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

Ragnhild B Skeie¹, Jan Fuglestvedt¹, Terje Berntsen¹, Glen P Peters¹, Robbie Andrew¹, Myles Allen²,³ and Steffen Kallbekken¹

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

Keywords: Brazilian proposal, Paris agreement, responsibility, ethics, time horizon, short-lived climate forcers

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 (CBD-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 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 CO₂ concentrations and radiative forcing and the increase in CO₂ 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
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 CO₂ from fossil-fuel combustion and cement production (hereafter CO₂FF) the list can be expanded to include other long-lived GHGs, CO₂ from Land Use Change (LUC), changes in albedo, and short-lived gases and aerosols (short-lived climate forcers; SLCFs) 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 policies.

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 CO₂ 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 CO₂-equivalent emissions based on the emission metric Global Temperature change Potential (GTP) (Shine et al 2007). We also show results using cumulative CO₂-equivalent emissions based on GWP₁₀₀ 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...
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 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
CO₂ fossil fuel emissions (CO₂FF, 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 CH₄ and N₂O, the Annex-I contribution decreases to 54%.

Including CO₂ from LUC leads to a decrease in the Annex-I contribution compared to the CO₂FF case. The relative contributions from Indonesia and Brazil increase from below 1% to 4.5% and 4.0%, respectively, when LUC CO₂ 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 CO₂ emissions (Houghton et al 2012) and there are also inconsistent definitions of what the net LUC flux actually comprises (Pongratz et al 2014). For CO₂ 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 SO₂. 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 CO₂ emissions through the early 20th century, while emerging economies now have a much larger share of global CO₂ 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, CO₂FF (left) and the KP gases (right), using 2012 as evaluation year in both cases. For the case of CO₂FF 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 CO₂FF are 78% and 73%. An evaluation year later than 2012 would make the KP case more similar to the CO₂FF 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 SO₂ 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; CO₂FF 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
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 values (vertical axis) and the default contributions (horizontal axis).
(vertical axis) and the default contributions (horizontal axis) presented in section 3.1; for both the CO2FF 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 CO2FF 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 CO2 emissions (Matthews 2016) or cumulative CO2-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 CO2 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 CO2, 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-CO2 compounds, and cheap labor giving net export of consumer goods, would be better off choosing an early start year, late evaluation year, CO2-only, and a consumption based perspective.

Figure 5 shows how much the relative contributions for the two biggest CO2 emitters, China and USA, change with different perspectives. For comparison, we also include cumulative CO2 emissions as well as so-called cumulative CO2-equivalent emissions based on weighting of CH4 and N2O 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 SO2, 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)
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 CH4 and N2O emissions and of CO2 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 CO2 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 SO2. Li et al (2016) point to the uncertainties of contributions from BC, OC, SO2, 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 CO2 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 CO2 emitters, China and USA, our study finds contributions ranging from 6%–13% and 15%–26%, respectively.

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

Acknowledgments

This work was funded by the Norwegian Ministry of foreign affairs and the European Union’s Seventh Framework Programme project EUCLEIA under grant agreement no 607085. We thank Borgar Aamaas for help with the references and Paolo Zupin for help with figures.

References

Aamaas B, Berntsen T K, Fuglestvedt J S, Shine K P and Belloumi N 2016 Regional emission metrics for short-lived climate forcers from multiple models Atmos. Chem. Phys. 16 7451–68
Andrew R M, Davis S J and Peters G P 2015 Climate policy and dependence on traded carbon Environ. Res. Lett. 8 034011
Baer P, Athanasiou T and Kartha S 2007 The Right to Development in a Climate Constrained World, The Greenhouse Development Rights Framework (Berlin: Heinrich-Böll Foundation)
Berntsen T, Fuglestvedt J, Myhre G, Stordal F and Berglen T F 2006 Abatement of greenhouse gases: does location matter? Clim. Change 74 377–411
Davis S J, Peters G P and Caldeira K 2011 The supply chain of CO2 emissions Proc. Natl Acad. Sci. 108 18534–9
den Elzen M, Fuglestvedt J, Höhne N, Trudinger C, Lowe J, Matthews B, Romstad B, de Campos C P and Andronova N 2005 Analysing countries’ contribution to climate change: scientific and policy-related choices Environ. Sci. Policy 8 614–36
den Elzen M G J, Olivier J G J, Höhne N and Janssens-Maenhout G 2013 Countries’ contributions to climate change: effect of accounting for all greenhouse gases, recent trends, basic needs and technological progress Clim. Change 121 397–412

Edenhofer O and Kowarsch M 2015 Cartography of pathways: A new model for environmental policy assessments Environ. Sci. Policy 51 36–64

Fuglestvedt J, Berntsen T, Myhre G, Rypdal K and Skeie R B 2008 Climate forcing from the transport sectors Proc. Natl Acad. Sci. 105 454–8

Fuglestvedt J S and Kallbekken S 2016 Climate responsibility: Fair shares? Nature Clim. Change 6 19–20

Gardiner S M 2004 Ethics and global climate change Ethics 114 553–600

Hansis E, Davis S J and Pongratz J 2015 Relevance of methodological choices for accounting of land use change carbon fluxes Glob. Biogeochem. Cycles 29 1230–46

Houghton R A, House J I, Pongratz J, van der Werf G R, DeFries R S, Hansen M C, Le Quéré C and Ramankutty N 2012 Carbon emissions from land use and land-cover change Biogeosciences 9 5123–42

Höhne N et al 2011 Contributions of individual countries’ emissions to climate change and their uncertainty Clim. Change 106 359–91

James R, Otto F, Parker H, Boyd E, Cornforth R, Mitchell D and Allen M 2014 Characterizing loss and damage from climate change Nat. Clim. Change 4 938–9

Kallbekken S, Salen H and Underdal A 2014 Equity and spectrum of mitigation commitments in the 2015 agreement. (Copenhagen: Nordic Council of Ministers) (https://doi.org/10.6027/tn2014-519)

Kinsky S and Dowlatabadi H 2009 Conceptualizations of justice in climate policy Climate Policy 9 88–108

Lange A, Löschel A, Vogt C and Ziegler A 2010 On the self-interested use of equity in international climate negotiations Eur. Econ. Review 54 359–75

Le Quéré C et al 2015 Global carbon budget 2015 Earth Syst. Sci. Data 7 349–96

Li B et al 2016 The contribution of China’s emissions to global climate forcing Nature 531 357–61

Mace M J and Verheyen R 2016 Loss, damage and responsibility after COP21: all options open for the Paris agreement Review of European, Comparative and International Environmental Law 35 197–214

Matthews H D 2016 Quantifying historical carbon and climate debts among nations Nat. Clim. Change 6 60–4

Matthews H D, Tanya I G, Serge K, Cassandra L, Donny S and Trevor J S 2014 National contributions to observed global warming Environ. Res. Lett. 9 014010

Mattoo A and Subramanian A 2012 Equity in Climate Change: An Analytical Review World Dev. 40 1083–97

Mehlner R and Schinko T 2016 Identifying the policy space for climate loss and damage Science 354 290–2

Myhre G et al 2013 Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T F Stocker et al (Cambridge: Cambridge University Press)

 Müller B, Höhne N and Ellermann C 2009 Differentiating (historic) responsibilities for climate change Clim. Policy 9 593–611

Olivier D and Stober N 2010 Emulating AOGCM results using simple climate models Clim. Dynam. 35 1257–87

Parikh J and Parikh K 2009 Climate change: a parking place model for a just global compact (www.researchgate.net/profile/Jyoti_Parikh/publication/265104060_Climate_Change_A_ParkingPlace_Model_for_A_Just_Global_Compact/links/54abc0b080fcd2cc6f608b4d0.pdf)

Peter G P, Robbie M A, Susan S and Pierre F 2015 Measuring a fair and ambitious climate agreement using cumulative emissions Environ. Res. Lett. 10 105004

Pongratz J, Reich C H, Houghton R A and House J I 2014 Terminology as a key uncertainty in net land use and land cover change carbon flux estimates Earth Syst. Dynam. 5 177–95

Prather M J et al 2009 Tracking uncertainties in the causal chain from human activities to climate activity Geophys. Res. Lett. 36 L05707

Raupach M R, Davis S J, Peters G P, Andrew R M, Canadell J G, Ciais P, Friedlingstein P, Jotzo F, van Vuuren D P and Le Quéré C 2014 Sharing a quota on cumulative carbon emissions Nat. Clim. Change 4 873–9

Rive N and Fuglestvedt J S 2008 Introducing population-adjusted historical contributions to global warming Glob. Environ. Change 18 142–52

Rive N, Torvanger A and Fuglestvedt J S 2006 Climate agreements based on responsibility for global warming: Periodic updating, policy choices, and regional costs Glob. Environ. Change 16 182–94

Robiou du Pont Y, Jeffery M L, Gutschow J, Rogeli J, Christoph P and Meinsheim M 2017 Equitable mitigation to achieve the Paris Agreement goals Nat. Clim. Change 7 38–43

Rosa L P, Ribiero S K, Muylaert M S and Pires de Campos C 2004 Comments on the Brazilian Proposal and contributions to global temperature increase with different climate responses—CO2 emissions due to fossil fuels, CO2 emissions due to land use change Energy Policy 32 1899–910

Shine K P, Berntsen T K, Fuglestvedt J S, Skeie R B and Stuber N 2007 Comparing the climate effect of emissions of short- and long-lived climate agents Phil. Trans. R. Soc. A 365 1903–14

Shine K P, Fuglestvedt J S, Hailmeriam K and Stuber N 2005 Alternatives to the Global warming potential for comparing climate impacts of emissions of greenhouse gases Clim. Change 68 291–302

Skeie R B, Berntsen T, Aldrin M, Holden M and Myhre G 2014 A lower and more constrained estimate of climate sensitivity using updated observations and detailed radiative forcing time series Earth Syst. Dynam. 5 139–75

Stott P A, Tett S F B, Jones G S, Allen M R, Mitchell J F B and Jenkins G J 2000 External control of 20th century temperature by natural and anthropogenic forcings Science 290 2133–7

Thompson A and Otto F E L 2015 Ethical and normative implications of weather event attribution for policy discussions concerning loss and damage Clim. Change 133 439–51

Underdal A and Wei T 2015 Distributive fairness: A mutual recognition approach Environ. Sci. Policy 51 35–44

UNFCCC 2014 Report of the Conference of the Parties on its Twentieth Session (Lima, 1–14 December 2014) (http://unfccc.int/resource/docs/2014/cop20/eng/10a01.pdf)

Victor D G 2011 Global Warming Gridlock: Creating More Effective Strategies for Protecting the Planet (Cambridge: Cambridge University Press)

Victor D G 2014 Copenhagen II or something new Clim. Policy 14 853–5

Ward D S and Mahowald N M 2014 Contributions of developed and developing countries to global climate forcing and surface temperature change Environ. Res. Lett. 9 074008