LETTERS
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Quantifying historical carbon and climate debts among nations

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Contributions to historical climate change have varied substantially among nations[1–5]. These differences reflect underlying inequalities in wealth and development, and pose a fundamental challenge to the implementation of a globally equitable climate mitigation strategy[6–8]. This Letter presents a new way to quantify historical inequalities among nations using carbon and climate debts, defined as the amount by which national climate contributions have exceeded a hypothetical equal per-capita share over time[6,8,9]. Considering only national CO_2 emissions from fossil fuel combustion, accumulated carbon debts across all nations from 1990 to 2013 total 250 billion tonnes of CO_2, representing 40% of cumulative world emissions since 1990. Expanding this to reflect the temperature response to a range of emissions, historical climate debts accrued between 1990 and 2010 total 0.11 °C, close to a third of observed warming over that period. Large fractions of this debt are carried by industrialized countries, but also by countries with high levels of deforestation and agriculture. These calculations could contribute to discussions of climate responsibility by providing a tangible way to quantify historical inequalities, which could then inform the funding of mitigation, adaptation and the costs of loss and damages in those countries that have contributed less to historical warming.

The question of who is responsible for anthropogenic climate change requires an acknowledgement of the differences among nations in their contributions to greenhouse gas emissions and the resultant climate warming. Recent analyses have highlighted the large disparities in per-capita contributions to historical warming, which have varied by more than a factor of ten among the world's largest emitters of greenhouse gases[1,10,11]. Many factors affect this variation in per-capita emissions, including climate conditions, country size and access to renewable resources[12], as well as the levels of national wealth, consumption and development[13]. In the context of this uneven distribution of global emissions, some authors have argued that the atmosphere is a finite and shared resource, which should therefore be treated as a common good with equal per-capita access[6,8,14,15]. The fact that historical use of the atmosphere has not been equal, has prompted the idea that some countries have over-used this resource and consequently owe a debt to countries who have used less than their share[6,9]. Here, I quantify these debts (and credits) across all countries, as an explicit measure of how much historical greenhouse gas emissions and consequent contributions to climate warming have deviated over time from a hypothetical equal per-capita distribution.

The difference between actual historical and equal per-capita emissions has previously been referred to as an 'historical emissions debt'[6], defined such that a country whose emissions exceed its per-capita share would accumulate a debt owed to countries with emissions lower than the world per-capita average. I begin here by calculating the accumulation of 'carbon debts' for each country since 1960, using historical estimates of national fossil fuel CO_2 emissions[16] and population[17] (see equation (1) in Methods). The resulting time series of accumulated carbon debts (and the equivalent temperature change, calculated using the Transient Climate Response to cumulative carbon Emissions (TCRE; refs 18,19); see Methods) are shown in Fig. 1. Cumulative values of carbon debts and credits at 2013 are plotted in Fig. 2, along with a list of the top ten debtor and creditor countries. The United States is a clear leader among debtor countries, with historical CO_2 emissions that have consistently exceeded the world per-capita average. Among creditor countries, India and China are the most notable for historically low per-capita emissions, although in the mid-2000s China's emissions rose above the global average, as indicated by the inflection point between increasing and decreasing carbon credit. The cumulative world debt/credit at 2013 is approximately 500 billion tonnes (Gt) of CO_2 since 1960, and 250 $GtCO_2$ since 1990. Given cumulative world CO_2 emissions of 630 $GtCO_2$ since 1990, this implies that 40% of these emissions were produced by countries in excess of the levels that would have been consistent with their shares of world population.

I now incorporate emissions of CO_2 from land-use change, as well as other greenhouse gases (methane and nitrous oxide) and sulphur dioxide (which causes cooling as a result of the formation of reflective sulphate aerosols). To calculate the accumulated debts and credits associated with this broader range of emissions, I compared the temperature change at each year caused by each country's emissions, to a value of temperature change that is proportional to each country's share of world population at that year (see equation (2) in Methods). The resulting 'climate debts' (shown in Fig. 3c) represent the accumulated difference between the actual temperature change caused by each country (Fig. 3a) and their per-capita share of global temperature change (Fig. 3b). The United States is again the largest debtor, claiming 32% of the cumulative world climate debt from 1990–2010. Other significant climate debtor countries are Russia (10%), Brazil (9.8%), Canada (3.9%), Germany (3.4%), Australia (3.3%) and Indonesia (3%). At the other extreme, India has the largest climate credit (35% of the total credit), followed by China (26%), Bangladesh (4.9%), Pakistan (4.3%) and Nigeria (2.4%).

The total world climate debt shown here is 0.11 °C, similar to the temperature equivalent of the world carbon debt (0.10 °C for 1990–2013). Although not an observable temperature change (as total debts and credits sum to zero), this value does represent a quantitative measure of the magnitude of historical inequalities among nations, which can be equated to close to a third of historical warming since 1990. In the case of both carbon and climate debts, the United States carries by far the largest share of debt. Climate and carbon debts for Russia, Canada, Germany and the United

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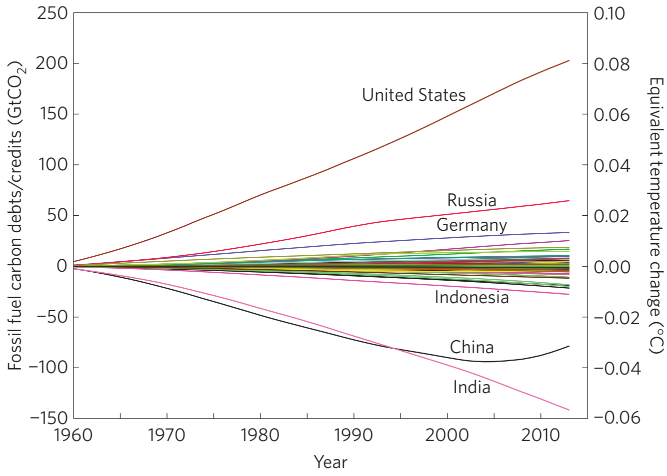
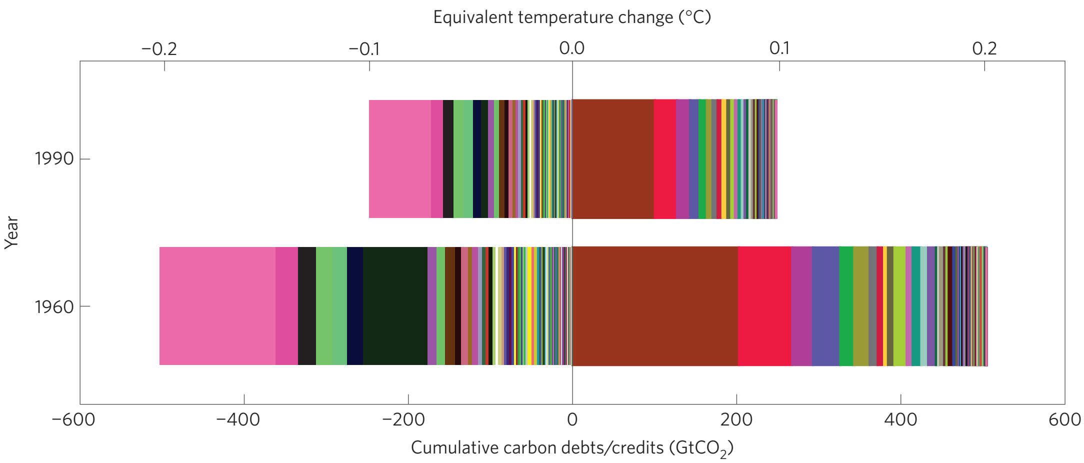


Figure 1 | Accumulation of historical carbon debts from fossil fuel CO_2 emissions since 1960. Carbon debts (and credits) are calculated as the sum of annual differences between actual national CO_2 emissions, and a share of emissions based on national fractions of world population (see equation (1) in Methods). The right *y* axis shows the equivalent temperature change calculated using an estimate of the transient climate response to cumulative carbon emissions (TCRE) of 0.4 °C per 1,000 $GtCO_2$.

Kingdom are also similar in magnitude, as are climate and carbon credits for India, Bangladesh, Pakistan and Nigeria. China's climate credit, however, is notably larger than its carbon credit, owing to an additional climate credit from lower than equal per-capita emissions of land-use CO_2 and non-CO_2 greenhouse gases, as well as very high recent SO_2 emissions which resulted in an increased climate credit owing to the cooling effect of the resulting reflective sulphate aerosols (see Supplementary Methods and Supplementary Fig. 1 for additional discussion of the effect of including reflective aerosols in addition to greenhouse gases). More markedly, by including a wider range of emissions, some countries change from holding a carbon credit to carrying a climate debt. This change in sign can be explained by high levels of deforestation in Brazil and Indonesia in particular, in addition to a contribution from CH_4 and N_2O emissions associated with agricultural activities.

These calculations of climate and carbon debts underscore the inequalities among nations in their contribution to historical global warming. A central assumption here is that equal per-capita entitlements are a reasonable benchmark against which to quantify these inequalities. Equal per-capita entitlements to emissions have received some criticism in the literature, however, on the grounds that this approach may be overly egalitarian in not acknowledging the potentially unequal needs of individuals across countries[20]. For example, a country's climate and geography can have a large effect on energy needs and the resulting greenhouse gas emissions[12], and these differences in basic needs do introduce some inequality into an equal shares model[14,20,21]. Consequently, some authors have suggested the need for a 'modified equal shares' approach that would allow for the weighting of a country's share of emissions based on different basic needs[14].

In principle, it would be possible to incorporate modified equal shares into these calculations by weighting individual country populations to increase or decrease the share of world emissions or temperature changes allocated to each country (see Supplementary Methods and Supplementary Fig. 2 for an illustration of this approach). In practice, however, it is not straightforward to identify



	1990	1960		1990	1960
India	−75.6	−141.5	United States	100.3	202.7
Indonesia	−14.2	−27.6	Russia	27	64.7
Bangladesh	−12.8	−21.4	Japan	15.9	25.3
Pakistan	−12.1	−19.8	Germany	11.6	33.4
Nigeria	−11.6	−18.2	Canada	9.0	16.9
Brazil	−10.1	−19.1	United Kingdom	6.8	18.7
China	−8.5	−78.7	Australia	6.1	9.9
Ethiopia	−7.0	−10.8	Saudi Arabia	6.0	7.8
Philippines	−6.5	−10.7	South Korea	5.9	4.7
Vietnam	−6.4	−11.7	South Africa	4.8	7.9

Figure 2 | Total accumulated national carbon debts and credits at 2013. Carbon debts (and credits) are calculated using a start date of 1960 (lower bar) or 1990 (upper bar). Equivalent transient temperature changes (calculated as in Fig. 1) are shown on the upper axis. All countries are included in the stacked bar chart; the top ten creditors and debtors (ranked based on the calculation beginning in 1990) are listed, showing their cumulative debt or credit in billions of tonnes of CO_2, including values for both 1990–2013 and 1960–2013.

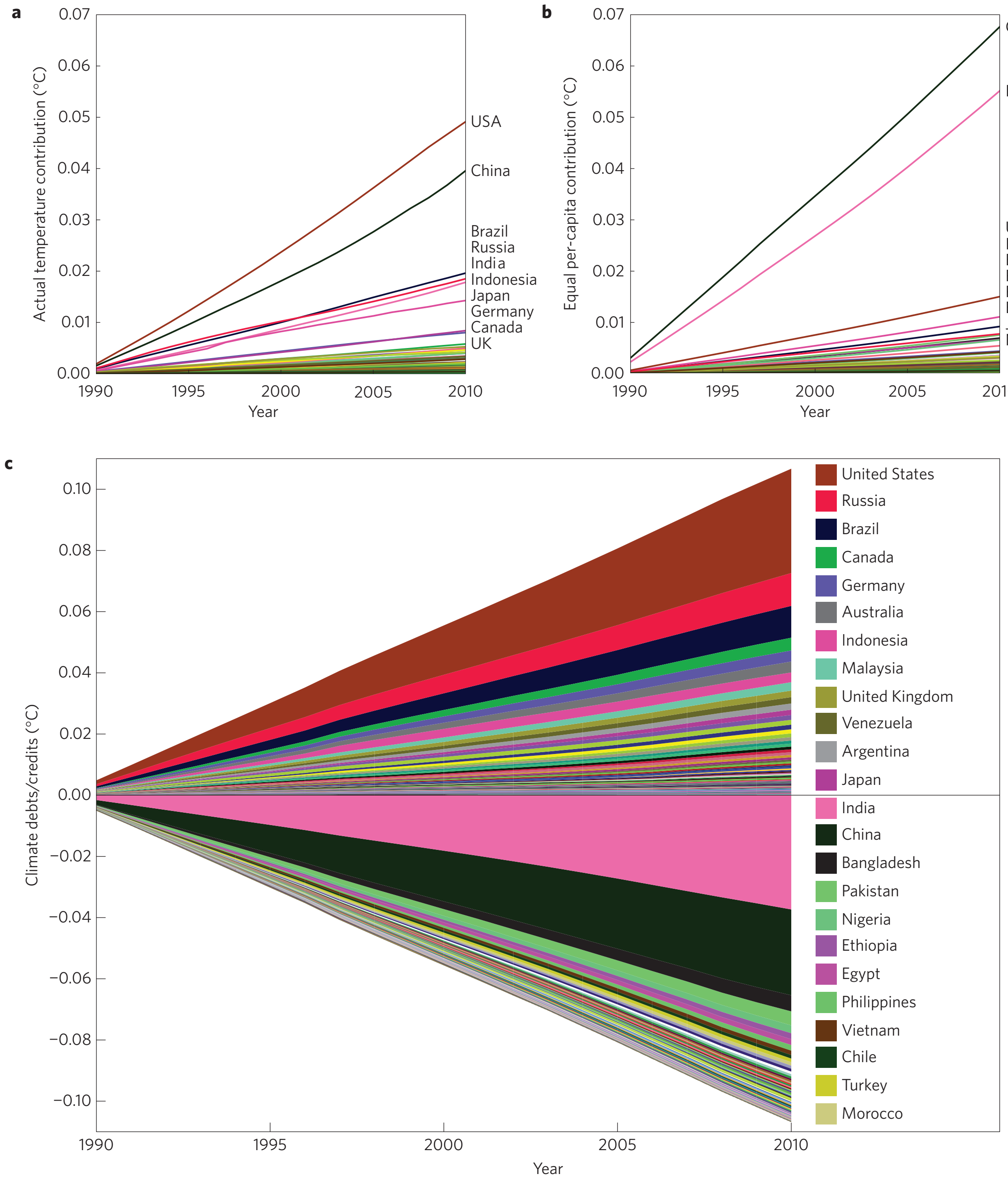


Figure 3 | National climate debts and credits. a, Actual national contributions to historical temperature changes. **b**, Hypothetical equal per-capita national shares of historical temperature increases. **c**, Climate debts and credits for each country, calculated according to equation (2) (see Methods) as the accumulated difference between a country's actual contribution to historical temperature changes (**a**) and its equal per-capita share of temperature increases (**b**). The climate debt/credit values are shown as a stacked area plot, whereby the width of each coloured area slice represents that country's accumulated climate debt or credit over time. All countries are included in each figure panel, with the top 12 debtor and creditor countries listed and identified by colour in the legend accompanying the lower panel.

what would constitute a valid claim to increasing the entitlements of one set of countries, which necessarily requires other countries to accept decreased per-capita entitlements. Some factors could be relatively objectively represented by a set of population weights (for example, colder temperatures have been shown to increase energy needs for heating and consequent per-capita emissions[12]), although others are much less clear and more subjective (for example, if a country's infrastructure was built historically around automobile use, does that justify a claim to higher emission needs by the current population?[14]). I do acknowledge that using equal per-capita shares as a benchmark is a substantial simplification of the range of factors that could be used to assess a given nation's 'fair share' of global emissions[21,22]. However, given the potential ethical and political difficulties associated with quantitatively defining anything other than an equal shares approach, I see considerable merit in choosing the simplest approach as a starting point for what is already a complex scientific, ethical and political issue.

Another important consideration is that all of the calculations presented above are based on territorial, or production-based, emissions estimates, and do not include any accounting for the international transfer of emissions associated with the export and import of consumable goods and services, food or other resources. By contrast, a consumption-based approach would allocate emissions associated with the consumption of goods to the consumer country, rather than to the producer country[23,24]. The very high levels of deforestation and agriculture-related emissions in Brazil and Indonesia, for example, are driven in part by food and resource demand from other countries[25,26].

The effect of production versus consumption emissions can be illustrated using estimates of consumption-based fossil fuel CO_2 emissions[16] (see Supplementary Methods and Supplementary Fig. 3). For some large emitters (for example, the US, Canada and India), the resulting transfers of debts and credits associated with the trade in consumable goods would represent a small adjustment ($<5\%$) of the production-based values. For others, however, (for example, Japan, Germany and the UK as large importers and Russia as a large exporter of carbon debt) the transferred debt/credit is a more substantial portion ($>35\%$), and China's exported carbon debt is almost twice as large as their production-based carbon credit over the same time period. However, these results do need to be taken with some caution, as producer countries also derive economic benefits from exported goods, and it remains an open question as to what extent producer or consumer countries should be held accountable for the associated emissions.

Finally, the carbon and climate debts calculated here have the potential to inform discussions of responsibility for who should bear the cost of mitigation and climate-related loss and damages. Climate responsibility is a topic that is open to a wide variety of perspectives, opinions and arguments[21,27]. In addition to the discourse surrounding producer versus consumer responsibility[28], some authors have suggested that there may be merit in assigning responsibility for climate change to corporations rather than nations[29], or that within nations we should rather consider assigning responsibility to wealthy individuals whose climate footprints are much larger than the average for the nation as a whole[21,27].

The period of time over which emissions are counted also has a large bearing on a country's contribution to climate change[2,4] and hence on the allocation of responsibility[21]. Some authors have argued the merits of a full historical accounting of all emissions since the beginning of the industrial revolution[6], which would of course greatly increase the calculated climate debt and implied responsibility for countries that industrialized early. On the other hand, these countries did not have access to low-CO_2 technologies that are widely available now, suggesting a need to discount past emissions to account for this technological progress[3]. Furthermore, many authors have argued that as the scientific basis of anthropogenic climate change was well established and widely understood only around 1990, it was only then that awareness of the problem was sufficiently advanced to hold polluters responsible for their actions[7,14,27]. Given the limited quality and availability of both emissions and population data before mid-century, I selected 1960 as a reasonable starting date for carbon debt calculations, which is a date that is comprehensible in terms of both human lifetimes, as well as the operating lifetimes of energy infrastructure[22]. For the climate debt calculations, emissions records for some gases were not available back to 1960; I therefore began calculations in 1990 so as to align with the arguments surrounding awareness of the problem as a requirement to allocate responsibility.

In conclusion, the carbon and climate debts presented here offer a new lens with which to examine historical disparities among countries with respect to their contributions to climate warming. Fossil fuel carbon debts are easy to calculate, carry lower uncertainty, and could also potentially be monetized using estimates of the economic cost of climate damages from CO_2 emissions (see Supplementary Methods for discussion of how carbon debts could be monetized using the Social Cost of Carbon[30]). Historical carbon debts could therefore be a helpful tool to inform policy discussions relating to historical responsibility and burden sharing[11], by providing a measure of who should pay (and how much they might be expected to pay) for the costs of mitigation, adaptation or loss and damages in countries with lower historical emissions. Climate debts and credits provide a more complete (albeit more uncertain) picture of countries' over- or under-contribution to historical warming. As estimates of national emissions improve, the calculation of climate debts will also become a more robust and policy-relevant way to quantity both historical and potential future inequalities among nations with respect to their contributions to and responsibility for anthropogenic climate change.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions
H.D.M. conceived the idea for this work, conducted the analysis, and wrote the paper.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints.

Competing financial interests
The author declares no competing financial interests.

Methods

Description of data sets used. Fossil fuel CO_2 emissions, including emissions transfers associated with international trade are taken from the 2014 Carbon Budget of the Global Carbon Project[16]. Fossil fuel emissions were available here from 1959 to 2013, with consumption-based emissions covering the period from 1990 to 2012. To calculate per-capita emission histories, I obtained national time series of population data beginning in 1950 from the United Nations World Population Prospects[17]. Given the constraint on population data availability, I did not attempt to merge the Global Carbon Project fossil fuel CO_2 emissions data with other data sets that provide CO_2 emissions records before 1959, but rather focused on 1960 and 1990 as starting dates for the calculations presented here.

Regional land-use CO_2 emissions are also available from the 2014 Carbon Budget up to the year 2010 (ref. 16). To disaggregate this data to the national level, I used the methodology described in ref. 1, whereby I allocated regional data to countries within the region according to their relative changes in forest vegetation cover. In addition, I used the national estimates of land-use CO_2 emissions from the MATCH database (http://www.match-info.net)[2]. Given some country-level differences between these two data sets, I used the average value for each country in the final calculation of land-use CO_2 carbon debts.

National emissions of CH_4, N_2O and SO_2 are available from the EDGAR database (http://edgar.jrc.ec.europa.eu) covering the period from 1970 to 2010. As in the case of land-use CO_2, I also used national CH_4 and N_2O emissions data from the MATCH database (http://www.match-info.net)[2], and averaged the two available data sets for CH_4 and N_2O to minimize the potential errors associated with national-level data. For consistency across data sets, as well as with the dates most commonly discussed in the climate responsibility literature[7,27], I used only the data from 1990 to 2010 to calculate climate debts (see Supplementary Methods for discussion of additional uncertainties associated with historical emission estimates).

Calculation of carbon and climate debts. For the case of fossil fuel CO_2 emissions, I calculated the 'carbon debt' of a country over a given window of time (t) as:

$$\text{Carbon debt}_{\text{country}} = \sum_{t=\text{start yr}}^{\text{end yr}} \left(\text{Emissions}(t)_{\text{country}} - \text{Emissions}(t)_{\text{world}} \left(\frac{\text{Population}(t)_{\text{country}}}{\text{Population}(t)_{\text{world}}} \right) \right) \quad (1)$$

Recent analyses have shown that the climate response to CO_2 emissions can be approximated well by a constant value that does not change over time[18,31]. This conclusion is based on a number of recent studies that have demonstrated a linear relationship between cumulative CO_2 emissions and global temperature change in both global climate models, as well as in the observational record[18,31–33]. This linear relationship has been defined recently as the 'transient climate response to cumulative carbon emissions' (TCRE), with a best estimate of 0.4 °C per 1,000 $GtCO_2$ emitted and a likely (67%) uncertainty range of 0.2–0.7 °C per 1,000 $GtCO_2$ (0.8–2.5 °C per 1,000 Gt C; ref. 19). The TCRE has been shown to be independent of both time and emissions scenario owing to the opposing effects of: decreasing effectiveness of CO_2 radiative forcing at higher CO_2 concentrations (leading to less temperature change per unit increase in atmospheric CO_2); and decreasing strength of land and ocean carbon sinks with increasing CO_2 concentration and climate changes (leading to a larger increase in atmospheric CO_2 per unit CO_2 emission)[34]. Consequently, the climate response to cumulative emissions can be considered to remain approximately constant for total emissions up to at least 7,300 $GtCO_2$ (2,000 Gt C) and until the time at which temperatures peak[19]. This means also that the above carbon debt calculation can be meaningfully applied to any particular historical time window (as defined by the start and end year), without any need to treat past emissions differently from current or future emissions. And as CO_2 emissions produced over time have the same per-unit effect on global temperatures, accumulated carbon debts represent a direct national contribution to climate warming in excess of (or below) a share based on their fraction of world population over time. For the limited portion of the historical period studied here, this method is a very reasonable approximation of the climate response to accumulated CO_2 emissions over time.

For the case of temperature changes caused by CO_2 emissions from fossil fuels and land-use change, in addition to non-CO_2 greenhouse gases and aerosols, I generalized the calculation of carbon debts to calculate a country's 'climate debt' as:

$$\text{Climate debt}_{\text{country}} = \sum_{t=\text{start yr}}^{\text{end yr}} \left(\mathrm{d}T(t)_{\text{country}} - \mathrm{d}T(t)_{\text{world}} \left(\frac{\text{Population}(t)_{\text{country}}}{\text{Population}(t)_{\text{world}}} \right) \right) \quad (2)$$

Here, ($\mathrm{d}T(t)_{\text{country}}$) is each country's actual temperature contribution (shown in Fig. 3a), and the second term represents the country's population multiplied by the global average per-capita warming over time (shown in Fig. 3b).

Calculation of national temperature contributions. As in the case of carbon debts discussed above, I calculated the temperature contribution of fossil fuel and land-use CO_2 emissions using a linear temperature response to cumulative CO_2 emissions of 0.4 °C per 1,000 $GtCO_2$ (consistent with the best estimate of the Transient Climate Response to cumulative carbon Emissions from ref. 18). This resulted in the allocation of a total CO_2-induced warming from fossil fuel and land-use emissions of 0.25 °C between 1990 and 2010.

As a linear temperature-cumulative emissions relationship can be used only to estimate the CO_2-induced temperature change, a different methodology is required for non-CO_2 gases, which must also account for their variable atmospheric lifetimes. Various methods have been used previously to calculate national temperature contributions, ranging from simple calculations of historical cumulative emissions equated using CO_2-equivalence metrics such as Global Warming Potential[2–4], to more complex methods involving multiple model simulations using climate models of varying complexity[2,4,5]. Here, I calculated the temperature contribution of non-CO_2 gases using the methodology described in ref. 1, which is both relatively simple, and also includes an explicit method to account for the more limited atmospheric lifetime of temperature changes caused by shorter-lived non-CO_2 gases. I first used the University of Victoria Earth System Climate Model[35,36] to simulate the temperature response to historical concentration increases followed by zero emissions of each gas, specifying a concentration decay according to the atmospheric lifetime of each gas as in ref. 37. I then used the simulated decrease of global temperatures after zero emissions as a normalized weight applied to past emissions, such that present-day emissions were assigned a full weight, and emissions in the past were assigned a weight of less than one to represent the proportion of warming from those emissions still present in the atmosphere (see Supplementary Fig. 4).

Finally, I calculated weighted cumulative emissions for each country at each year (beginning in 1990) and used these weighted emissions to allocate the total amount of warming for each gas to individual countries according to their relative portion of global weighted emissions. I allocated a total of 0.15 °C for CH_4, 0.025 °C for N_2O and –0.1 °C for SO_2 as an estimate of the approximate contribution of each gas to temperature changes between 1990 and 2010. These values were selected to be representative of the relative magnitude of radiative forcing changes between 1990 and 2010 for CH_4, N_2O and the direct effect of SO_2 (ref. 38), as well as to reflect the idea that recent emissions of short-lived gases have had a larger effect on recent temperature changes relative to earlier historical emissions, as compared to gases with longer atmospheric lifetimes. Further details of this method, as well as comparison of the resulting national climate contributions to previous studies, can be found in ref. 1.

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