Trends and patterns in the contributions to cumulative radiative forcing from different regions of the world

D. M. Murphy[a,1] **and A. R. Ravishankara**[b,c,1]

[a]Earth System Research Laboratory, Chemical Sciences Division, National Oceanic and Atmospheric Administration, Boulder, CO 80305; [b]Department of Chemistry, Colorado State University, Fort Collins, CO 80524; and [c]Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80524

Contributed by A. R. Ravishankara, November 12, 2018 (sent for review August 17, 2018; reviewed by John H. Seinfeld and Keith Shine)

Different regions of the world have had different historical patterns of emissions of carbon dioxide, other greenhouse gases, and aerosols as well as different land-use changes. One can estimate the net cumulative contribution by each region to the global mean radiative forcing due to past greenhouse gas emissions, aerosol precursors, and carbon dioxide from land-use changes. Several patterns stand out from such calculations. Some regions have had a common historical pattern in which the short-term offsets between the radiative forcings from carbon dioxide and sulfate aerosols temporarily led to near-zero radiative forcing during periods of exponential emissions growth with few emission controls. This happened for North America and Europe in the mid-20th century and China in the 1990s and 2000s. However, these same periods lead to a commitment to future radiative forcing from the carbon dioxide and other greenhouse gases that stay in the atmosphere long after the aerosols. For every region, this commitment to future radiative forcing (2018–2100) from emissions already in the atmosphere is larger than the cumulative radiative forcing to date (1900–2017). This comparison again highlights how the full radiative forcing from greenhouse gases is unmasked once the aerosol emissions are reduced to improve air quality. The relative contributions from various regions to global climate forcing depends more on the time the contributions are compared (e.g., now or 2100) and future development scenarios than on whether cumulative radiative forcing, ocean heat content, or temperature is used to compare regional contributions.

cumulative radiative forcing | aerosols | greenhouse gases | climate change | regional contributions

It is well documented that the increasing greenhouse gases since industrialization due to anthropogenic activities are the major drivers of climate change in the 20th and 21st centuries. The greenhouse gases (GHGs) have been increasing since industrialization and this is particularly so for carbon dioxide, a product of fossil fuel combustion and land-use changes such as deforestation. In addition to the GHGs, humans have and will continue to influence climate through emissions of aerosols and their precursors. While GHGs trap outgoing infrared radiation and, thus, lead to a warming, aerosols overall cool the Earth. This decrease could occur by direct scattering of incoming solar radiation or via increasing clouds and their propensity to reflect sunlight. Currently, there is some uncertainty regarding the magnitude of the overall contribution of aerosols to the total net radiative forcing. But, it is generally agreed that the overall influence of aerosols has been cooling (1) with an aerosol radiative forcing of around -1 W m^{-2}.

Climate change at a given point in time is not simply due to the contribution of GHGs and aerosols at that time, but the history of the abundances of those species in the atmosphere. Concentrations of GHGs persist in the atmosphere subsequent to their emissions from a decade in case of methane, over a century in case of N_2O, to multiple centuries in case of CO_2. Therefore, emissions of these gases not only enhance the energy retained by Earth at the time of emissions but also continue accumulating energy for a long period of time. Aerosols, on the other hand, are very short lived, on the order of weeks, so that their radiative influence is essentially simultaneous with their emission time.

The relative emissions of GHGs and aerosols have not been the same in different regions. One reason is that some regions have had more emissions from industrial activity than other regions, and in other regions land-use/land-cover change (LULC) has been an important driver of emissions. Here we explicitly deal with only the largest component of the latter—the influence of LULC on CO_2. A second, important reason for regional differences in emissions is that aerosols (often referred to as particulate matter, PM) pose a direct health threat to humans and, hence, have been regulated to various degrees in different parts of the world as an air-quality/human health issue. Not surprisingly, bad air quality, which was a direct consequence of industrial growth, was first regulated in the developed countries (2, 3). In contrast, many of the rapidly developing economies in Asia do not yet have stringent air-quality regulations and the amounts of aerosol from these countries are large. It is anticipated that these large aerosol/PM levels are not sustainable over long periods as society demands cleaner air to breathe.

Previous work (4–10) has examined the contribution of various nations and developing or developed economies to GHG emissions and to model calculated changes in temperature, sea-level rise, etc., and discussed the contributions of aerosols as well as GHGs from various nations to temperature change and ocean heat content. Others have looked at the global warming potentials (GWP) weighted emissions of various GHGs to evaluate

Significance

The cumulative radiative forcing (CRF), an integral of radiative forcing over a given time, is used to calculate the contribution to the global mean net radiative forcing due to greenhouse gases and aerosols from various regions. For every region, the commitment to future radiative forcing from emissions already in the atmosphere is larger than that to date. For individual regions, the CRF is near zero during rapid industrialization and it increases when air-quality regulations come in and/or exponential growth ceases, a pattern repeated by North America, Europe, and China. The relative contributions from regions depends more on when the contributions are compared (e.g., now or 2100) and development scenarios than the metric used (i.e., CRF, ocean heat content, or temperature).

Author contributions: D.M.M. and A.R.R. designed research; D.M.M. performed research; D.M.M. and A.R.R. analyzed data; and D.M.M. and A.R.R. wrote the paper.

Reviewers: J.H.S., California Institute of Technology; and K.S., University of Reading.

Conflict of interest statement: A.R.R. and John H. Seinfeld appear as coauthors on a 2016 Perspective. D.M.M. and John H. Seinfeld are coauthors on a 2017 review article.

[1]To whom correspondence may be addressed. Email: daniel.m.murphy@noaa.gov or a.r.ravishankara@colostate.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1813951115/-/DCSupplemental.

responsibility for climate change (e.g., https://www.ucsusa.org/global-warming/science-and-impacts/science/each-countrys-share-of-co2.html#.XAb3ONtKhhF), but this will account only for the GHG emission contributions. Here we emphasize a temporary offset by aerosol to the total radiative forcing during periods of exponential emissions growth with few air-quality controls. Such an offset has occurred for several regions at different times and is likely to occur in other regions. Those periods of offsetting emissions leave behind a commitment to future warming, mostly from CO_2. We examine the contributions of different regions using several metrics and find that because of their different industrialization histories, the fraction of the global forcing ascribed to each region depends more on when the comparison is made, for example the present day only or including commitments to the future, than on the metric used to compare regions (see *Other Metrics of Future Contributions*).

Cumulative Radiative Forcing: Metric to Compare Regional Contributions to Global Radiative Forcing

There are two reasons that the radiative forcing (F) at a given time is not a complete measure of the regional contributions to climate change at that time or in the future. First, the past history of radiative forcing (RF) attributable to those regions must be considered to understand changes in temperature and especially ocean heat content. Second, the contributions "baked in" to the future by past actions are not included in RF but need to be considered because long-lived GHGs carry a commitment to future RF.

One measure of sustained contributions to RF is the cumulative RF, that is, the integral of the time-dependent RF over time. This metric has certain advantages. Regional contributions to cumulative RF can be compared without knowing the response of the climate system, as is necessary for regional contributions to temperature change. When looking ahead to the future, comparing the cumulative RF from various regions is analogous to comparing the GWPs of various GHGs: Both integrate RF over a specified time period.

To elucidate the meaning of the cumulative RF, one can start with the linearized climate equation (11)

$$N \approx F - \lambda \Delta T, \tag{1}$$

where N is the net flux imbalance, F is the RF, λ is the inverse climate sensitivity, and ΔT is the change in global mean temperature. Integrating over time and rearranging:

$$\int_{t1}^{t2} F dt \approx \Delta E + \int_{t1}^{t2} \lambda \Delta T dt, \tag{2}$$

where ΔE, the integral of the net flux imbalance between t1 and t2, is the energy gained by the Earth, largely by the oceans, during that interval. Both terms on the right-hand side of Eq. **2** are roughly proportional to ΔT, since for a given depth of heat penetration into the ocean, ΔE is the product of heat capacity of the ocean layer and ΔT.

The relative size of the terms on the right-hand side of Eq. **2** depends on the magnitude of λ. In today's world, the $\int \lambda \Delta T dt$ term is larger than ΔE (12). As ΔT gets larger in the future, the $\int \lambda \Delta T dt$ term will be even more important compared with ΔE. Put simply, the cumulative RF represents energy that is either gained by the Earth (ΔE) or used to maintain the Earth at a warmer temperature ($\int \lambda \Delta T dt$).

The advantage of cumulative RF is that it does not require either a knowledge of λ or a model of energy flows to compute regional contributions, but this is also a limitation. Without knowing λ one cannot predict the magnitude of the temperature change and without an energy model one cannot predict its time response. As Eq. **2** shows, the cumulative RF is closely related to the integral of the temperature change rather than the maximum temperature or rate of temperature change, either of which is arguably more closely related to impacts than is the integral over time. However, the cumulative RF does not depend on complex models and can be a useful quantity for comparison of contributions, akin to the concept of GWP or GWP weighted emissions (i.e., GTCO2eq).

One can also estimate the temperature change from a given time history of RF. Our calculations here use the temporal kernel method (13). These kernels describe a multimodel mean response to a step change in RF. Briefly, an arbitrary time history of RF can be described as a series of small step changes. To the extent that the climate response is linear, the temperature or ocean heat content can be computed as a sum of responses to those step changes. The kernels provide a formal way of computing these changes from model experiments with step changes in CO_2. The kernel method assumes that the temperature response to all other forcing agents is proportional to their RF with the same climate sensitivity as for CO_2. Comparing regional contributions using temperature rather than cumulative RF brings the comparison closer to impacts but introduces additional uncertainty since the kernels are derived from global climate models. Just as regional contributions to cumulative RF are analogous to GWPs, regional contributions to temperature are analogous to global temperature change potentials (GTPs), with many of the same advantages and disadvantages (4, 14, 15). The tradeoffs when using ocean heat content to compare regional contributions are intermediate between those for cumulative RF and temperature change.

We begin our calculations of emissions in 1850, when regionally apportioned databases for industrial and land-use emissions are available. We start the integration of cumulative RF (Eq. **2**) in 1900. We choose 1900 as the start since CO_2 concentrations exceeded 300 ppm around this time and industrialization accelerated. It also allows some time for emissions to accumulate before starting the integration. Because RF was small before 1900 compared with today, our calculations are not very sensitive to the exact starting year.

Methods for Regional Contributions to RF

We first estimate the contribution to RF due to emissions from different regions. We emphasize that we are calculating the contributions by regions to global RF, not the RF over specific regions. In the current study, we have divided the world into nine regions: (*i*) North America (Canada and United States); (*ii*) Western Europe; (*iii*) Russia and other Eastern Europe; (*iv*) China and its immediate surroundings; (*v*) The Indian Subcontinent (India and some of its neighbors); (*vi*) Asia excluding China (but including South Korea, which is highly industrialized); (*vii*) Middle East and Africa; (*viii*) Latin America (including Mexico); and (*ix*) the Pacific (mostly Japan, Australia, and New Zealand). These regions correspond to regions and subdivisions thereof used by the Representative Concentration Pathway (RCP) scenarios (16). *SI Appendix* lists the countries in each region. One could debate this division and it could be changed if one chooses to do so. For example, former Eastern-bloc countries that are now in the European Union could arguably be grouped with either Western Europe or with Russia as economies in transition. Indeed, one could do an analysis country by country although the uncertainties for some small emitters would be very large. The purpose of using regions is to keep the figures and discussion manageable while preserving similarities in geography and economic development paths.

The RF due to emissions from each region could in principle be obtained from a regionally resolved emissions inventory along with knowledge of the atmospheric lifetime and forcing of each species. In practice, for most gases the concentration history, from direct atmospheric measurements and from gas trapped in firn and ice, is known better than the emission history. Therefore, in this work we started from the atmospheric concentration history of carbon dioxide and other GHGs. Using the estimated atmospheric lifetimes, we derived an inferred time history of global emissions that created the observed concentrations. The inversion process used for CO_2, N_2O, and CH_4 essentially takes time derivatives so the forcings were smoothed over 7 y before the inversions. (The emission history of chlorofluorocarbons and related ozone-depleting gases is well known.) For carbon dioxide, the global time series of the inferred emissions closely matches the direct emissions estimates. Other gases also compare well to the less complete emissions inventories available for them.

We took this extra step of an inferred global emissions history because it guarantees self-consistency between the emissions, atmospheric lifetimes, and the known atmospheric concentrations. Otherwise, one might take the emissions from one reference and the lifetime from another reference and calculate an RF that was inconsistent with the atmospheric concentrations. Starting from the concentration history also keeps the calculations more self-consistent if the airborne fraction of CO_2 changes. However, information to date suggests that the airborne fraction of CO_2 has not changed significantly (17, 18).

For aerosols, there is no record of atmospheric concentrations comparable to those for CO_2, N_2O, CH_4, and halocarbons. Here we use literature estimates of the time history of global RF from aerosols and apportion the forcing by sulfate emissions. Sulfate is the largest component of anthropogenic change of aerosols but is not all of it. Apportioning the entire anthropogenic aerosol effect by sulfur does not mean that other aerosol species are ignored but rather that the regional patterns of their emissions are assumed to be similar to the regional pattern of sulfur emissions. This is reasonable since the emitted black carbon, nitrates, and secondary organics are also often proportional to economic activity.

Details of the data sources are shown in *SI Appendix*, Fig. S1. CO_2, N_2O, CH_4, and halocarbon RFs are from Skeie et al. (19), with more recent years from the National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Division (20). Global aerosol forcings, including both direct and aerosol–cloud interaction effects, are scaled to sulfur emissions from Smith et al. (21) and Klimont et al. (22), with an average value of -1.0 W m^{-2} for the period 1980–2005 (12). Forcings beyond the last available year from each reference were assumed to be the same until 2017.

Once time histories of global emissions were derived, the emissions inventories were used to apportion the global emissions to each region. National emissions inventories for the GHGs are from Climate Analysis Indicators Tools (23, 24). CO_2 histories go back to 1850; other emissions histories are available only from 1990. Regional fractions of N_2O, CH_4, and halocarbons for 1990 were used for prior years. Carbon emissions from land-use and land-cover changes are from Houghton and Nassikas (25). National sulfur emissions are from Smith et al. (21) and Klimont et al. (22). Gas-phase and aerosol species emissions before 1850 were assumed to be zero. RFs for methane and halocarbons were scaled to make a partial allocation of the forcing from tropospheric and stratospheric ozone, respectively. Methane is the largest single contributor to changes in tropospheric ozone (1). The recent RF of methane changes from about 0.5 to 0.8 W m^{-2} if one includes its indirect effects on ozone (26), with a somewhat smaller ozone forcing in more recent estimates (1, 27). Scaling methane can approximate just under half of the tropospheric ozone forcing (1).

A simplification implicit in using cumulative net forcing is that climate change is driven by the net forcing. Although it is a good first approximation, this is not strictly true: Offsetting forcings can lead to important changes, particularly in precipitation and the hydrologic cycle (28, 29).

Calculation of the future commitment due to the emissions already taken place to date is straightforward. It is essentially due to gases remaining in the atmosphere in the future. We took the concentrations of each GHG, computed its forcing going forward in time based on its atmospheric lifetime with no further emissions, and multiplied the integral of that future forcing by the fraction of that gas in the atmosphere in 2017 due to emissions from each region (which is not the same as either the regional fraction of 2017 emissions or the regional fraction of total emissions from 1900 to 2017). Note that the contributions due to aerosols are zero to the future cumulative RF since they are essentially gone from the atmosphere after the year in which they are emitted. We are not including the impact of regional contributions of aerosols or other short-lived forcing agents on the carbon cycle. We also computed regional contributions for RCP scenarios until 2100. To make the calculations consistent with the other inventories, we computed the RCP scenarios in a manner similar to that for past emissions, i.e., we started with the RCP forcings, computed the emissions required to get them, then allocated along the RCP regional emissions.

There are numerous uncertainties in the time histories of RF by various species. Most have little impact on the general results presented here. Ignoring emissions before 1850 probably underestimates the later RF from Europe, especially from land-use change that took place in that region. There are of course uncertainties in the emissions inventories, especially for CO_2 from land-use and land-cover change. The aerosol analysis assumes that the global mean forcing per unit aerosol emission is independent of where the aerosols were emitted. Bellouin et al. (30) found that the specific RF for sulfur emissions from Europe and East Asia are within about 50% of the world average. In this regional discussion, we are not including the relatively small amounts of RF due to alterations in albedo induced by land-use changes and we have only a very approximate treatment of the forcing due to ozone. We estimate the largest uncertainty to be the time history of global aerosol RF. The effects of some alternate assumptions for aerosol forcings on our calculations are shown in *SI Appendix*.

Results and Discussion

Fig. 1 (*Top*) shows the calculated net RF as a function of year since 1900 by the entire world. The dark line, which includes all of the contributions, closely follows Intergovernmental Panel on Climate Change (IPCC) evaluations. The other two panels apportion the global RF by region.

Many key features of this figure are worthy of comment. The calculated changes in the global RF are well documented and discussed in the literature. The largest changes started around 1970. An inflection is clearly visible in the dark curve that includes both GHG and aerosol forcing. It is less apparent when aerosols are excluded. Also evident is that before 1970 the global net RF was not significantly positive if CO_2 from LULC is excluded.

The middle and lower panels show the individual contributions from each of the nine regions from 1900 to date to the overall forcing shown in the top panel. Until about 1970, the contributions of each of the nine regions were less than 0.1 W m^{-2}.

North America, Western Europe, Russia and Eastern Europe, and China have successively followed a common pattern of near-cancellation of aerosol and GHG forcing followed by rapid growth of their net contributions to global forcing (Fig. 1, *Middle*). A similar pattern was also followed by the Pacific Rim countries (Fig. 1, *Bottom*). There are two conditions for the RF by aerosols to nearly cancel that by longer-lived gases during periods of economic development. First, there must be few emissions controls on the aerosol pollution. Second, the long atmospheric lifetime of CO_2 means that its RF in a given year depends on the integrated past emissions. Maintaining a near-cancellation between the forcing from integrated

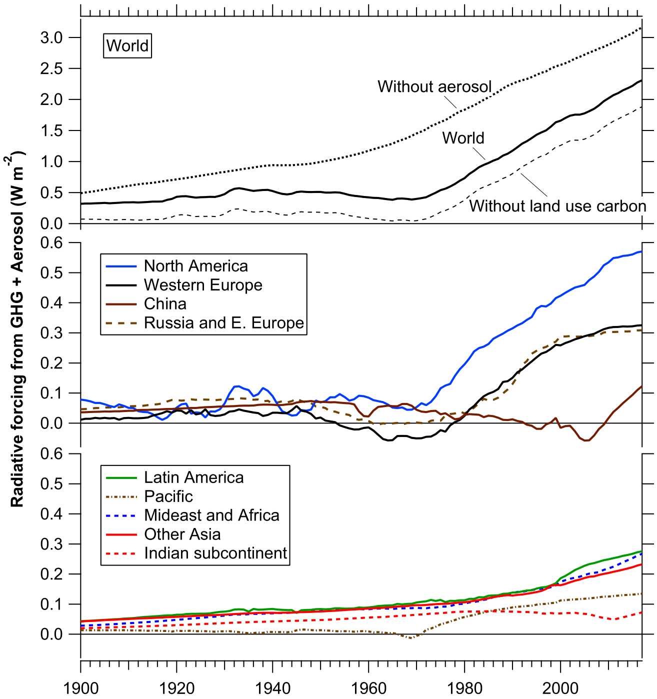

Fig. 1. (*Top*) The net RF as a function of year due to combined contributions of GHGs, land-use carbon changes, and aerosols. The dark solid line is the global forcing and includes the contributions due to LULC and aerosols. The dotted line shows the forcing if aerosol forcing were not included. The dashed line shows the forcing if land-use carbon were not included. (*Middle* and *Bottom*) The portions of the net global mean RF allocated to regions based primarily on GHG (including land-use carbon emissions) and sulfur emissions from the nine regions noted in the text. The regions are separated into two panels to minimize overlap between curves.

emissions of CO_2 and the emissions from aerosols at a given time requires that the emissions follow a pattern that is proportional to its own integral, i.e., an exponential function. So, an economy that follows exponential growth with few emission controls can have near-zero net RF for a period of time. This happened for North America in the 1950s and 1960s (also for the Pacific region), for Western Europe slightly after that, and for China in the 1990s and 2000s. More details for North America and Western Europe are shown in *SI Appendix*, Fig. S5. The Indian subcontinent region may still be in a stage with near-cancellation. Other areas such as Latin America and other Asia without a sharp inflection in net RF have strong contributions from LULC compared with fossil fuel use (Fig. 2).

The near-cancellation of aerosol and GHG RF ends when either air-quality regulations are imposed on aerosols, aerosol emissions are limited for another reason, or the region's economy can no longer maintain exponential emissions growth. What remains in the atmosphere is a commitment to future RF that cannot be taken back without active decarbonization of the atmosphere.

Cumulative Contribution to RF. Fig. 2 shows the net cumulative RF from the nine regions noted above due to emissions from 1900 to date. We acknowledge that this figure would be slightly different if the starting date were changed, say to 1850 or 1950, but the relative contributions would remain roughly the same. [The *y* axis is 1 yottajoule, YJ (10^{24} J). For reference, the total annual electrical energy consumed globally is currently about 0.00007 YJ (https://yearbook.enerdata.net/electricity/electricity-domestic-consumptiondata.html)]. The figure also shows the contribution to future RF by the emissions that have taken place to date (i.e., no further emissions after 2017).

It is striking that for all regions, the future commitments up to 2100 from GHGs already in the atmosphere (gray bars) are larger than the cumulative RF to date (dark bars). The differences between these contributions to the past and future arise because the offset due to aerosols is completely absent for the future as opposed to the past emissions. In addition, the atmospheric lifetime of CO_2 is long and there is more time for the contribution from now until 2100 relative to that up to now since 1970 (when the growth accelerated). The differences are also evident when we compare China and the Indian subcontinent. Even though the net contributions to date by these two countries are similar, the commitment by China until 2100 is much larger than that of the Indian subcontinent. This is simply because China has emitted more GHGs, whose effect to date has been offset by China's large aerosol contribution.

For those regions such as Latin America that have not had large cancellations by sulfate emissions, the future commitment is only slightly larger than the cumulative RF to date. These are the same regions that have a relatively large contribution from LULC carbon (compare the right-hand bars).

The region with the largest contribution to the cumulative RF is North America. Western Europe, other Asia (Japan and Korea), Eastern Europe (including Russia), Middle East and Africa, and Central and South America all have contributed roughly equally to date. Note that the absolute values for regions depends on how the regions are defined. For example, combining the Indian subcontinent with other Asia would naturally yield a larger bar in Fig. 2. The hashed area to the right shows the varied influence of land-use carbon changes for different regions. The land-use carbon change makes little difference for western Europe, where most land-use changes occurred well before 1900. The largest fractional influences due to land use change area for Latin America and other Asia, where large-scale deforestation has taken place in the past century. There is significant contribution due to land-use changes in North America. One reason is that North American deforestation in the 19th and early 20th century produced CO_2 that has been in the atmosphere a long time and hence has contributed significantly to the integrated forcing.

If one parses Fig. 2 by the level of economic development, the total cumulative RF from Organization for Economic Cooperation and Development nations (OECD economically developed countries) is roughly comparable to that from the rest of the world. On a per capita basis, the OECD forcing is much larger. We show these in *SI Appendix*, Fig. S6. More detailed comparisons between the developed and developing world are in

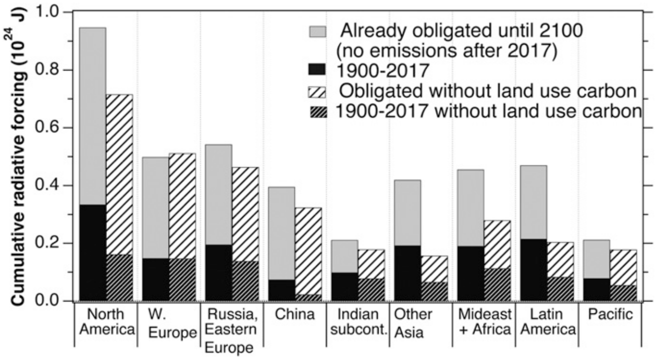

Fig. 2. The cumulative contributions to global mean net RF by emissions from the nine regions of the world. The dark bars on the left side for each region are the cumulative RF to date due to emissions from 1900 to 2017. The gray bars above the dark bars are what would be retained by 2100 due to emissions to date, i.e., what the world has already committed to because of GHGs that are already in the atmosphere. The hatched bars to the right are the same quantities without land-use carbon changes.

Ward and Mahowald (9) and Wei et al. (10). Our findings are similar to those authors. In particular, we note that the contributions of the developed countries are much larger on a per capita basis than that by the developing countries.

Other Metrics of Future Contributions. Fig. 2 shows that considering only today's RF can be misleading because the commitment to future RF from GHGs already in the atmosphere exceeds the net cumulative forcing to date. Fig. 3 shows several metrics (cumulative RF, ocean heat content and temperature) of the regional contributions to today's and future climate forcing. (The details of this calculation are given in *SI Appendix*.) The regions are shown as percentages of the global total because that minimizes, although does not entirely eliminate, the dependence on overall climate sensitivity. The solid black bars in the Fig. 3 (*Top*) are equivalent to the solid black bars in Fig. 2.

The "no emissions after 2017" (second panel from the top) in Fig. 3 is not intended as a realistic scenario but instead shows future commitment already baked in due to past emissions. The bottom two panels show calculations based on the widely used scenarios presented in the IPCC reports, i.e., the RCPs. Here we explore the future under two commonly used RCPs—RCP 8.5 when the forcing in 2100 would be 8.5 W m^{-2} [the so-called "business as usual" scenario] (16), and RCP-2.6 when the forcing in 2100 would be 2.6 W m^{-2}, which would require major controls in place (31). One simple message that emerges in Fig. 3 is that the contribution of North America is the largest to date, irrespective of the metric used. North America's contribution remains roughly the same, except for the RCP 8.5 scenario where China contributes slightly more than North America by 2100.

Some other general conclusions about regional contributions can be seen by examining the contribution from China in the various panels. China provides a good example because it has large and rapidly changing emissions (32) rather than any special feature of its mix of emissions. In Fig. 3, China's percentage of the global total varies much more from the top to bottom panels than it does for various metrics within each panel. Considering the top two panels, there is a very large change in China's contribution if only current conditions are considered or if future commitments are included, but the various bars for China are not all that different within each comparison. Considering the bottom two panels for China, the scenario for future emissions matters much more than which metric is used to measure the regional contributions.

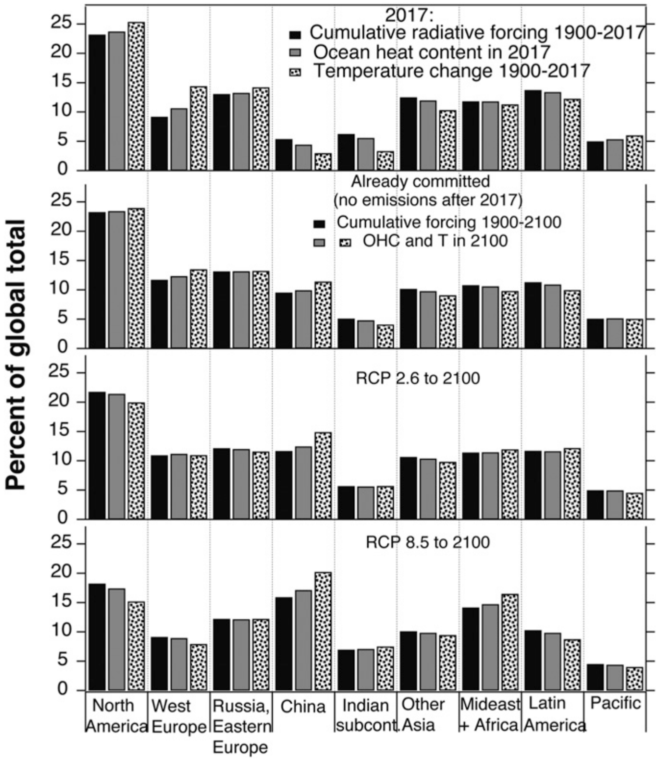

Fig. 3. Metrics of regional contributions to climate forcing now and in 2100. Shown are the estimated contributions to cumulative RF, ocean heat content, and temperature for today or 2100 under various scenarios.

The choice of metric to measure regional contributions is more important for 2017 (Fig. 3, *Top*) than commitments to 2100 (second from top). Again, using China as an example, the choice of metric can make about a factor of 2 change to its contribution to 2017 climate but only a modest change to its contribution to 2100. The reason is that the metrics respond differently to short-lived climate forcing, especially aerosols, which have a shorter lifetime than any of the GHGs. In contrast, for percentage contributions to the commitment to climate forcing it hardly matters which metric is used. Even by 2100—less than 100 y from now—most of the already committed climate forcing is from one species, CO_2. In that case, and further into the future, the choice of metric becomes less important than it is for estimating contributions in the present (4). Beyond 2100, most of the committed forcing is from CO_2 so the percentage contributions of various regions to cumulative forcing past 2100 is fairly similar to their percentage contributions to cumulative CO_2 emissions.

Overall, Fig. 3 shows that the percentage contribution of each region to the global climate is strongly affected by two factors: the pattern of economic development (e.g., RCP 2.6 or 8.5), and by how commitments to future RF are included. The latter is analogous to the known dependence of GWPs on the time horizon used to calculate GWP. In contrast, the choice of climate variable is less important to the percentage contributions by different regions.

Features of the Trends in Cumulative RF. Our calculations show the impact of the offsetting effects of the GHG emissions and aerosol emissions. As noted in Fig. 1, the difference between the RF with and without aerosols is roughly 1 W m^{-2}. This contribution, which has significantly offset the GHG contributions in many regions, can change markedly as air quality is improved, which is important for health benefits now as well as in the future. In the past, net RF has rapidly increased for North America, the Pacific region, and Europe. China is just recently "breaking out" as its emissions are not increasing exponentially, and measures are being taken to control air pollution. Accelerating emissions are required for aerosol cooling to continue to offset the warming by long-lived GHGs. The accelerating emissions are tied to both economic growths and any controls that are placed due to air quality. India is starting to consider air-quality deterioration and its aerosol emissions are unlikely to continue to accelerate indefinitely. Therefore, one should expect that India would also break out to positive cumulative RF in the next decade or two. Of course, avoiding this pattern could be one of the goals of other regions.

In the future, other regions may experience rapid growth in their contributions to net RF as air quality is improved. Indeed, if all emissions (including GHGs) ceased in 2017, global net RF would be larger than today for 15–20 y until GHG concentrations decayed enough to offset the roughly −1 W m^{-2} of aerosol forcing (33). How could the rest of the world avoid the temporary cancellation/huge commitment scenario followed by North America, Europe, and China? In the absence of large-scale removal of CO_2 from the atmosphere, avoiding the commitment would require a transition to low-GHG emissions before the exponential growth/high-pollution pattern rather than first using a high-GHG economy and then transitioning away from GHGs.

One of the differences between cumulative RF and either ocean heat content or temperature change is the inclusion in cumulative RF of the energy represented by $\int \lambda \Delta T dt$ term. This term represents the energy that maintained/maintains the Earth at a warmer temperature. The regional contributions to global temperature in, for example, 2100, consider only the temperature in 2100, not keeping the Earth warmer between now and 2100. Because it takes into account the energy needed to maintain a warmer Earth, the cumulative RF may be a useful and appropriate measure of future commitments. On the other hand, the temperature is more closely related to impacts of climate change than cumulative RF. The same considerations apply to GTP and GWP metrics: GTP is more closely related to climate impacts but GWP calculations are simpler and more certain.

The relative contributions of different regions and nations to the forcing of climate change depends more strongly on what is included in the comparison and the time frames of the examination rather than whether the metric is cumulative RF, temperature change, or ocean heat content. This result is analogous to the calculation of GWPs for individual climate forcing agents: The time horizon chosen for the GWP is generally more important than other details of the way the GWP is defined. One should not minimize the importance of the metric: Even a few percentage points in a global contribution might have large economic consequences. But, the time frame of the comparison (e.g., now, 2100, or some other time horizon) and the inclusion or exclusion of future RF from GHGs already in the atmosphere are much more important to regional contributions than the specific metric used to compare various regions.

ACKNOWLEDGMENTS. We are grateful to Scott Denning of Colorado State University (CSU), Pieter Tans of NOAA, John Seinfeld of California Institute of Technology, Keith Shine of University of Reading, and Reto Knutti of Eidgenössische Technische Hochschule (ETH) Zürich for helpful discussions, P. Forster for sending data from ref. 11, R. G. Skeie for sending data from ref. 19 in digital form, and R. A. Houghton for sending land-use carbon data in ref. 25 in digital form. Work of A.R.R. was funded by CSU. Work of D.M.M. was funded by NOAA.

1. Myhre G, et al. (2013) Anthropogenic and natural radiative forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Stocker TF, et al. (Cambridge Univ Press, Cambridge, UK).
2. Vastag B (2010) The long fight against air pollution. Available at https://www.smithsonianmag.com/science-nature/the-long-fight-against-air-pollution-21017286/. Accessed August 1, 2018.
3. Brimblecombe P (1986) *The Big Smoke: A History of Air Pollution in London Since Medieval Times* (Methuen & Co, New York).
4. Aamaas B, Peters GP, Fuglestvedt JS (2013) Simple emission metrics for climate impacts. *Earth Syst Dynam* 4:145–170.
5. den Elzen MGJ, Olivier JGJ, Höhne N, 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.
6. Hardy RD, Nuse BL (2016) Global sea-level rise: Weighing country responsibility and risk. *Clim Change* 137:333–345.
7. Matthews HD, et al. (2014) National contributions to observed global warming. *Environ Res Lett* 9:014010.
8. Matthews HD (2016) Quantifying historical carbon and climate debts among nations. *Nat Clim Chang* 6:60–64.
9. Ward DS, Mahowald NM (2014) Contributions of developed and developing countries to global climate forcing and surface temperature change. *Environ Res Lett* 9:074008.
10. Wei T, et al. (2016) Developed and developing world contributions to climate system change based on carbon dioxide, methane and nitrous oxide emissions. *Adv Atmos Sci* 33:632–643.
11. Forster PMF, Taylor KE (2006) Climate forcings and climate sensitivities diagnosed from coupled climate model integrations. *J Clim* 19:6181–6194.
12. Murphy DM, et al. (2009) An observationally based energy balance for the Earth since 1950. *J Geophys Res Atmos* 114:D17107.
13. Larson EJL, Portmann RW (2016) A temporal kernel method to compute effective radiative forcing in CMIP5 transient simulations. *J Clim* 29:1497–1509.
14. Peters GP, Aamaas B, Berntsen T, Fuglestvedt JS (2011) The integrated global temperature change potential (iGTP) and relationships between emission metrics. *Environ Res Lett* 6:044021.
15. Shine KP, Berntsen TK, Fuglestvedt JS, Skeie RB, Stuber N (2007) Comparing the climate effect of emissions of short- and long-lived climate agents. *Philos Trans A Math Phys Eng Sci* 365:1903–1914.
16. Riahi K, Grubler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol Forecast Soc* 74:887–935.
17. Ballantyne AP, Alden CB, Miller JB, Tans PP, White JW (2012) Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature* 488:70–72.
18. Tans P (2009) An accounting of the observed increase in oceanic and atmospheric CO2 and an outlook for the future. *Oceanography* 22:26–35.
19. Skeie RB, et al. (2011) Anthropogenic radiative forcing time series from pre-industrial times until 2010. *Atmos Chem Phys* 11:11827–11857.
20. Butler JH, Montzka SA (2018) The NOAA annual greenhouse gas index (AGGI). Available at https://www.esrl.noaa.gov/gmd/aggi/aggi.html. Accessed August 1, 2018.
21. Smith SJ, et al. (2011) Anthropogenic sulfur dioxide emissions: 1850–2005. *Atmos Chem Phys* 11:1101–1116.
22. Klimont Z, Smith SJ, Cofala J (2013) The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions. *Environ Res Lett* 8:014003.
23. Boden TA, Marland G, Andres RJ (2016) *Global, Regional and National Fossil-Fuel CO2 Emissions* (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US. Department of Energy, Oak Ridge, TN. Available at https://cdiac.ess-dive.lbl.gov/trends/emis/overview_2013.html. Accessed August 1, 2018.
24. (2013) Climate Analysis Indicators Tool (CAIT) 2.0 (World Resources Institute, Washington, DC).
25. Houghton RA, Nassikas AA (2017) Global and regional fluxes of carbon from land use and land cover change 1850-2015. *Global Biogeochem Cycles* 31:456–472.
26. Shindell DT, et al. (2009) Improved attribution of climate forcing to emissions. *Science* 326:716–718.
27. Shindell D, et al. (2013) Attribution of historical ozone forcing to anthropogenic emissions. *Nat Clim Chang* 3:567–570.
28. Bala G, Duffy PB, Taylor KE (2008) Impact of geoengineering schemes on the global hydrological cycle. *Proc Natl Acad Sci USA* 105:7664–7669.
29. Cox SJ, Wang WC, Schwartz SE (1995) Climate response to radiative forcings by sulfate aerosols and greenhouse gases. *Geophys Res Lett* 22:2509–2512.
30. Bellouin N, et al. (2016) Regional and seasonal radiative forcing by perturbations to aerosol and ozone precursor emissions. *Atmos Chem Phys* 16:13885–13910.
31. van Vuuren DP, et al. (2007) Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Clim Change* 81:119–159.
32. Li B, et al. (2016) The contribution of China's emissions to global climate forcing. *Nature* 531:357–361.
33. Hare B, Meinshausen M (2006) How much warming are we committed to and how much can be avoided? *Clim Change* 75:111–149.