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National contributions to observed global warming

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Abstract

There is considerable interest in identifying national contributions to global warming as a way of allocating historical responsibility for observed climate change. This task is made difficult by uncertainty associated with national estimates of historical emissions, as well as by difficulty in estimating the climate response to emissions of gases with widely varying atmospheric lifetimes. Here, we present a new estimate of national contributions to observed climate warming, including CO₂ emissions from fossil fuels and land-use change, as well as methane, nitrous oxide and sulfate aerosol emissions. While some countries' warming contributions are reasonably well defined by fossil fuel CO₂ emissions, many countries have dominant contributions from land-use CO₂ and non-CO₂ greenhouse gas emissions, emphasizing the importance of both deforestation and agriculture as components of a country's contribution to climate warming. Furthermore, because of their short atmospheric lifetime, recent sulfate aerosol emissions have a large impact on a country's current climate contribution. We show also that there are vast disparities in both total and per-capita climate contributions among countries, and that across most developed countries, per-capita contributions are not currently consistent with attempts to restrict global temperature change to less than 2 °C above pre-industrial temperatures.

Keywords: global warming, climate footprint, greenhouse gas emissions, natural attribution, climate change

1. Introduction

Global temperatures have increased by almost a degree since pre-industrial times, and it is clear that human greenhouse gas emissions have been the primary driving force behind this temperature increase (Gillett *et al* 2012). However, the sources of these emissions have and continue to vary dramatically between regions and individual countries, with countries in the developed world responsible for the vast majority of historical emissions (Bolin and Kheshgi 2001, Raupach *et al* 2007, Matthews and Solomon 2013). While some rapidly developing countries have begun to overtake developed countries in terms

of current emissions—China, for example, is now the largest national emitter of carbon dioxide (Peters *et al* 2012)—there remains a general pattern of disparity between countries in the developed and developing world with respect to total historical emissions, and consequent contributions to observed global warming.

There was a concerted recent attempt to quantify the contributions of individual countries to historical warming, as part of the MATCH network (the ad hoc Group for the Modelling and Assessment of Contributions to Climate Change—www.match-info.net). This group of researchers produced several papers (den Elzen and Schaeffer 2002, den Elzen *et al* 2005, Höhne *et al* 2010, Ito *et al* 2008) the most recent of which (Höhne *et al* 2010) represents a detailed analysis of the many uncertainties associated with determining historical national emissions of carbon dioxide, methane and



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nitrous oxide, as well as the difficulty in translating those emissions into national contributions to global temperature increases. This body of literature reveals several remaining challenges associated with attributing historical warming to individual countries: (1) regional data on historical emissions of CO₂ from land-use and land cover change are highly uncertain (Houghton 2008), and not easily downscaled to the resolution of individual countries; (2) CO₂ and non-CO₂ greenhouse gases vary greatly in their atmospheric residence times (Solomon *et al* 2010), and as such it is not clear how to best compare the climate effects of historical emissions of short- versus long-lived gases; and (3) national aerosol emissions have thus far been neglected, despite the fact that they represent an important contribution to observed climate change

In this paper, we present a new analysis of national contributions to observed global warming incorporating the most important greenhouse gas and aerosol emissions—carbon dioxide, methane, nitrous oxide and sulfate aerosols—that have driven global warming over the past two centuries. For CO₂ emissions, we have used the linear relationship between cumulative emissions and global temperature change (Matthews *et al* 2009) to allocate warming to individual countries based on cumulative historical emissions. For CO₂ emissions from land-use and land cover change, we have developed a new method to assign cumulative historical emissions to individual countries based on observed changes in forested areas within countries. We have also incorporated a novel approach for representing the effect of short-lived greenhouse gas and aerosol emissions, wherein we have allocated temperature change to each country based on a calculation of cumulative national historical emissions that is weighted according to the atmospheric lifetime of the temperature response to each type of emission. This new methodology allows for an improved national attribution of historical temperature changes, which incorporates the warming influence of emissions of CO₂ (from both fossil fuels and land-use) methane and nitrous oxide, as well as the cooling effect of sulfate aerosols.

2. Methods

National emissions data for CO₂ from fossil fuel combustion (including gas flaring and cement production) are available from the Carbon Dioxide Information and Analysis Centre (CDIAC) (Boden *et al* 2012). We used these data to calculate historical totals for each country up to and including the year 2005. We then estimated the resulting temperature change using the linear relationship between cumulative CO₂ emissions and global temperature change from (Matthews *et al* 2009). The climate response to cumulative CO₂ emissions has been well established in the literature as a robust relationship that does not depend on the source or timing of CO₂ emissions (see for example discussion of the ‘Transient Climate Response to cumulative carbon Emissions’ (TCRE) in the recent Summary for Policymakers of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), available at: www.climate2013.org/SPM (Stocker *et al* 2013). As such, the climate response to cumulative CO₂ emissions is well suited

to allocating warming to individual countries based on their total historical emissions. Here, we have used a best estimate of 1.6 °C warming per trillion tonnes of carbon emitted (the average value across climate-carbon models from (Matthews *et al* 2009).

CO₂ emissions data from historical land-use, land cover change and forestry (LUCF) are available up to the year 2005 from CDIAC for eight regions: the United States, Canada, South and Central America, Europe, North Africa and the Middle East, Tropical Africa, the former USSR, China, South and Southeast Asia, and the Pacific Developed Region (see <http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html>) (Houghton 2008). These data are based on regional estimates of land-use and land cover change, with carbon emissions derived from a book-keeping model which includes both direct emissions as well as delayed emissions associated with the production and use of wood products (Houghton 2003). With the exception of the data for the US, Canada and China, the regional emissions must be disaggregated to the level of individual countries. To accomplish this, we used a spatial dataset of historical changes in vegetation cover at 5' resolution from HYDE (History Database of the Global Environment; available at <http://themasites.pbl.nl/tridion/en/themasites/hyde/download/index-2.html>) (Klein Goldewijk *et al* 2011) to calculate the historical change in agricultural areas between 1800 and 2005 across all continents. We then compared this spatial change in agriculture with an estimate of global potential vegetation (the vegetation expected at each location in the absence of human land cover change) from SAGE (the Center for Sustainability and the Global Environment) (Ramankutty and Foley 1999). Where changes in agriculture occurred in areas of forest potential vegetation cover, we calculated the resulting change in forested area for each country up to 2005.

This approach is based on the argument that changes in standing forest carbon in a given country should be representative of cumulative LUCF CO₂ emissions in that country. We therefore assumed that within a given region, higher changes in forested area for an individual country would have resulted in higher national emissions of CO₂ over this period of time; this assumption is in turn contingent on an assumption of approximately constant carbon density across forested areas within a given region. Given each country's observed change in forested area, we allocated the total historical LUCF CO₂ emissions from a region to individual countries within that region according to:

$$\text{LUCF emissions for country } i = \frac{\Delta \text{forested area of country } i}{\text{regional } \Delta \text{ forested area}} \times \text{regional LUCF emissions}$$

where the regional change in forested area represents the sum of each country's forest area change within each region. Finally, this estimate of historical cumulative CO₂ emissions from LUCF for each country was converted to a global temperature change in the same way as for fossil fuel emissions (using a conversion factor of 1.6 °C per trillion tonnes of carbon (Matthews *et al* 2009)).

For non-CO₂ greenhouse gases, we used the database of historical national methane and nitrous oxide emissions up to 2005 from Höhne *et al* (2010, available at www.match-info.net). For aerosols, we used historical data of national emissions of sulphur dioxide from EDGAR (the European Database for Global Atmospheric Research—<http://edgar.jrc.ec.europa.eu>), which covers the period of time between 1970 and 2008 (though we included data only up to and including 2005 for consistency with other datasets).

To account for the variable atmospheric lifetimes of these gases and aerosols (ranging from days to a few weeks for aerosols, to about a decade for methane, to about a century for nitrous oxide) (Matthews and Zickfeld 2012) we developed the following methodology:

- (1) We used an intermediate-complexity global climate model (the University of Victoria Earth System Climate Model—UVic ESCM) (Weaver *et al* 2001, Eby *et al* 2009) to simulate the change in temperature resulting from observed historical increases in the forcing for each of methane, nitrous oxide and sulfate aerosols up to the year 2005.
- (2) We then assumed a scenario of zero future emissions, allowed the present-day forcing to decrease over time subject to the atmospheric lifetime of each gas, and simulated the temperature response to these zero-emissions scenarios as in Matthews and Zickfeld (2012).
- (3) The resulting decay of the global temperature anomaly following zero emissions represents the temperature legacy of current and historical emissions, and can therefore be used to weight the importance of past relative to current emissions, such that a more rapid temperature decay (e.g. as in the case of aerosols) implies a smaller contribution of past emissions to current temperatures. By contrast, a slower temperature decay (as in the case of nitrous oxide) implies that past emissions should carry a larger weight in their contribution to the current level of warming.
- (4) We therefore normalized the absolute value of this temperature decay for each of methane, nitrous oxide and aerosols, and used this time series of weights to calculate a weighted total of emissions for each country; in each case, current (taken here as the year 2005) emissions were assigned a weight of 1, with the weight assigned to past emissions decreasing with time before present according to the normalized temperature decay for each gas.
- (5) Finally, we calculated the temperature change associated with each country's methane, nitrous oxide and sulfate aerosol emissions by dividing the simulated global temperature change for each gas up to 2005 (from step (1) above) amongst countries according to their relative weighted historical cumulative emissions of the gas in question.

The combination of each type of emission considered here resulted in a total attributed global temperature change of 0.7 °C (table 1), which is reasonably close to the observed historical warming (0.74 ± 0.18 °C between 1906 and 2005)

Table 1. Contribution to total temperature change between 1800 and 2005 from each type of emissions. The total warming from CO₂ emissions represents the sum of all individual country contributions, estimated based on the climate response to cumulative emissions. The total warming from methane, nitrous oxide and aerosol emissions were each estimated from climate model simulations driven by historical forcing pathways for each gas, and were allocated to individual countries as described in section 2.

Category of emissions	Warming (°C)
Fossil fuel CO ₂	0.5
Land-use CO ₂	0.25
Methane	0.25
Nitrous Oxide	0.09
Aerosols	−0.4
Total warming	0.7

(Trenberth *et al* 2007). Additionally, the warming contributions of individual gases shown in table 1 are consistent with the relative strength of year-2005 radiative forcing from these gases (Forster *et al* 2007). It is worth emphasizing, however, that there is substantial uncertainty associated with both the emissions data we have used in these calculations as well as the climate response to these different types of emissions. Previous studies have shown that the amount of warming ascribed to individual countries is often highly sensitive to which types of emissions are included in the analysis, the uncertainty associated with national emission levels (particularly with respect to land-use CO₂ and historical non-CO₂ gas emissions), and the timeframe over which emissions are counted (den Elzen and Schaeffer 2002, den Elzen *et al* 2005, Höhne *et al* 2010). We are confident that the estimates we present here are a reasonable best guess at individual countries' overall climate contributions, but acknowledge nevertheless that we have not quantified the effect of uncertainties, and therefore must view our list of the top contributors as one realization of a complex calculation rather than as a definitive country ordering.

3. Results

Total contributions to global warming for each country are shown in figure 1. The United States is an unambiguous leader, with a contribution of more than double that of China, which falls second in the ranking. Russia, Brazil, India, Germany and the United Kingdom represent the third through seventh largest contributors to observed warming. In general, individual country climate contributions decrease rapidly moving down this list. These top seven countries alone account for 63% of the warming up to 2005; the top 20 countries (listed in table 2) account for 82% of the observed warming.

Figure 2 shows the contributions of different types of emissions to the total national climate contribution. The spatial pattern of warming from fossil fuel CO₂ emissions is a direct function of the spatial pattern of historical cumulative CO₂ emissions amongst countries, with obvious concentrations across the industrialized world. By contrast, the primary sources of CO₂ emissions (and hence warming) from land-use and land cover change are much more evenly distributed

amongst northern and tropical countries, reflecting both historical and current locations of intensive deforestation. The national climate contributions due to non-CO₂ gases represents a mixture of industrial and agricultural sources of emissions, with the result that current areas of extensive agricultural production in the developing world emerge as large contributors alongside more developed countries. Finally, the spatial pattern of climate cooling contributions from sulfate aerosols is very similar to that of fossil fuel CO₂, emphasizing the close historical coupling of these two types of emissions.

The top 20 national contributors to historical warming are listed in table 2, along with a breakdown of their climate contributions by category of emissions. What is immediately clear from table 2 is that there are often very different explanations for each country's position on the list, or indeed for their ranking amongst the top 20 contributors. The UK's position in the top-seven emitters is strongly tied to historic use of coal, which constitutes a large fraction of their cumulative fossil fuel CO₂ emissions; by contrast, much more recent coal use in China has led to a much faster current growth rate of cumulative CO₂ emissions, and hence a contribution to climate warming that will continue to increase rapidly in the coming years. Some other developing countries appear on this list in part owing to their prominent role as oil producing countries (e.g. Mexico and Venezuela), much of which is of course consumed in more developed countries.

Table 2 also reveals that the climate warming due to fossil fuel CO₂ emissions alone would result in a very different list of the top 20 countries. Brazil, for example, has a climate contribution that is dominated by land-use CO₂ and non-CO₂ gases, pointing to the critical importance of deforestation and agriculture in explaining their fourth-place ranking. The same is true of Indonesia, Columbia and Nigeria, whose fossil fuel CO₂ emissions are not nearly large enough to explain their position on this list. Also of interest is the relative magnitude of fossil fuel CO₂ and sulfate aerosol contributions. In general, higher fossil fuel CO₂ emissions are associated with higher aerosol emissions; however, while the climate warming from CO₂ evenly reflects a country's entire history of emissions, the climate cooling from aerosols is very strongly weighted towards recent emissions. As an example, when comparing China and Russia, China's much higher current emissions means that the effect of their aerosol emissions currently exceeds the contribution from their entire history of fossil fuel CO₂ emissions, whereas Russia's does not; this balance of recent aerosol versus historical CO₂ emissions means that China's climate contribution is much closer to Russia's than would otherwise be the case.

It is clear from this analysis that there are vast disparities between countries as to their individual contributions to global warming. Of course, there are also vast differences in the relative size and populations of countries, which make it difficult to directly compare the relative climate contributions shown in figure 1 and table 2. One strategy to normalize our calculation of climate contributions across countries is to compare each country's climate contribution to its geographic area. This comparison is illustrated in figure 3. Here, each country's area is scaled to represent its climate contribution

(Gastner and Newman 2004), with the colour of each country representing the amount by which its area has been inflated or contracted relative to its original geographical size. As expected, the United States, Western European countries and Japan have very large climate contributions relative to their areas, whereas most countries in the developing world have smaller ratios of climate contribution to geographic area. Interestingly, the climate contributions of China and Brazil are reasonably representative of their geographic sizes.

Accounting for population differences between countries is also critical in any discussion of national contributions to observed global warming. To calculate per-capita contributions to climate warming, we divided each country's total climate contribution by its year-2005 population, using data from the United Nations World Population Division (<http://data.worldbank.org/indicator/SP.POP.TOTL>). As shown in figure 4, there is an expected pattern of higher per-capita climate contributions across the developed world, though in this case, there are also several countries in Central America, South America, Central Africa and the Middle East whose per-capita contributions are similar to, and in some cases exceed, the per-capita contributions of the developed world. In general however, these are countries with both small total climate contributions and small populations, and are therefore not significant overall contributors to climate warming. Focusing therefore on the major contributors given in table 2, we have re-ranked these 20 countries in table 3 according to their per-capita climate contributions. Here, the disparity between developed and developing countries can be seen clearly, with the top seven positions now being occupied by developed countries. Notably, China and India drop to the bottom of the list, with per-capita climate contributions well below those of developed countries.

It is also interesting to note that the majority of the countries on this list, which represent the largest total contributors to climate warming, also exceed the current global average per capita climate contribution of 0.11 °C per billion people. If we were to envision a future world of nine billion people, in which we are able to maintain global temperatures at a maximum of 2 °C above pre-industrial temperatures, this would require a per-capita climate contribution of no more than double the current average: 0.22 °C per billion people (2 °C/9 billion people). This means that while there is room for the world as a whole to increase the average per-capita contribution to climate warming, this is much less true for the developed countries currently occupying the top of this list. If we are to have a chance of staying below 2 °C while also addressing fundamentally important issues associated with international equity, it is imperative that developed countries do not allow their greenhouse gas emissions to continue increasing at historical rates, therefore allowing an overall increase in per-capita climate contributions to be driven primarily by less developed countries.

4. Discussion

The story of how and to what extent individual countries have contributed to observed global warming remains a complex problem owing to both incomplete historical datasets of

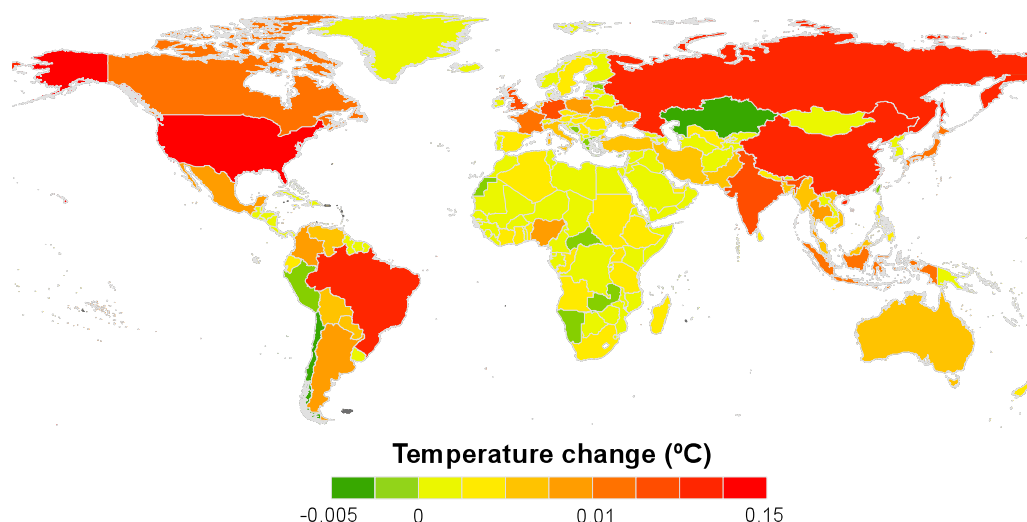


Figure 1. National contributions to historical climate warming, including CO₂ emissions from fossil fuels and land-use change, non-CO₂ greenhouse gases and sulfate aerosols,

Table 2. Top 20 contributors to global temperature change, ranked in order of their total climate contribution, and including a breakdown of the contribution of different types of emissions. All values here are given in °C of global temperature change.

Rank	Country	Total	Fossil Fuel CO ₂	Land-use CO ₂	All CO ₂	Non-CO ₂ GHG	All GHG	Aerosols
1	United States	0.151	0.143	0.026	0.170	0.044	0.213	−0.063
2	China	0.063	0.042	0.036	0.078	0.049	0.127	−0.065
3	Russia	0.059	0.059	0.014	0.072	0.020	0.092	−0.034
4	Brazil	0.049	0.004	0.032	0.036	0.018	0.054	−0.005
5	India	0.047	0.013	0.025	0.037	0.025	0.062	−0.015
6	Germany	0.033	0.035	−0.000	0.035	0.008	0.042	−0.009
7	United Kingdom	0.032	0.031	0.001	0.033	0.007	0.040	−0.007
8	France	0.016	0.014	−0.000	0.014	0.007	0.021	−0.005
9	Indonesia	0.015	0.003	0.013	0.015	0.006	0.021	−0.006
10	Canada	0.013	0.011	0.007	0.017	0.005	0.023	−0.009
11	Japan	0.013	0.021	0.001	0.022	0.002	0.024	−0.011
12	Mexico	0.010	0.006	0.008	0.014	0.003	0.017	−0.007
13	Thailand	0.009	0.002	0.006	0.008	0.004	0.012	−0.002
14	Columbia	0.009	0.001	0.006	0.007	0.003	0.010	−0.001
15	Argentina	0.009	0.002	0.003	0.005	0.005	0.010	−0.001
16	Poland	0.007	0.010	0.001	0.011	0.003	0.014	−0.007
17	Nigeria	0.007	0.001	0.001	0.002	0.005	0.007	0.000
18	Venezuela	0.007	0.002	0.002	0.004	0.003	0.008	−0.001
19	Australia	0.006	0.005	0.002	0.007	0.006	0.014	−0.007
20	Netherlands	0.006	0.004	0.000	0.004	0.002	0.006	−0.001

emissions, as well as the wide variety of individual gases that contribute to climate change. Here, we have formulated a new best estimate of national climate contributions to observed global warming, incorporating the most important greenhouse gas and aerosol emissions that have driven global temperature changes over the past 200 years. In addition, we have introduced two new representations of national climate contributions, showing how they vary with respect to countries' geographic areas and populations. These calculations in particular reveal new geographic patterns of contributions to historical climate warming that are critical to consider in addition to the calculation of total climate contributions

Our results are generally consistent with previous attempts to quantify country contributions to climate warming; these past studies, however, (notably den Elzen and Schaeffer 2002,

Höhne *et al* 2010) did not include aerosol emissions and have therefore reported national contributions as a percentage of total greenhouse gas warming (which is much larger than observed temperature change), rather than as an explicit temperature contribution as we have given in table 2. The results from Höhne *et al* (2010) represent the closest comparison to our analysis, and the percentage contributions to greenhouse gas warming (shown for selected countries in their figure 4) can be compared to the 'All GHG' column in our table 2 if the latter are expressed as a percentage of total greenhouse gas warming (1.09 °C from our table 1). This comparison reveals that our calculations do fall within the estimated uncertainty ranges provided by Höhne *et al* (2010), with many countries also falling very close to their best estimate. Differences from their results reflect our treatment of short-lived gases (which give

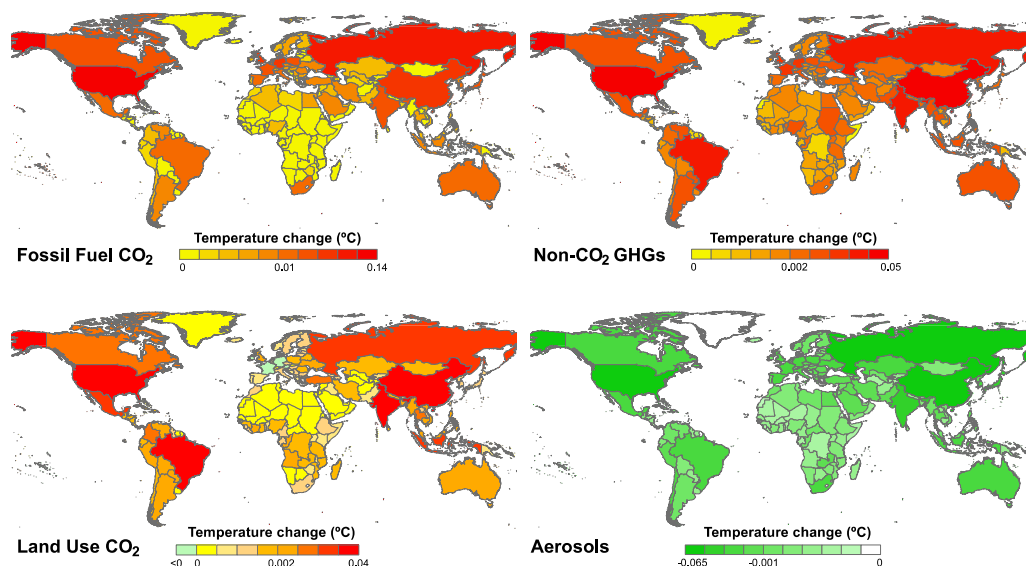


Figure 2. National climate contributions due to each of the four components included in figure 1: (a) fossil fuel CO₂ emissions; (b) land-use change CO₂ emissions; (c) non-CO₂ greenhouse gas emissions (methane and nitrous oxide); and (d) sulfate aerosol emissions.

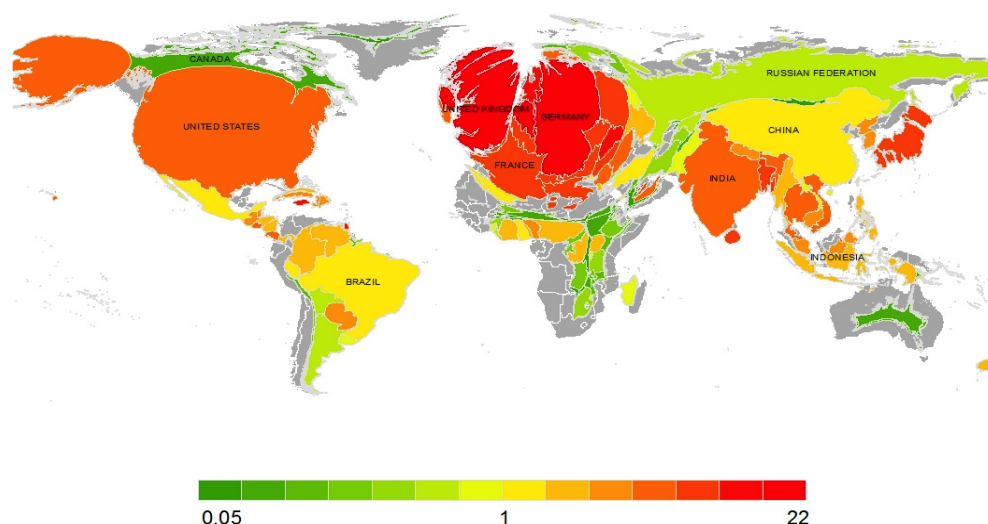


Figure 3. Cartogram of national climate contributions (density-equalized map) (Gastner and Newman 2004). Here, the geographic area of each country has been scaled such that the coloured area is proportional to its climate contribution. The colour scale shows the amount by which a country's size is expanded or contracted relative to its original size (shown in the light-grey background). This therefore represents a country's climate contribution relative to its geographic area, where red indicates countries with very high climate contributions per unit geographic area, and green indicates countries with very small climate contributions per unit area.

more emphasis to recent emissions) as well as differences in the allocation of regional land-use CO₂ emissions to individual countries.

Previous studies have highlighted the large uncertainty associated with global and regional land-use CO₂ emissions in particular as a weakness of attempts to attribute climate warming to individual countries (den Elzen *et al* 2005, Höhne *et al* 2010). Most previous estimates of the spatial pattern of land-use change emissions have been generated using spatial datasets of vegetation cover change as an input to a terrestrial

carbon cycle model, either offline or coupled to a global climate model (e.g. Pongratz *et al* 2009, Houghton *et al* 2012). Our approach differs from these previous estimates in that we have not relied on simulated carbon fluxes from a spatial vegetation model, but rather have used observed changes in forest cover (as a proxy for changes in standing forest carbon) as a direct estimate of a given country's relative share of regional cumulative CO₂ emissions. Despite this different approach, our spatial pattern of land-use change emissions is consistent with other estimates: comparing our figure 2(b) to

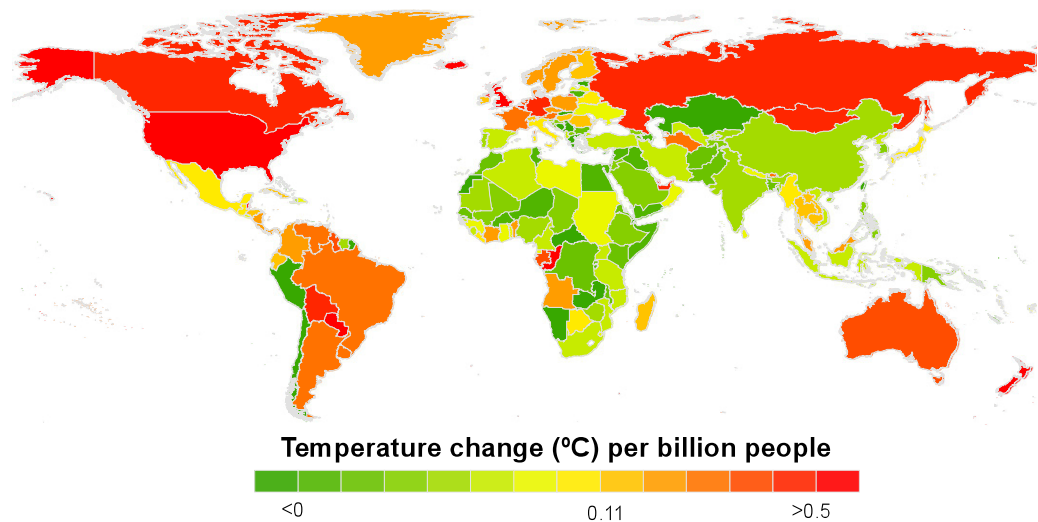


Figure 4. National per-capita contributions to climate warming. Colours indicate values above or below the global average, where orange and red are higher, and yellow and green are lower than the current (year 2005) world average of 0.11 °C per billion people.

Table 3. Total versus per-capita contributions to temperature change for the world’s top 20 total emitters from table 2. Rows with light shading indicate countries whose total or per-capita climate contribution is above the current global average (0.004 °C per country; 0.11 °C per billion people). Rows with dark shading indicate countries whose contribution is also above the projected global average for a world with 9 billion people, 196 countries and a global warming of 2 °C above pre-industrial (0.01 °C per country; 0.22 °C per billion people).

Rank	Total warming °C		Warming per billion people	
1	United States	0.151	United Kingdom	0.54
2	China	0.063	United States	0.51
3	Russia	0.059	Canada	0.41
4	Brazil	0.049	Russia	0.41
5	India	0.047	Germany	0.40
6	Germany	0.033	Netherlands	0.34
7	United Kingdom	0.032	Australia	0.30
8	France	0.016	Brazil	0.26
9	Indonesia	0.015	France	0.26
10	Canada	0.013	Venezuela	0.25
11	Japan	0.013	Argentina	0.23
12	Mexico	0.010	Colombia	0.21
13	Thailand	0.009	Poland	0.19
14	Columbia	0.009	Thailand	0.14
15	Argentina	0.009	Japan	0.10
16	Poland	0.007	Mexico	0.09
17	Nigeria	0.007	Indonesia	0.07
18	Venezuela	0.007	Nigeria	0.05
19	Australia	0.006	China	0.05
20	Netherlands	0.006	India	0.04

figure 3 of Pongratz *et al* (2009), for example, shows similar patterns of high CO₂ emissions in the US, Brazil, Central Africa, Southeast Asia and northern Eurasia.

Another large area of uncertainty in our analysis, which has not been included in previous studies, is reflected in our inclusion of sulfate aerosol temperature contributions. Accounting here for national aerosol emissions does affect the ranking of countries shown in table 2; for example, amongst the top ten countries, adding aerosol contributions increased the

ranking of Brazil, France and Indonesia, each of which was characterized by relatively lower aerosol emissions than the neighbouring countries in this list. Of course, the uncertainty associated with the climate response to aerosol emissions (Forster *et al* 2007) necessarily affects the results we have presented here. Nevertheless, the overall structure of our top 20 list is reasonably robust to variation in the strength of the aerosol climate response: in the case of either a 50% increase or decrease in the total temperature change due to sulfate aerosols, the top-seven countries all remain in the top seven (with the US still unambiguously in first position), and individual countries within the top 15 do not change by more than three positions in the list. Notably, in the case of a 50% increase in the aerosol contribution, China and Mexico both drop three positions in the list, and the second, third and fourth rankings become occupied by Brazil, Russia and India. While these changes may be of political interest, the more general conclusions apparent in table 2 (that seven countries account for the majority of observed warming, and that this top 20 list is a reasonable representation of the major contributors to global warming) are unaffected by aerosol uncertainty.

Arguably more important than uncertainty in the climate effect of the emissions that we have considered, is the uncertainty associated with emissions and processes that are not included in our analysis. We have not included, for example, information about pre-industrial CO₂ emissions from land-use change, which have been shown to result in small increases in cumulative historical land-use emissions in regions where large amounts of land clearing occurred prior to the industrial revolution (Pongratz and Caldeira 2012) Our estimate of land-use emissions does implicitly account for carbon sinks associated with forest regrowth, given that we have used observed net changes in forest cover as being representative of the cumulative land-use CO₂ emissions from individual countries. We have not, however, incorporated any changes in terrestrial carbon sinks which have been driven by increases in CO₂ emissions themselves and the resulting CO₂ fertilization

of forested regions, which have been shown to also influence the extent by which atmospheric CO₂ increases might be attributed to different regions (Ciais *et al* 2013).

With respect to other greenhouse gas and aerosol emissions, we have not included any information about aerosol emissions other than sulfate aerosols; black carbon emissions in particular constitute an important contribution to warming (Weaver 2011). We have also not included emissions of ozone precursors, nor the large number of individual gases represented by the halocarbon category of emissions, both of which have made non-trivial contributions to observed warming (Forster *et al* 2007). While the global effect of these omitted greenhouse gas emissions is similar to the effect of omitted cooling aerosols (considering also the indirect effect of sulfate aerosols) (Forster *et al* 2007), it is unlikely that this would remain true at the scale of individual country emissions. Given the incomplete nature of historical data pertaining to national-level emissions of these gases and aerosols, our calculations are also necessarily incomplete. Nevertheless, including the primary three greenhouse gases, and in particular the cooling effect of the most important aerosol species, represents an importance advance over previous estimates of national contributions to climate change, and the methodology which we have presented here could be readily applied to a broader range of national emissions data as this information becomes available.

Another important caveat is that our national climate contribution estimates account only for emissions produced within a given country, and not the transfer of emissions associated with the international trade of products and resources. There is an emerging body of literature which has shown that a consumption-based representation of CO₂ emissions leads to a shift in the allocation of current emissions from major producer countries such as China towards major consumer countries in North America and Western Europe (Davis and Caldeira 2010, Peters *et al* 2011, 2012). As a consequence, a substantial portion of recent emissions from developing countries could be equally allocated to the developed countries that consume the goods produced. The same could be argued for emissions associated with agriculture and resource extraction; it remains an open question as to whether these emissions should be allocated to the country of production or extraction, or to the country of ultimate consumption of the food or resource in question.

It is worth noting that, while we have only considered emissions up to the end of 2005 for the sake of consistency across available emission datasets, we have reason to believe that including more recent emissions would not dramatically affect the ordering of countries given in table 2. When we updated the top seven contributors to the end of 2011 (using all available data for the categories of included emissions), only China and Russia changed their position in the list, and both remained well below (less than half) the value of the United States. This reversal of China and Russia was caused by a greater increase in aerosol emissions in China compared to Russia, which resulted in China's climate contribution increasing less than Russia's between 2005 and 2011. Overall, however, the proportion of the total warming from these seven

countries allocated to any one country changed by less than 1% between 2005 and 2011, suggesting that recent emissions have not changed enough since 2005 (in relative terms across countries), to radically alter the contribution of individual countries to observed warming.

Finally, the disparities that we have illustrated regarding differences in per-capita contributions to global warming underline the critical issues of international equity that are at the core of current efforts to decrease global greenhouse gas emissions. Population and population growth is consistently cited as a driver of greenhouse gas emissions (Rosa and Dietz 2012). However, it is also clear that population alone does not determine a country's climate contribution, given the vast differences in per-capita energy and resource consumption between the developed and the developing world. This inequality between countries in itself could be seen as a driving force behind recent global emissions increases, as has been argued may be the case for social inequality within individual countries (Wilkinson and Pickett 2010). Balancing the current inequities in per-capita contributions to climate warming across countries may be a fundamental requirement if we are to make the changes necessary to decrease emissions and stabilize global temperatures.

It is these very questions of equity and responsibility that currently represent major barriers to progress in international negotiations attempting to set national emissions targets, and yet are critical to resolve as we move forward with climate mitigation efforts. The recently released Summary for Policymakers of the IPCC's Fifth Assessment Report highlighted the finding that we have used up at least half of the total allowable emissions budget that is consistent with 2 °C of global warming (Stocker *et al* 2013). How we choose to allocate the remaining emissions budget is a critical political challenge which can easily become mired in non-trivial arguments surrounding questions of blame and historical responsibility for global warming. A clear understanding of national contributions to climate warming provides important information with which to determine national responsibility for global warming, and can therefore be used as a framework to allocate future emissions allowances amongst countries (Neumayer 2000). Our analysis has the potential to contribute to this discussion, by providing both an improved estimate of current contributions, as well as a relatively simple, yet robust method with which to calculate a given country's current and potential future contribution to global warming.

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