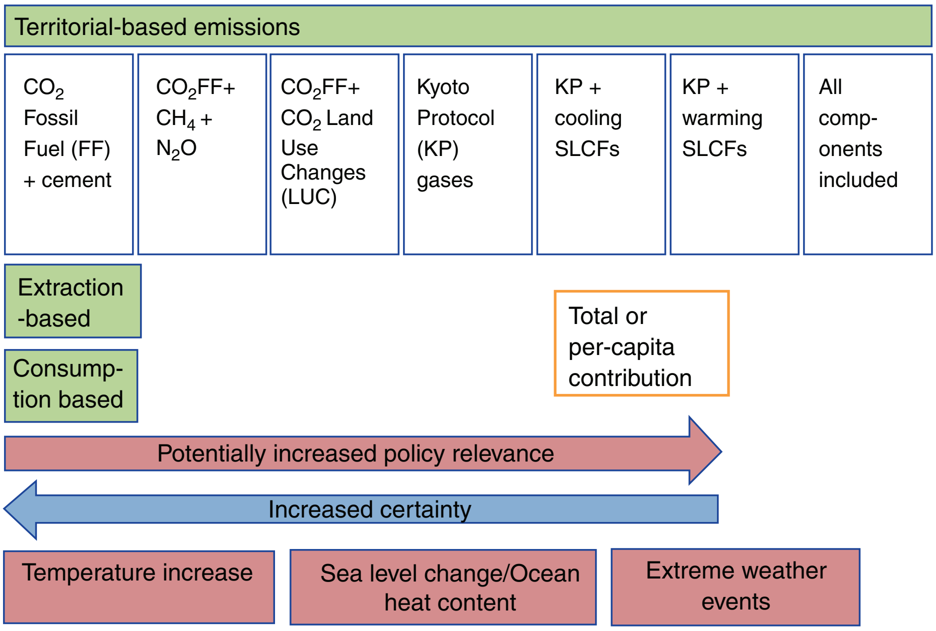

Figure 1. Schematic overview of four of the six dimensions used in calculations of historical contributions; choice of components, accounting basis (green boxes), climate indicator (red boxes) and total or per capita contribution. (SLCF: Short-lived climate forcers. LUC: Land use change). In addition, also different combinations of start year and evaluation year are included in the analysis.

sufficient data. We explore six main dimensions in calculating historical contributions:

First is the question of *which components* should be included in the calculations (section 3.1). From a minimum of only CO_2 from fossil-fuel combustion and cement production (hereafter CO_2FF) the list can be expanded to include other long-lived GHGs, CO_2 from Land Use Change (LUC), changes in albedo, and short-lived gases and aerosols (short-lived climate forcers; SLCF) that were not included in the Kyoto Protocol (KP).

Second, the *start year* from which emissions are included is a crucial choice, and is closely linked to questions beyond natural science (section 3.2). To what extent should current generations be held responsible for historic emissions?

Third, the choice of which year the climate response is evaluated—*evaluation year*—is related to the question of response times in the climate system (section 3.3). It may also be related to a target year as given by climate polices.

Fourth, what is the appropriate *accounting basis* for calculating historical contributions (section 3.4)? The standard method for allocating emissions to a country is to use the emissions actually occurring *in* the territory (territorial emissions). Other perspectives are to calculate historical contributions due to the emissions occurring when fossil fuel extracted in a country is burned (extraction-based emissions) or to allocate the emissions due to production to the country where the products are consumed (consumption-based emissions) (Davis *et al* 2011). For the extraction and consumption based methods, only emissions of fossil fuel CO_2 are available, and the emissions are available for a shorter period than for territorial based emissions.

Fifth is the question of whether variations in *population* size between countries should influence how historical contributions are calculated (section 3.5). Neither present nor historical population are normally used as bases for calculating contributions to global warming, but there are arguments supporting their use. (An alternative—which we do not explore here—is normalizing the contributions to the GDP of the countries.)

Finally, there is a choice of *indicator* of climate change (section 3.6). Global mean surface temperature (GMST) change is the most commonly used indicator of climate change, and thus also for quantifying the relative contributions of emissions from different regions. Here we use a simple climate model (SCM) (see supplementary material available at stacks.iop.org/ERL/12/024022/mmedia) to calculate the GMST, but this corresponds to using cumulative CO_2-equivalent emissions based on the emission metric Global Temperature change Potential (GTP) (Shine *et al* 2007). We also show results using cumulative CO_2-equivalent emissions based on GWP_{100}, and ocean heat content (OHC). However, other indicators such as incidence of extreme events and damage costs could be seen as more policy relevant, albeit much harder to calculate and attribute.

We calculate relative contributions to global climate change for the regions/countries indicated in figure S1 as well as for international shipping and aviation for seven set of components (the boxes in figure 1). The uncertainties in both the regional emissions and the calculated response increase from left to right in figure 1. On the other hand, the policy

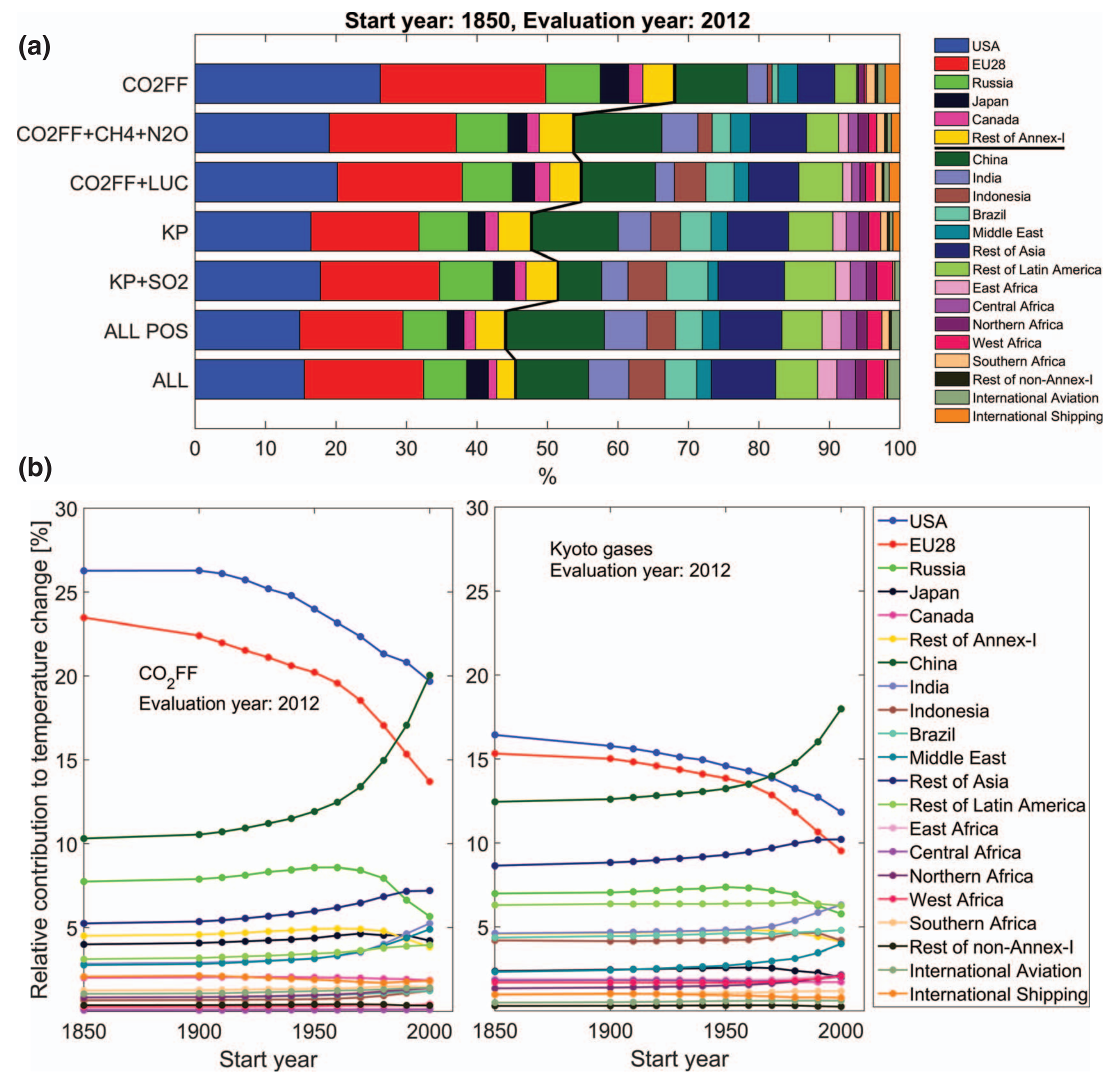

Figure 2. Overview of contributions to GMST in 2012 of total territorial emissions. Panel (*a*) Impact of various choices with regard to which components to include. Annex-I countries to the left of the black line. Panel (*b*) Impact of start year of emission for the CO_2FF only case (left) and for Kyoto gases case (right). In the supplementary material panel (*b*) is presented in the same format as panel (*a*).

relevance increase to the right due to broader coverage of anthropogenic drivers affecting climate.

While there are significant uncertainties in input parameters, we do not perform an uncertainty analysis of climate system parameters, since our focus here is on the impact of the various user choices for any given climate response. Hence, we limit our calculations by using the best estimates of each parameter. All the evidence is that large-scale climate change, once averaged over stochastic variability, is a deterministic response to external forcing (e.g. Stott *et al* 2000). Our approach, therefore, assesses the relative impact of user choices on the real-world GMST response, even though we do not know precisely what that real-world response actually is. Even if we did a complete uncertainty analysis (e.g. a Monte Carlo analysis), the different contributions would need to be compared across the same climate system parameter set, similar to our use of best estimates. The impact of response uncertainty on the impact of user choices is a second-order effect, and previous studies show that uncertainties in climate and carbon cycle models have smaller effects than effect of user choices such as time period, evaluation year etc. (e.g. Höhne *et al* 2011), further supporting our chosen approach.

3. Results

In this section, we calculate historical contributions to change in GMST and Ocean Heat Content (OHC, which is a clear indicator of one main component of sea level rise) for the six different perspectives described in section 2. We explore various policy related choices, and illustrate the difference in historical contributions for the various choices. In all cases, except one (section 3.4), we use territorial emissions.

3.1. Components included

Figure 2(*a*) (and table S1) shows how the contributions to GMST change depend on the choice of which components that are included, considering the total contribution from territorial emission between 1850 and 2012, with 2012 as the evaluation year. When only

CO_2 fossil fuel emissions (CO_2FF, incl. cement production) are taken into account, the Annex-I countries as a group contribute 68% of total warming More than two thirds of this is from USA and the EU28. When we include CH_4 and N_2O, the Annex-I contribution decreases to 54%.

Including CO_2 from LUC leads to a decrease in the Annex-I contribution compared to the CO_2FF case. The relative contributions from Indonesia and Brazil increase from below 1% to 4.5% and 4.0%, respectively, when LUC CO_2 emissions are included. In figure 1 we have indicated that the uncertainties in contribution to GMST change generally increase as more components are added. There is a large spread between different estimates of global LUC CO_2 emissions (Houghton *et al* 2012) and there are also inconsistent definitions of what the net LUC flux actually comprises (Pongratz *et al* 2014). For CO_2 LUC we have used emissions for that year, but the emissions might be due to LUC before the start year and emissions may continue for several years after the LUC (Hansis *et al* 2015). See supplementary material for explanation of our approach.

When all Kyoto Protocol gases are included (KP case), the contribution (from emissions between 1850 and 2012) from Annex-I countries is less than 50%, and the contributions from the USA, the EU28 and China are 16%, 15% and 12%, respectively. Including cooling components (with the contribution from international shipping removed from the sum), the Chinese contribution is reduced from 12% to 6%. Finally, including all warming components, both short- and long-lived, the contribution from the Annex-I countries decreases compared to the KP case.

Considering all components, both warming and cooling, short- and long-lived, the relative contributions to GMST change are similar to the Kyoto gases case, with two exceptions. The international shipping sector has not contributed to net warming when all components are included, while for the KP case the contribution was 1%. This is due to the cooling effect of SO_2. For international aviation, the change is in the opposite direction, from 0.5% in the KP case to 1.7% when all components are considered, including contrails. (Figure S5 shows the radiative forcing (RF) for the countries/regions by component/mechanism for the case with all components).

3.2. Start year

A key question is in which year accounting should begin. The historical development of emissions has been very different from country to country. Early industrialized countries had a large share of global CO_2 emissions through the early 20th century, while emerging economies now have a much larger share of global CO_2 emissions than just a few decades ago.

The calculations in section 3.1 all used 1850 as the start year. Figure 2(*b*) illustrates the consequences for historical contributions when the start year is varied. We show this impact for two cases, CO_2FF (left) and the KP gases (right), using 2012 as evaluation year in both cases. For the case of CO_2FF only, the contribution from the EU28 and the USA decreases with later start years, whereas for China the contribution increases. China is the third largest contributor for a start year before 1990 after the USA and the EU28. China is the second largest contributor for start year of 1990, and if the start year is 2000, it passes the USA, and is the largest contributor.

For the KP case, the relative contributions of Annex-I countries are shifted to lower values over the entire period of start years considered, and China is the largest contributor with start year later than 1970. Note also that the region Rest of Asia has relative contribution equal to the EU28 with 1990 as a start year. The nine countries/unions USA, the EU28, Russia, Japan, Canada, China, India, Indonesia, Brazil are responsible for 69% with start year 1850, and 65% with start year 1990 for the KP case. The corresponding numbers for CO_2FF are 78% and 73%. An evaluation year later than 2012 would make the KP case more similar to the CO_2FF case.

3.3. Evaluation year

The evaluation year is often set equal to most recent year with emission estimates. Later evaluation years may also be chosen to capture the response of the climate system. As mentioned, this choice may also be seen in relation to a target year in climate agreements. A figure similar to figure 2(*a*) but with evaluation year 2100 is shown in the supplementary material. When the evaluation year is moved to 2100 (for emissions during the period 1850–2012) the differences between the cases with various sets of components included are reduced. This is due to the limited roles of the shorter-lived components on this timescale. For China, the variation contributions for evaluation year vary between 6.3 and 14.1% with 2012 as evaluation year but changes to 10.7%–11.5% for 2100. Due to the short-lived effect of SO_2 cooling the historical contribution from international shipping to GMST change in 2100 is positive.

3.4. From extraction to consumption

For some countries, the relative contribution to GMST can be very different depending on where in the extraction-to-consumption chain contributions are calculated. Figure 3 shows the results for extraction/territorial/consumption based emissions (start year 1990 and end year 2013; CO_2FF only, evaluation year 2013) for the top 15 countries in each of the three cases (in total 23 different countries) in addition to the 'rest of the world'. The difference between the calculated contributions using territorial and consumption-based is small (a few percentage points) while the impact of choosing extraction-based emissions is much larger. Several countries have a very low share (Japan, Italy, Korea, France, Spain), while other countries such as Norway, Venezuela, Australia, Saudi

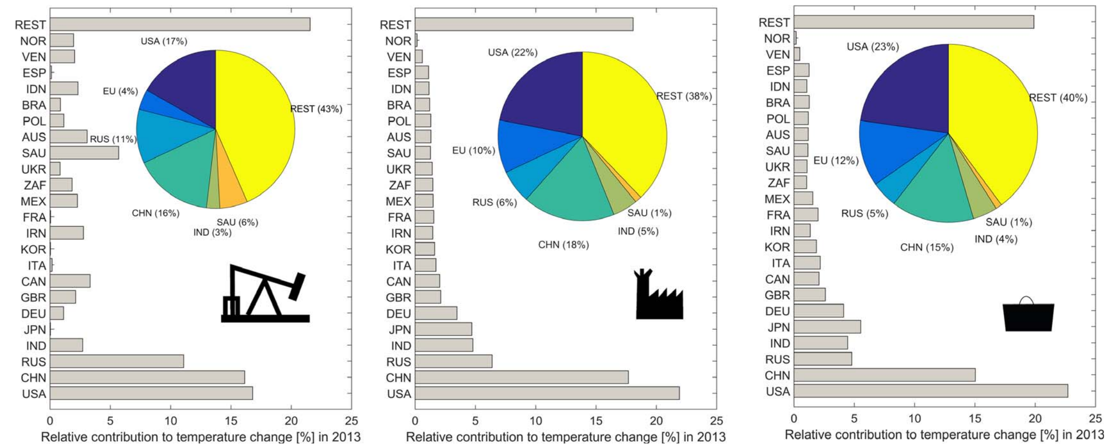

Figure 3. Contributions to GMST change for CO_2FF only for three different perspectives: (*a*) extraction (*b*) territorial (*c*) consumption.

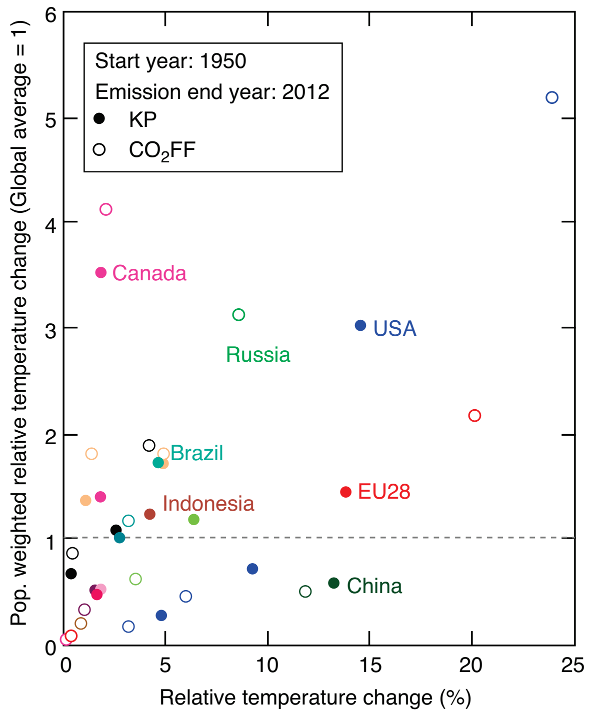

Figure 4. Contributions to GMST change for both population adjusted contributions to GMST change normalized to the global mean values (vertical axis) and the default contributions (horizontal axis).

Arabia have a large increase in contribution when shifting from a territorial to an extraction-based perspective. In other words; trade in embodied carbon is less than trade in real fuels (Andrew *et al* 2013).

3.5. A Per capita perspective

Instead of comparing countries in terms of absolute emissions, an alternative approach is to adjust for population of the countries, which is commonly done for emissions. This has also been used for GMST change (Rive and Fuglestvedt 2008, Matthews 2016) but is less straightforward in this case, mainly due to difference between the time when emissions took place and population at that time and the time period for when climate response materialize. Here we apply this perspective for contributions to GMST change based on one of the approaches presented in Rive and Fuglestvedt (2008). It may seem somewhat counter-intuitive to run a per capita emissions data set (with units of tons of emissions/capita) in a climate model. However, we can instead think of the data as representing the annual emissions of a 'fictitious country' whose annual emissions are equal to the per capita annual emissions of the country in which we are interested. In other words, this can be interpreted as emissions scaled to the size of one person (see supplementary material).

Figure 4 shows relative contributions to GMST change for both population adjusted contributions to GMST change, normalized to the global mean value (vertical axis) and the default contributions (horizontal axis) presented in section 3.1; for both the CO_2FF case and the KP case. The figure shows that USA has a high score in both perspectives, but that it is significantly reduced from the CO_2FF to the KP case. Canada has a high score in the population-adjusted perspective and not in the default perspective, while the opposite is the case for China. We may also note that for Brazil and Indonesia the rankings (on both perspectives) increase substantially if a KP perspective is adopted. In addition, one could go a step further and introduce population adjustments to the extraction perspective. (See figure S3.)

3.6. Other climate indicators

In calculations of historical contributions, GMST has been the default indicator. In some cases cumulative CO_2 emissions (Matthews 2016) or cumulative CO_2-equivalent emissions (den Elzen *et al* 2013) have been used. It may be argued that other indicators may be more policy relevant—also in the context of Loss and Damage; e.g. precipitation, extreme events, sea level rise. In the supplementary material, results for ocean heat content, a proxy for thermal sea level rise, are shown in figure S2. Using OHC as indicator gives more weight to countries with high and early CO_2 emissions.

4. Discussion

Our results span a larger range of choices for the calculations of historical contributions compared to earlier studies. We also go beyond previous studies by calculating historical contributions based on extraction- and consumption-based emissions, and we are doing a consistent comparison across different choices. The results of our individual calculations broadly confirm results from earlier studies (e.g. den Elzen *et al* 2005, Höhne *et al* 2011, Matthews *et al* 2014, Ward and Mahowald 2014).

We show that the various choices can significantly affect the calculated contributions for some countries. In general, the choices we have considered have the largest impact for countries that are different from the world average in the mix and timing of their emissions. Given that 'Individual countries can decide, largely on their own, what is in their interest' (Victor 2014), and COP20 inviting each Party to show 'how the Party considers that its intended nationally determined contribution is fair', it is likely that many countries would make choices that minimize their own contribution. A typical developed, industrialized country with a long emission history dominated by CO_2, and a substantial import of consumer goods might want to choose a late start year, early evaluation year, including all components and a territorial based perspective. A developing country with a short emission history, significant emissions of non-CO_2 compounds, and cheap labor giving net export of consumer goods, would be better off choosing an early start year, late evaluation year, CO_2-only, and a consumption based perspective.

Figure 5 shows how much the relative contributions for the two biggest CO_2 emitters, China and USA, change with different perspectives. For comparison, we also include cumulative CO_2 emissions as well as so-called cumulative CO_2-equivalent emissions based on weighting of CH_4 and N_2O by Global Warming Potentials (GWP) from IPCC AR5 (Myhre *et al* 2013). Due to the rapid increase in Chinese emissions over recent decades, the choice of start year has the largest impact, while the choice of which components to include has less of an impact. For the USA the picture is more mixed, but there is a strong impact of the choice of components. The choice of start year is significant also for the US.

The question of start year for accounting for climate impacts of emissions is a controversial issue. Müller *et al* (2009) argue that the key to assign responsibility is that the action (emissions) must have its origin with the agent, and that the agent must be aware of what she/he is doing, or 'could have reasonably been expected to know'. The challenging question is when countries could have been expected to know that human-induced climate change was a real problem. An important milestone in this context is the first IPCC report from 1990, and some argue for using this as a starting point (e.g. Parikh and Parikh 2009). Others studies apply an earlier starting year (e.g. 1970 chosen by Mattoo and Subramanian 2012). Underdal and Wei (2015) further note that it is possible to argue for much earlier starting years based on 'accumulated competitive advantages' as the emissions occurring during early periods of technological innovation and economic growth are reflected in higher wealth today.

The question of which components to include is also challenging. A broad set of components have impacted the radiative balance and climate in the short and long term, causing both warming and cooling effects. International climate agreements, currently, focus on the emissions of long-lived GHGs, but short-lived components also have important climate effects, which can persist for decades despite their short lifetimes (e.g. Shine *et al* 2005, Fuglestvedt *et al* 2008). Further, some short-lived components have a cooling effect, particularly SO_2, in addition to causing air pollution with adverse health effects. A further complication with short-lived components is the higher level of uncertainty (e.g. Myhre *et al* 2013). Which components to include will include a variety of scientific and value choices, and not least, how to deal with cooling species. Giving climate credits for air pollution is obviously politically difficult.

In addition to the two choices discussed above, there are also impacts of uncertainties in emission data, atmospheric lifetimes, radiative forcing efficiencies and climate responses. Prather *et al* (2009)

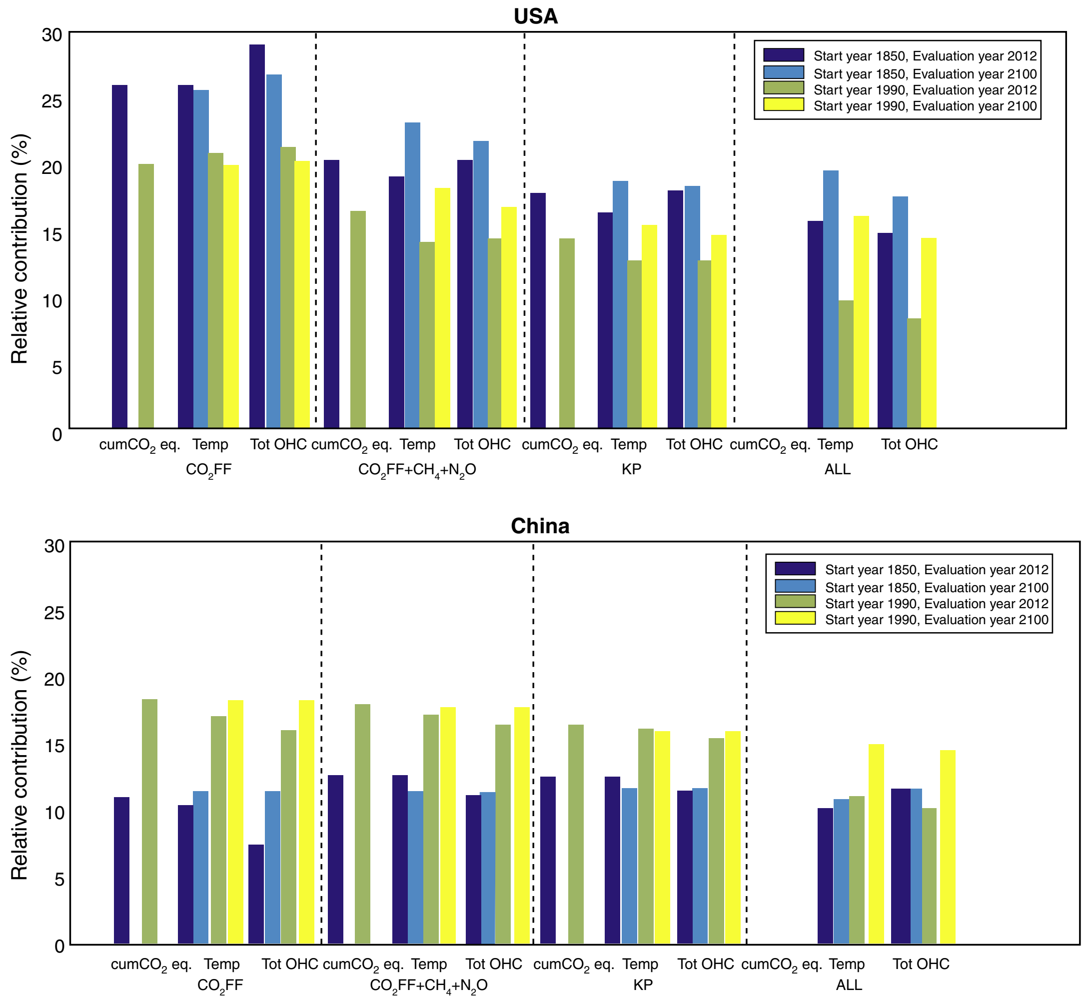

Figure 5. Impact of the different choices on calculated historical contributions for USA and China.

quantified uncertainties in the causal chain from emissions to temperature response from developed nations' emissions of KP gases from 1990 to 2003 and found +0.11 °C with an uncertainty range of +0.08 °C to +0.14 °C (68% confidence). Höhne *et al* (2011) found that uncertainty in historical contributions differs between countries due to different mixes of GHGs and their temporal developments. High shares of CH_4 and N_2O emissions and of CO_2 emissions from land-use change and forestry increase the uncertainty. They found that larger uncertainty related to emissions from the distant past, does not dominate the uncertainty of contributions to current temperature increase for most countries and most indicators. Höhne *et al* (2011) also found that the uncertainty introduced by uncertain historical emissions is larger than the uncertainty introduced by the use of different climate and carbon cycle models. However, value choices and subjective assessment will play an important role in evaluating uncertainties. An earlier start date will introduce a larger share of the more uncertain emissions from land-use change, accounting for about 30% of cumulative CO_2 emissions since 1870 (Le Quéré *et al* 2015). The inclusion of short-lived species will also introduce greater uncertainties.

Li *et al* (2016) found that China contributes 10 ± 4% of the current global radiative forcing and that the relative contribution to the positive (warming) component of global radiative forcing, mainly induced by well-mixed GHGs and black carbon (BC) is 12 ± 2%. Our estimated contributions from China in terms of radiative forcing are very similar (within a few percentage points) but cannot be directly compared since we have included the indirect cloud effects of SO_2. Li *et al* (2016) point to the uncertainties of contributions from BC, OC, SO_2, NOx and VOC. As in our study, these uncertainties arise from uncertain emissions, large uncertainties in radiative efficiency and climate impact. In addition, the impact on GMST change depends on the location of the emissions (e.g. Berntsen *et al* 2006, Aamaas *et al* 2016), an effect that is not fully accounted for here. However, the total impact of these short-lived climate forcers is small compared to CO_2 and other WMGHG.

The importance of considering a comprehensive range of choices becomes apparent when comparing the ranges identified in this study with the specific numbers from other studies. For the two biggest CO_2 emitters, China and USA, our study finds contributions ranging from 6%–13% and 15%–26%, respectively.

This only considers the impact of altering one choice at a time, and the range would have been even wider if we considered the full range for all combinations of choices. By comparison, what is probably the most widely known effort sharing scheme, the Greenhouse Development Rights framework (Baer *et al* 2007) assigns 36.4% of responsibility (defined as cumulative emissions since 1990, excluding emissions from consumption below a development threshold) to the USA and 5.2% to China.

5. Conclusions

Our results support the view that there is no simple and single correct answer to the question of how much each country has contributed to global warming. Too many fundamental value-related and ethical questions, to which it is not possible to agree upon a single answer, remain. With the 1992 UNFCCC all countries agreed to the principle of common but differentiated responsibilities and respective capabilities as the primary principle of distributive fairness. However, interpretations of how to operationalize the principle have always diverged, and these divergences tend to reflect countries' self-interest (e.g. Lange *et al* 2010). Consequently, and as is often pointed out in the literature, historical contributions are difficult to use directly in negotiations. It is not possible to find 'the single fairness formula', and perhaps even counter-productive to search for one (Fuglestvedt and Kallbekken 2015, Underdal and Wei 2015, Victor 2011). This study is therefore also a reminder that scientific studies and assessments of historical contributions that aim to inform policy should not present just one set of calculated contributions—based on some of many choices, but rather present a spectrum of results showing how the calculated contributions vary according to a broad set of choices. This is a general point that holds for many situations where value judgements are crucial inputs to scientific assessments (see e.g. Edenhofer and Kowarsch 2015, for a proposal on how this can be handled). It is also worth keeping in mind that contributions will change in the future (Höhne *et al* 2011, Rive *et al* 2006).

Calculations of contributions to global warming can be used as background information to inform and justify positions in negotiations, and may also be useful for countries' own assessment of what is a reasonable and fair contribution to limiting global warming, as they are now asked to define this themselves. Since countries define their own contributions, comparisons of country pledges on a consistent conceptual framework is difficult. The use of top-down methods to show a range of possible sharing principles, informed by historical contributions, has been found to be an effective way to compare the fairness and ambition of pledges (Peters *et al* 2015).

Our results provide detailed analysis following the perspective of the so-called Brazilian proposal by quantifying historical contributions to global warming. Other factors like capability and equality could be included in a burden sharing analysis building on the results given here. We clearly expose some of the core points in the burden-sharing debate, including the impacts of early vs late emitters. A practical concern is that applying certain perspectives on historical responsibility can lead to infeasible mitigation outcomes. Raupach *et al* (2014) found that using historical responsibility back to 1990 meant that some countries have already consumed their allocated share of the carbon budget for certain temperature stabilization targets.

The Paris Agreement has changed the role of calculations of historical responsibilities. Both because of the bottom-up approach formulated as Nationally Determined Contributions (NDCs) and the role of Loss and Damage. A natural research question to ask is whether it will be possible to go further and attribute loss and damage to nations' emissions. Alternatively, on a less ambitious level: Can quantitative scientific evidence be used to discuss questions of climate justice not necessarily in the context of liability and compensation, but with respect to recognition and reconciliation? Looking forward, calculations of contributions may also be applied to assess how commitments made under the Paris Agreement alter the share of responsibility for future changes in global temperature, sea level rise and possibly also various types of extreme events.

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