

On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead

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The observed increase in the concentration of greenhouse gases (GHGs) since the preindustrial era has most likely committed the world to a warming of 2.4°C (1.4°C to 4.3°C) above the preindustrial surface temperatures. The committed warming is inferred from the most recent Intergovernmental Panel on Climate Change (IPCC) estimates of the greenhouse forcing and climate sensitivity. The estimated warming of 2.4°C is the equilibrium warming above preindustrial temperatures that the world will observe even if GHG concentrations are held fixed at their 2005 concentration levels but without any other anthropogenic forcing such as the cooling effect of aerosols. The range of 1.4°C to 4.3°C in the committed warming overlaps and surpasses the currently perceived threshold range of 1°C to 3°C for dangerous anthropogenic interference with many of the climate-tipping elements such as the summer arctic sea ice, Himalayan–Tibetan glaciers, and the Greenland Ice Sheet. IPCC models suggest that ≈25% (0.6°C) of the committed warming has been realized as of now. About 90% or more of the rest of the committed warming of 1.6°C will unfold during the 21st century, determined by the rate of the unmasking of the aerosol cooling effect by air pollution abatement laws and by the rate of release of the GHGs-forcing stored in the oceans. The accompanying sea-level rise can continue for more than several centuries. Lastly, even the most aggressive CO₂ mitigation steps as envisioned now can only limit further additions to the committed warming, but not reduce the already committed GHGs warming of 2.4°C.

committed | global warming

In the late 1980s, an advisory group formed by the World Meteorological Organization, the International Council of Scientific Union, and the United Nations Environment Program recommended (1) 2°C global mean surface warming from preindustrial levels as the threshold for dangerous anthropogenic interference (DAI). This recommendation has now been accepted by the German Advisory Council on Global Change (2) and the European Council (3), among other national and international bodies. More recently, Hansen *et al.* (4) have adopted a similar approach and define 1°C above the global mean temperature of the year 2000 as the DAI threshold value. It is now recognized that DAI must involve a range of threshold values of global and regional surface temperature change (5) depending on the elements of the climate system that are being impacted by the warming. This perception has led to the notion of climate tipping elements (6), some of which are hypothesized to be triggered by global warming in the range of 1°C to 2°C, and many others when global warming is in the range of 3°C to 5°C (see Fig. 1 and refs. 7 and 8).

Such a distributed DAI threshold is also consistent with the findings reported by the Intergovernmental Panel on Climate Change (IPCC) in its fourth assessment report (9, 10), referred to as IPCC-AR4. IPCC-AR4 (see tables TS.3 and TS.4 in ref. 10) specifies 1°C to 3°C global warming as the range when we commit the planet to widespread loss of biodiversity, widespread deglaciation of the Greenland Ice Sheet, and a major

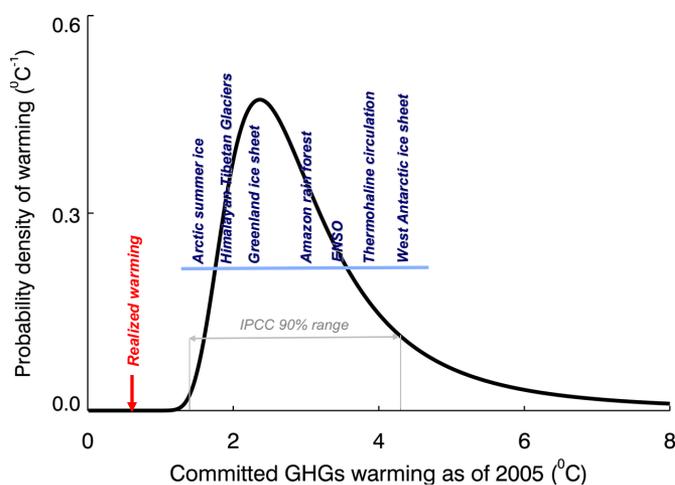


Fig. 1. Probability distribution for the committed warming by GHGs between 1750 and 2005. The normalized distribution is calculated from the probability density function given by Roe and Baker (7), and the mean and standard deviation of the uncertainties associated with feedback processes are fitted for Sanderson *et al.* (8). Shown are the climate-tipping elements and the temperature threshold range that initiates the tipping. Except those for the HKHT glaciers, the rest of the elements and the temperature thresholds are taken from ref. 6. ENSO, El Niño—Southern Oscillation.

reduction of area and volume of Hindu-Kush-Himalaya-Tibetan (HKHT) glaciers, which provide the head-waters for most major river systems of Asia. Furthermore, northern polar temperatures are increasing at twice the rate of global mean trends, and the larger polar trend is likely to continue, thus enhancing the vulnerability of the arctic sea ice and the Greenland Ice Sheet (10). We should also be aware that DAI cannot be prescribed solely within the scope of natural sciences for it involves value judgments based on nationality, ethnicity, economic well being, and numerous other social norms (5, 9). However, no

matter what or whose definitions we adopt, the DAI threshold for many of the major regional and global climate elements falls within the range of 1°C to 3°C warming from preindustrial levels

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(see Fig. 1). How far is the planetary warming that is currently under way from attaining such thresholds?

This article uses the greenhouse gases (GHGs) forcing of 3 (2.6 to 3.5) Wm^{-2} estimated by the IPCC-AR4 (11) for the preindustrial to present (year 2005) period and the IPCC-AR4 (12) climate sensitivity of 3°C (2°C to 4.5°C range) for a doubling of CO_2 . Using these data, this study infers that we have already committed the planet to a global warming of 2.4°C (1.4–4.3°C), as detailed below. This value is the global mean equilibrium (also referred to as steady state) warming above the preindustrial temperatures, caused solely by the increase in GHGs from preindustrial to now (the year 2005), i.e., the committed equilibrium warming caused by GHGs, CEW_G, is the warming (above preindustrial values) that the planet will witness, if the concentrations of GHGs were held constant at their 2005 values, but without any other anthropogenic forcing (e.g., aerosol forcing or land surface albedo changes). Furthermore, we also suggest that without strong CO_2 mitigation policy the commitment can exceed 3°C as well in ≈ 25 years.

The present value of 2.4°C for the committed equilibrium warming should not be confused with the value of $\approx 1.3^\circ\text{C}$ estimated by earlier pioneering studies of the problem (13, 14) included by IPCC-AR4 (15). These studies not only fix GHGs but also aerosols at current values and thus include the negative forcing, i.e., surface cooling effect of manmade aerosols in their estimate of the committed warming. To distinguish between the CEW_G values discussed in this study from the estimates of committed warming obtained by fixing the concentrations of both GHGs and aerosols, we refer to the latter as CEW_{G+A}. As shown later, if we adopt the IPCC (11) central value of -1.2 Wm^{-2} for the aerosol cooling effect, our estimate for CEW_{G+A} is 1.4°C, which is very similar to the values estimated by IPCC (15) and earlier studies (13, 14). Which of these two, CEW_G or CEW_{G+A}, is more appropriate for the policy community? We first note that both values of the committed warming, CEW_G and CEW_{G+A}, are large enough to be taken seriously by the policy community. But, as explained below, the question we raise for the policy makers is still relevant.

We will refer to manmade aerosols as atmospheric brown clouds (ABCs) to highlight their air pollution origin. The cooling effect of ABCs is at best a masking effect of the GHGs warming, for when air pollution laws succeed in eliminating the emissions, aerosols and

their negative climate forcing will disappear immediately given their much shorter life times of weeks. Such unmasking of the aerosol cooling effect is already happening rapidly in many developed nations, especially in Europe (16). On the other hand, the concentration of most GHGs and their positive forcing will linger for a decade or more (for methane and many halocarbons) to more than a century (for CO_2 , nitrous oxide, and some halocarbons) even after their emissions are eliminated. The primary message in this article is that CEW_G, and not CEW_{G+A}, is the relevant quantity for comprehending the potential climate changes of the 21st century, particularly because coupled ocean–atmosphere model studies reveal that $>90\%$ of the committed warming will manifest in ≈ 50 years (e.g., see figure 3 of ref. 14) and if large reductions in emissions of ABCs witnessed since the 1980s continue, ABCs are bound to decrease significantly in that time period, while many GHGs continue to increase. The objective of this article is to communicate this message to the larger community of scientists and policy makers, not well versed in the interconnections between global warming and air pollution. Given the complex technical nature of the issues described below, we encapsulate the technical issues first with metaphors in Box 1.

IPCC (12) recommends a climate sensitivity of 3°C (2–4.5°C) warming for a doubling of CO_2 . The radiative forcing (i.e., additional energy trapped) caused by CO_2 doubling is 3.7 Wm^{-2} (11). Thus it takes $\approx 1.2 \text{ Wm}^{-2}$ (0.8–1.9) of forcing to warm the planet by 1°C. The preindustrial to present (year 2005) GHGs forcing is 3 (2.6 to 3.5) Wm^{-2} (Fig. 2). It then follows that the expected warming caused by the 3 Wm^{-2} forcing is 2.4°C (1.4–4.3°C), i.e., if the only anthropogenic climate forcing on the planet is caused by the build-up of GHGs and even if we prevent further increases in the GHGs beyond their 2005 levels, the planetary warming (since the preindustrial era) would reach $\approx 2.4^\circ\text{C}$ (1.4–4.3°C). The probability distribution of this committed warming, determined by the uncertainty of the current understanding in climate feedback processes (7), is shown in Fig. 1. Why have we not seen this large warming?

First, we have to consider the effect of aerosols, which start off as urban haze or rural smoke and ultimately become transcontinental and transoceanic plumes of ABCs (17) consisting of sulfate, nitrate, hundreds of organics, black carbon, soil dust, fly ash, and other aerosols (11). ABCs have masked GHG warming by enhancing the albedo (percent of incoming solar radiation re-

Box 1: GHGs and ABCs: A Metaphorical Description. GHGs act like the blanket that keeps us (the planet) warm on a cold night by trapping the body heat (the heat radiation from the planet). This heat (heat radiation) would have otherwise escaped to the surrounding room (outer space). The build-up of GHGs caused by human activities has thickened this blanket by $\approx 2\%$ (17). Many aerosol species in ABCs, e.g., sulfates and nitrates, reflect visible solar radiation, which gives rise to the hazy skies; while black carbon aerosols, a major constituent of soot, absorb visible solar radiation, which gives rise to the brownish color of the haze. The reflecting aerosols in ABCs act like tiny (tens of nanometers to a few micrometers) mirrors on the GHGs blanket and make the planet brighter, which will have a climate cooling effect. On the other hand, the black carbon in ABCs will make the blanket brownish by absorbing more UV and visible sun light, which in turn warms the blanket and the surface. Our current understanding (summarized in figure 2 from refs. 11 and 18) is that the global cooling effect of the mirrors is much larger than the warming effect of the brownish soot with the result that ABCs have masked a significant fraction of the warming effect of the GHGs blanket. We first need to understand the warming effect of the thicker blanket because the blanket will remain at least 2% thicker (if not much more because of future additions of GHGs) for a century or longer, even if their emissions remain constant at current levels (for CH_4 , halocarbons, and ozone) or decrease substantially (for CO_2 and N_2O). ABCs, on the other hand, are a shorter-term problem, first because their lifetimes are few weeks or less, and next because air pollution abatement laws are being implemented worldwide to reduce their negative health and ecosystem impacts. Without the ABCs, the full committed impact of the thicker GHGs blanket will be unmasked and the need for reducing CO_2 emissions becomes even more urgent.

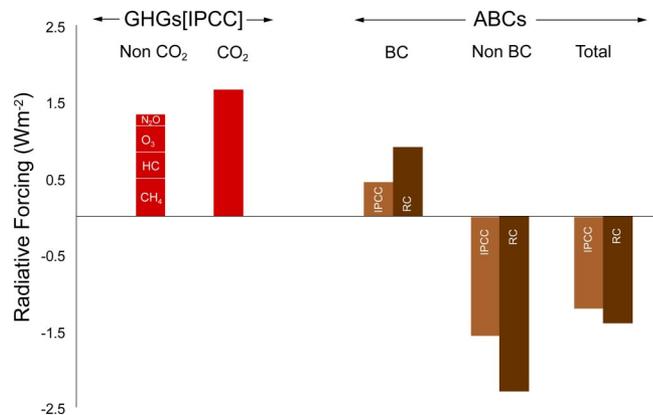


Fig. 2. Global mean radiative forcing by GHGs and anthropogenic aerosols (HC denotes halocarbons). References used were: ref. 11 for IPCC and ref. 18 for estimates given by Ramanathan and Carmichael (RC). Uncertainties (90% confidence ranges) in IPCC forcings (Wm⁻²): CH₄, ±0.05; N₂O, ±0.02; O₃, -0.1, +0.3; HC, ±0.03; CO₂, ±0.17; black carbon (BC), ±0.25. Total forcing by ABCs: direct effect, ±0.4; cloud albedo effect, -1.1, +0.4. Uncertainty in the BC forcing given by RC is estimated as ±50% (about ±0.45 Wm⁻²), and uncertainty in the total ABCs forcing should be similar to that in the IPCC report.

flected back to space) of the planet. A recent review of available literature (18) estimates the masking effect of ABCs to be ≈47% (-1.4 Wm⁻²) with a 90% confidence interval of 20–80%. The IPCC-AR4 (11) value for the masking is 40% (see Fig. 2). Effectively, the forcing “felt” by the climate system is only 53%, i.e., 1.3°C, which is identical to CEW_G+A, the committed warming adapted by earlier studies (13–15). About 8% of the committed warming (0.2°C) is compensated by increases in the surface albedo because of land-use changes; ≈20% (0.5°C) is delayed by the thermal inertia of the oceans (14, 15) and it is only the balance of ≈25%, i.e., 0.6°C, that should by now have manifested as observed warming (14). This algebraic exercise demonstrates that the observed surface warming of 0.76°C (since the latter half of 1800s) (12) is not inconsistent with the committed warming of 2.4°C.

The fundamental deduction (subject to the assumption of IPCC climate sensitivity) is that if we get rid of the ABCs today the Earth could warm another 1.6°C (which includes the delayed warming caused by ocean thermal inertia) unless we act now to reduce GHG concentrations. As shown by coupled ocean atmosphere models used in IPCC (14, 15), ≈50% of this warming can happen in few decades, and most of the balance will manifest during the course of this century. The situation with respect to sea-level rise is considerably more complex. Sea-level rise caused by thermal expansion (in the range of 10 to 30 cm per century; see refs. 13 and 14) is likely to continue for centuries (even if the warming asymptotes to values close to CEW_G by 2100) because of the time

required for mixing of the heating to deeper oceans. In addition, the range of CEW_G (1.4–4.3°C) raises another major DAI-related issue. As suggested by the IPCC (12) the Greenland Ice Sheet can disappear completely if surface warming is maintained in excess of 1.9–4.6°C for millennia and raise sea level by 7 m or more.

Proposed future reductions in emissions of CO₂ and other long-lived GHGs (e.g., see figure 10.22 of ref. 15) will have no impact on the 1.6°C warming. If, however, CO₂ emissions are eliminated completely in 2005 (an unrealistic scenario), CO₂ concentrations will decrease by 40 ppm from its 2005 value of 379 ppm (see figure 10.3 of ref. 15), and the committed warming will decrease by ≈0.5°C. This extreme example illustrates the formidable challenges in mitigating the committed warming. Our estimate for CEW_G includes ≈0.2–0.3°C caused by the short-lived tropospheric ozone increase (11), and we retained it because, as the demand for transportation grows in Asia and other developing nations (major source of ozone precursors NO_x = NO + NO₂), global ozone is not likely to decrease below the 2005 levels in the coming decades. In fact, IPCC-AR4 (15) projects tropospheric ozone increases of 20–25% by 2050 and 40–60% by 2100 over the present-day levels.

Turning our attention to the role of ABCs in the committed warming, we will now compare the central value of CEW_G (= 2.4°C) with that of CEW_G+A. The current (year 2005) ABC forcing as estimated by IPCC-AR4 (11) is -1.2 Wm⁻². The combined GHGs and ABC forcing central value becomes 1.8 Wm⁻² (= 3-1.2 Wm⁻²), resulting in a central value of 1.4°C for

CEW_G+A. If instead we use the more recent estimate (18) of ABC forcing (Fig. 2) of -1.4 Wm⁻², the CEW_G+A is 1.2°C, both of which are within 10% of the committed warming of ≈1.3°C estimated by earlier studies (14, 15). However, CEW_G+A is subject to much larger uncertainties than CEW_G because of the larger uncertainties in the aerosol forcing (also see refs. 13 and 15). ABCs have a direct effect on radiative forcing by reflecting solar radiation back to space, and it ranges from -0.1 to -0.9 Wm⁻² with a central value of -0.5 Wm⁻² (11). Note, however, not all aerosols have a cooling effect. Black carbon found in soot has a large positive forcing (18) (Fig. 2), but the large cooling effect of non-BC aerosols (sulfates, nitrates, some organics; see Fig. 2) results in a net negative forcing. ABCs also nucleate more cloud drops, which enhances the brightness of clouds, and the additional solar radiation reflected to space (referred to as cloud albedo effect) exerts a forcing that can range from -0.3 to -1.8 Wm⁻² with a central value of -0.7 Wm⁻² (11). The sources of these uncertainties have been discussed in detail in published literature (11, 18) and include uncertainties in emission inventories of precursor gases and primary aerosols in ABCs, chemistry of aerosol formation, physics of aerosol radiative properties, the microphysical interactions with clouds, and the smaller scales of the critical interactions between aerosols and clouds that are not resolved in climate models. The 6- to 9-fold uncertainty range for the IPCC-AR4 aerosol forcings should be contrasted with the order of magnitude smaller uncertainty range (2.6–3.5 Wm⁻²) for the GHGs radiative forcing (11). This difference in uncertainties is critical in the context of this article. The range of 1.4°C to 4.3°C for the committed warming (CEW_G) is mostly from the uncertainties in climate sensitivity. On the other hand, the CEW_G+A is subject to the uncertainty in the climate sensitivity and the much larger uncertainty in aerosol forcing. Let us now consider the options we have for regulating emissions of CO₂ and ABCs.

Fossil fuel combustion is currently adding ≈7.5 Gt C/yr of carbon (as CO₂) to the atmosphere. With 55% of the added carbon remaining in the air, we are now adding ≈2 ppm of CO₂ to the air each year. The energy demand is projected by the 2007 report of the International Energy Agency (19) to grow by 1.8% annually for the next 25 years. In the absence of mitigation policies, CO₂ emission will approach 12 Gt C/yr by 2030, and its concentration should increase from 379 ppm (in 2005) to 441

ppm by 2030. Assuming no further increase in the other GHGs after 2005, an unrealistic scenario, the committed warming increases to 3.1°C (1.8–5.4°C). Further likely increases in the powerful GHG, N₂O, caused by increased fertilizer use for feeding the additional 1.5 billion in population and increased use of biofuels (e.g., ethanol from corn, rapeseed etc; see ref. 20) will make our estimates even more discouraging. We should be wary of projections of energy use. For example, the IPCC (9) and the World Energy Outlook 2007 (19) assume an annual growth rate of 2.5–5% for CO₂ emissions from China, whereas a more realistic province-based estimate (21) puts the annual growth rate at ≈11% for 2004–2010.

Currently coal, oil, and natural gas contribute 41%, 39%, and 20%, respectively, to the fossil fuel CO₂ emission (19). If we just compare CO₂ emissions per joule of energy released, natural gas is the cleanest fuel among fossil fuels: coal emits ≈25 kg C/GJ (kg of carbon per giga joule of energy), oil emits ≈20 kg C/GJ, and natural gas emits ≈15 kg C/GJ. Fossil fuel contributes ≈80% of the total CO₂ emission, and other CO₂ emissions include cement production (2%) and land-use changes (18%) (22). Weighting the percent contribution of each fuel to total CO₂ emission with the CO₂ climate forcing (as of 2005), we obtain the following: coal, oil, and natural gas contributed ≈18%, 17%, and 9%, respectively to the committed warming of 2.4°C. The rest of the committed warming is from CO₂ emission caused by cement production and land-use changes (11%) and from emission of other GHGs (45%) (11). On the other hand, viewed in terms of surface warming, coal and oil are also the major sources of SO₂ emissions (the precursor for sulfate aerosols in ABCs) as they are responsible for ≈55% and 25% of global SO₂ emissions and natural gas <1% (year 2002). Sulfate aerosols contribute ≈70% of the 47% masking effect by ABCs (18). When we factor in the sulfate masking effect, gas is likely the strongest global warming fossil fuel. It should be pointed out, however, that coal and oil only look favorable if their associated SO₂ emissions are allowed to continue unabated. With respect to oil, however, diesel is a major source of black carbon, and when this is factored in, oil may emerge as the strongest global-warming agent (23). The above estimates illustrate the significance of the GHG–air pollution interactions in determining the actual warming potential of fuels. The GHG–SO₂ coupling illustrated above is consistent with a more quantitative modeling study (24). This

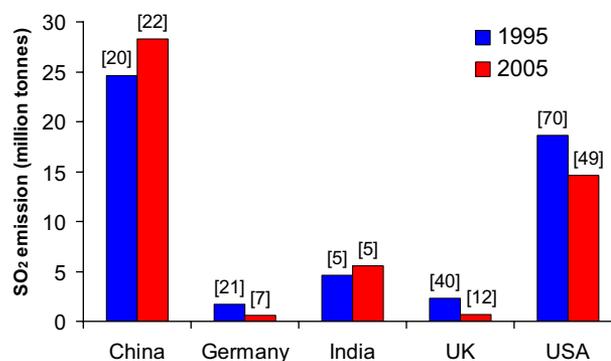


Fig. 3. Total SO₂ emission by nation (China, Germany, India, United Kingdom, and United States), for 1995 and 2005. The per-capita emissions (in kg) are indicated by the numbers in brackets on top of each bar. For 1995 emission in China, the mean value is calculated from refs. 25–27, and for 2005, the mean is calculated from refs. 25, 28, and 29 for China. Ref. 30 is used for emissions in Germany and the United Kingdom in 1995 and 2005. Ref. 31 is used for the United States, and ref. 32 is used for India.

study showed that when fossil fuel related CO₂ emission is considered along with fossil fuel-related SO₂ emission, Organization for Economic Cooperation and Development countries emerged as the “dominant contributor” to recent global warming, because of their great success in reducing SO₂ emissions (see Fig. 3 and refs. 25–32).

Switching from coal to “cleaner” natural gas will reduce CO₂ emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C). We are not arguing in favor of more coal combustion (a major contributor to ABCs) but simply point out that increasing natural gas consumption by 70% from 2005 to 2030 as projected now by the International Energy Agency (19) without an overall reduction in fossil fuel consumption could significantly accelerate the warming. The large warming experienced since the 1970s may, in part, be caused by the dramatic (+160%) increases in consumption of natural gas from 1970 to 2005. The other likely contributor is the decrease in SO₂ emissions from a peak of ≈75 Mton (million tons) of sulfur in early 1970s to ≈62 Mton of sulfur by 2003.

The estimates above do not imply that we have to keep the ABCs in the air, for their negative impacts on health, food, and water security are large. For example, reduction of solar radiation (dimming) over the North Atlantic by ABCs is suggested to be the main driver for the Sahelian drought of the mid to late 20th century (33), and the observed 50+-year-long negative trend of the Indian monsoon rainfall is attributed (34) to the observed ABC-induced dimming over Southern Asia and the North In-

dian Ocean. On the other hand, the situation juxtaposed above demonstrates that, as we curb air pollution, the need for reducing CO₂ emissions becomes even more urgent. In summary, it is not the consumption of fossil fuels that is the issue but rather, it is the emissions that result, unless NO_x, SO₂, BC, etc. are scrubbed out and CO₂ is captured and stored.

The bottom line is that the committed warming of 2.4°C (1.4–4.3°C) falls in the upper end of the DAI threshold of 1–3°C (Fig. 1). How much time do we have before the realized warming reaches the upper end of the DAI range? That will largely depend on policies for reduction of air pollution. An examination of changes in emissions of SO₂ from 1995 to 2005, the period that experienced the largest warming trend, is instructive (Fig. 3). SO₂ emissions decreased drastically (by a factor of three or more) in many regions of Western Europe, but the decrease in the United States was much smaller and even increased in China and India. If we compare the per-capita emissions (the bracketed numbers in Fig. 3) of the United States (49 kg per person) and China (22 kg per person) with those of Germany and the United Kingdom at 7 and 12 kg per person, respectively, major reductions are possible soon from China and the United States. Thus it is likely we will witness large reductions in SO₂ emissions and the ABC masking effect in the coming decades.

CO₂ mitigation policies are aimed mainly at stabilization of the CO₂ concentration at levels larger than 2005 values (4, 7, 12, 35) and thus cannot decrease the committed warming of 2.4°C (1.4–4.3°C) or delay the time for realizing it. However CO₂ mitigation policies are extremely critical if we want to limit further increases in the committed

warming. Although we have been using the central value of 2.4°C, the 90% confidence interval allows the possibility that the commitment as of 2005 can be as large as 4.3°C. Furthermore, the distribution has a long super-Gaussian tail on the positive warming side (Fig. 1). The high probability that the DAI threshold is already in our rearview mirror highlights the urgency issue raised by several studies recently (2–4, 35). But as noted above, CO₂ emission reduction actions and proposals are aimed at containing CO₂ concentrations at ≈450 to 550 ppm (9, 12, 35), but this will help neither the 2.4°C (1.4°C to 4.3°C) warming commitment from the accumulated GHGs that are already in the atmosphere, nor the projected commitment of 3.1°C (1.8–5.4°C) as of 2030.

Viewed in this context, reductions in black carbon emissions and ozone levels as proposed (4, 23) are options for reducing the warming commitment. Regional ABC-chemical-transport model simulations (18) suggest that replacement of solid fuel (fire wood, dung, coal, and crop residues) cooking with sootless cooking fuels will reduce the black carbon levels over the South Asian region by >60%. In addition to their role in global warming, black carbon through its solar heating of the atmosphere and deposition over ice and snow is emerging as a major driver for the HKHT glacier retreat and the decrease of the Indian summer monsoon rainfall (18, 34). In addition to the climate tipping elements identified in ref. 6, HKHT should also be included as a cli-

mate tipping element because it is predicted to retreat rapidly over the next several decades (10). Such a rapid retreat over the next few decades [as predicted by the IPCC (10, 15)] can impact water and food security of >2 billion south, southeast, and east Asians. Lastly, black carbon is also a major public health issue. For example, inhalation of indoor cooking smoke is responsible for >500,000 annual fatalities in India alone (36). However, any mitigation step must undergo field trials to permit cost-benefit analysis and, more importantly, to identify possible inadvertent climate effects as in the case of biofuels (20). Field studies that replace solid fuel cooking with soot-free cooking in rural India and China with scientific data collection on the impact on ABCs have been proposed to assess the efficacy of the black carbon-free cooking proposal (37).

Decisionmakers have to consider the tradeoffs between air pollution abatement and GHGs mitigation steps but they urgently need predictive tools for making such trade-offs rationally, informed fully of the consequences of policy actions, e.g., future climate changes caused by switching of fuel types, including switching to ethanol, bio diesel and other bio fuels; reducing SO₂ emission without warming-offsetting emission reductions in black carbon, NO_x, and CO₂. Basically, we need interdisciplinary and transformational research for guiding the path of future energy consumption. The climate science field has to step up to the plate. The natural

and social science communities working on the climate problem have to team up and develop end-to-end, socioeconomic-climate-impact-system models with predictive capability. A good beginning has been made by developing the framework for such integrative models (38), but we are still far from realizing the prediction objective. Such models can predict, of course in a probabilistic sense, the net climate-warming effect and impacts of each fuel and energy sector on local, regional to global scales. They can be used to provide a “seal of approval” for those paths that truly decrease the warming commitment. They can also give planners an ability to account for the implications of alternative emission reduction paths in shaping the adaptation measures that will surely need to be part of any strategy for responding to anthropogenic interference with the climate system. This is not easy and the costs may be substantial for developing such models and the associated observing systems, but we do not have much choice (2007 Bali Climate Declaration by Scientists; www.ccrcc.unsw.edu.au/news/2007/Bali.html).

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Global warming: Stop worrying, start panicking?

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In their excellent Perspectives article in this issue (1), Ramanathan and Feng (R&F) sound a harsh wake-up call for those concerned about anthropogenic climate change: the authors maintain that the greenhouse gas (GHG) emissions of the past have already loaded the Earth System sufficiently to bring about disastrous global warming. In other words, the ultimate goal of climate protection policy, as stipulated by the United Nations Framework Convention on Climate Change (UNFCCC) (2), appears to be a delusion. So should we stop worrying and rather start panicking now?

The scientific evidence about climate change comes in thousands of parcels, yet the monumental reports of the Intergovernmental Panel on Climate Change (IPCC) (3) are the guideposts for both experts and stakeholders. The IPCC format, perfected by the late Bert Bolin, is a painstaking self-interrogation process of the pertinent scientific community. In this process, virtually every stone in the cognitive landscape is turned and the findings, however mundane or ugly, are synthesized into encyclopedic accounts. Unfortunately, such an approach is inherently tuned for burying crucial insights under heaps of facts, figures, and error bars. Therefore, R&F must be commended for dredging up one of the most inconvenient truths hidden in the IPCC tangle, namely the aerosol masking of global warming (AMGW).

Also, by construction, the IPCC vessel tends to steer clear of value judgments that might be easily converted into “policy-prescriptive” statements. The downside of this well-meaning attitude is that the 2007 report does not, for instance, make a systematic attempt to characterize what dangerous anthropogenic interference (DAI) with the natural climate system is all about. Again, all of the relevant information is implicitly contained in the IPCC tomes, most notably in chapter 19 of the Working Group II report (3) (see also ref. 4). Yet even that chapter shies away from updating the “burning embers diagram” (5), which provides a direct scientific way to gauge the political target of limiting global mean temperature (GMT) rise to less than 2°C (6) against avoided climate impacts.

R&F (1) also dare to pull out this big issue from the IPCC ocean. They enrich their take on the two topics, i.e., DAI and AMGW, by recently published evidence

and add the insights up in three disturbing conjectures.

(i) Our planet is already committed to anthropogenic warming in the range of 1.4–4.3°C, where 2.4°C is the most likely amount. The main reason why only roughly a quarter (actually 0.76°C since the latter half of the 1800s) of that equilibrium temperature response to the current atmospheric GHG concentrations has been observed is the (predominantly) cooling effect of various aerosols that often accompany GHG emissions. Large scientific uncertainties remain regarding the forcing potential of the various aerosol species. There is certainty, however, that GHG concentrations (in particular, CO₂ levels) will rise further in the medium-term future and that clean-air policies will remove that accidental antidote against global warming in the decades to come. Thus, the likelihood of global warming even beyond the 2.4°C margin in the 21st century is frustratingly high.

(ii) The resulting expectations for the planetary temperature clearly qualify for DAI, whether one refers to the emerging political consensus on a long-term climate stabilization goal as implicitly debated at the Conference of the Parties to the UNFCCC in Bali (COP13) or to the growing scientific evidence about critical thresholds for tipping vital Earth System components (e.g., the Greenland ice sheet) into different modes of operation.

(iii) No conceivable international CO₂-reduction strategy (including the one hoped to transpire from the COP15 negotiations in Copenhagen next year) could possibly avoid that the planet will enter the DAI zone, where largely unmanageable climate impacts (like sea-level rise in the multimeter range) lurk. All we can do is to limit the warming *in excess* of the 2.4°C.

The first point made by R&F (1) is substantial and hard to dismiss. The tale about our dubious friend (namely “ordinary” air pollution as manifesting itself in atmospheric brown clouds laden with sulfates and nitrates) who luckily counteracts global warming by “global dimming” has been around for a while. Yet the authors succinctly summarize the state of the art and provide a convincing estimate of the still-hidden component of anthropogenic planetary temperature rise.

One needs to appreciate, however, that R&F’s assessment mainly results from clever composition of a limited number of syntheses done by other researchers [such as the paper by Roe and Baker (7)] and

by masterly back-of-the-envelope reasoning. The paper performs a basically static thought experiment by pulling back the aerosol veil while keeping all other factors fixed. In the real world, some aerosol emissions will be harder to reduce than others: whereas sulfate aerosols might face a quick decline, ammonium or nitrogen oxides might not. The AMGW might vanish quickly, as R&F suggest, but could also stick around for a while. Also, there will be intricate dynamic adjustment and feedback processes (involving, for example, the terrestrial and the marine carbon cycles) that can be captured only by simulation runs of fully fledged climate-system models. I will return to this crucial argument below.

Venturing into the 2+*x*°C-warming realm is risky, as the authors rightly emphasize in their second point, because large-scale nonlinear responses of the planetary machinery are likely to be triggered then (8, 9). These effects might even conspire to bring about—in the worst of all possible climate change science fictions—something like a runaway greenhouse effect. The present level of knowledge about the geobiosphere does not allow for rigorously ruling out such a cataclysmic accident, because we still do not possess genuine Earth models that could adequately simulate the hypercomplex dynamics involved. However, the research community keeps churning out relevant specific findings—for instance, about positive feedback processes such as methane release from Siberian thawing (10), teleconnections between tipping elements in the planetary system (11), or the volatility of the climate machinery as confirmed by empirical evidence about abrupt environmental transitions in the past (12). This topical information strengthens rather than weakens the R&F conjecture that we are heading toward DAI.

So the decisive question remains whether the authors’ third point is correct: Are we really doomed to sail straightly into those stormy seas? My answer is a qualified “no.”

The R&F projections make two pivotal assumptions, namely (i) that the atmo-

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See companion Perspective on page 14245.

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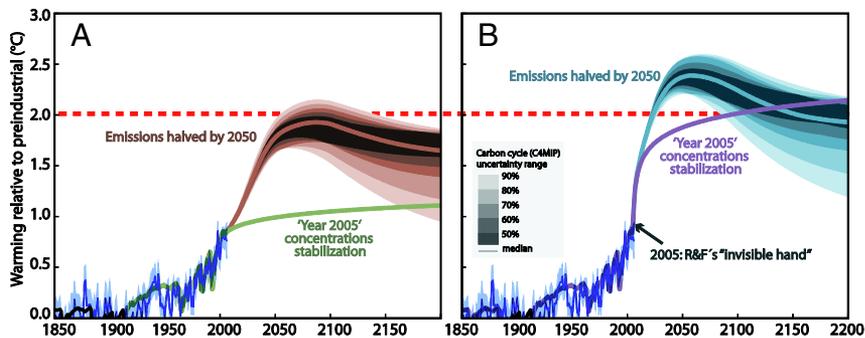


Fig. 1. Comparison of GMT development as resulting from fixing concentrations at 2005 levels ["concentrations stabilization scenario" (CSS)] and halving global Kyoto-GHG emissions by 2050 relative to 2000 levels ["mitigation scenario" (MS)], respectively. (A) Freezing of current air pollution and GHG levels in CSS, and concomitant gradual decrease of air pollution in MS. (B) The "invisible hand" of R&F (1) eliminates all forcings except those of long-lived GHGs and tropospheric ozone in 2005, i.e., aerosol cooling vanishes, in both CSS and MS. Climate sensitivity is chosen as 3°C throughout; other climate parameters (such as those affecting ocean inertia) are calibrated toward HadCM3; carbon cycle parameters are varied for representing the range of ten CMIP models (14) by using MAGICC 6.0 (13). Historical observations of GMT are taken from HadCRUT3v (15).

spheric GHG concentrations are at least constant or increasing throughout the next hundred years, and (ii) that clean-air policy operates much faster than GHG-emissions-reduction policy. Both assumptions can be challenged, as I will demonstrate by a quick model-based comparison of GMT rise in the R&F thought experiment, on the one hand, and a realistic (yet ambitious) climate protection scenario rooted in IPCC ground, on the other hand. The latter scenario anticipates that COP15 will adopt the long-term climate-stabilization goal endorsed by the recent Group of Eight (G8) Summit in Japan, namely to halve global emissions of the Kyoto-GHGs (CO_2 , methane, nitrous oxide, fluorinated gases) by 2050. 2000 is chosen as the reference year here, and a convergence to zero CO_2 emissions by 2100 is postulated. By way of contrast, the R&F assessment explores the effects of an artificial freezing of the Kyoto-GHG concentrations at their 2005 levels, tacitly assuming that climate policy could not possibly do any better.

The comparison is achieved by appropriate parameter choices in a well established climate-carbon cycle model (13) that emulates the ensemble dynamics of

the most advanced full-complexity models, and are summarized in Fig. 1. In Fig. 1A, GMT results without the "invisible hand" that instantaneously suppresses the aerosol effects (more precisely eliminating all forcings except those of long-lived GHGs and tropospheric ozone) are depicted. Note that the median trajectory in the G8-mitigation fan (as generated by state-of-the-art carbon-cycle uncertainties) avoids the 2°C line and even bends down again after peaking toward the end of this century. This favorable outcome is mainly due to the oceans' capacity to keep on taking up big quantities of certain GHGs for quite a while, so the concentrations of the latter will fall again—instead of just remaining constant—under the specified mitigation strategy. Also, in contrast to the R&F scenario, land-use changes (affecting surface albedo) and volcanic activities can be assumed to keep exerting some cooling effects. For the sake of validation and consistency, a control model run is done with concentrations of all global-warming-relevant atmospheric substances (including the ordinary pollutants) fixed at 2005 levels, which yields the slowly rising solitary curve below the G8 bundle.

In Fig. 1B, the corresponding results for switching off aerosol effects in 2005 are presented. The control curve generated by fixing the Kyoto-GHG concentrations nicely illustrates the R&F calculations by asymptotically approaching their equilibrium global warming estimate ($\approx 2.4^{\circ}\text{C}$). The really interesting result, however, is the elevated transient temperature fan produced by G8 mitigation plus abrupt sky cleaning: the median trajectory overshoots the political 2°C guardrail by $\approx 0.4^{\circ}\text{C}$ in 2070, and closely approaches it again some 70 years later. This can still be perceived as a dangerous climate excursion because it may be sufficient to trigger the collapse of the Greenland ice sheet, but the overall environmental dynamics differs fundamentally from the disturbing R&F scenario. And this is not the end of the story, because the assumption of instantaneous aerosol unmasking is certainly an unlikely one: relevant measures will be implemented rather inhomogeneously in geographical space and political time. On the other hand, the G8-mitigation scenario used here (16) already contains substantial removal of cooling air pollutants in phase with the substitution of fossil fuels and technological innovation. Therefore, the more realistic temperature developments under ambitious climate-policy conditions sit between the two fans depicted in Fig. 1A and B, respectively.

My conclusion is that we are still left with a fair chance to hold the 2°C line, yet the race between climate dynamics and climate policy will be a close one. The odds for avoiding DAI may be improved by aerosol management as suggested by R&F (taking the warming components such as black carbon out first), and even techniques for extracting atmospheric CO_2 (like bio-sequestration) might eventually prove necessary. However, the quintessential challenges remain, namely bending down the global Kyoto-GHG output curve in the 2015–2020 window (further procrastination would render necessary reduction gradients too steep thereafter) and phasing out carbon dioxide emissions completely by 2100. This requires an industrial revolution for sustainability starting now.

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