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 CO_2 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 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

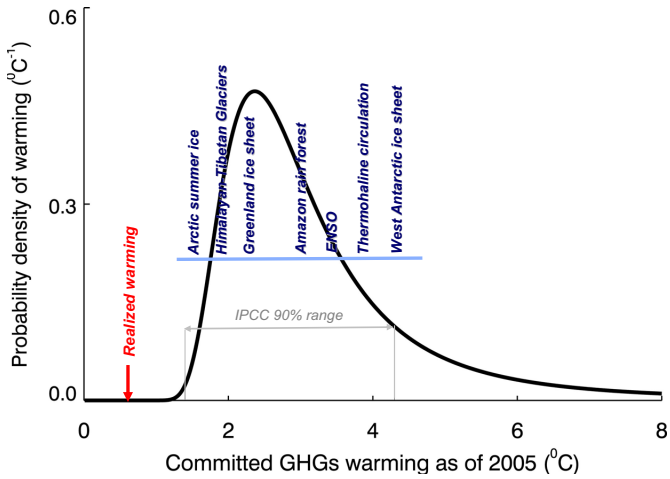

Fig. 1. Probability distribution for the committed warming by GHGs between 1750 and 2005. The normalized distribution is calculated from the probability density function given by Roe and Baker (7), and the mean and standard deviation of the uncertainties associated with feedback processes are fitted 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.

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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 ≈1.3°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 ≈1.2 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 ≈2.4°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 ≈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.

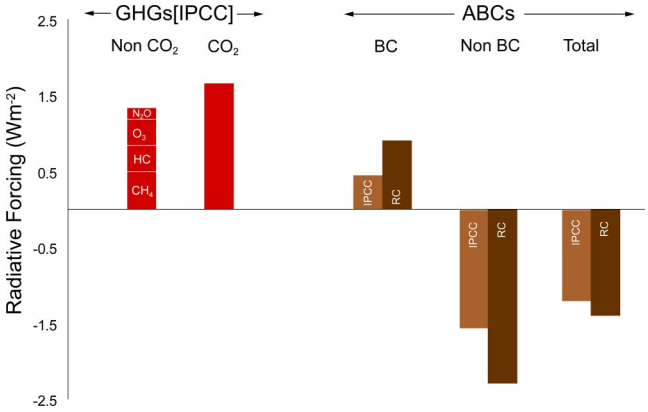

Fig. 2. Global mean radiative forcing by GHGs and anthropogenic aerosols (HC denotes halocarbons). References used were: ref. 11 for IPCC and ref. 18 for estimates given by Ramanathan and Carmichael (RC). Uncertainties (90% confidence ranges) in IPCC forcings (Wm^{-2}): CH_4, ±0.05; N_2O, ±0.02; O_3, −0.1, +0.3; HC, ±0.03; CO_2, ±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 CO_2 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, CO_2 emissions are eliminated completely in 2005 (an unrealistic scenario), CO_2 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 + NO_2), 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 CO_2 and ABCs.

Fossil fuel combustion is currently adding ≈7.5 Gt C/yr of carbon (as CO_2) to the atmosphere. With 55% of the added carbon remaining in the air, we are now adding ≈2 ppm of CO_2 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, CO_2 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, N_2O, 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 CO_2 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 CO_2 emission (19). If we just compare CO_2 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 CO_2 emission, and other CO_2 emissions include cement production (2%) and land-use changes (18%) (22). Weighting the percent contribution of each fuel to total CO_2 emission with the CO_2 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 CO_2 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 SO_2 emissions (the precursor for sulfate aerosols in ABCs) as they are responsible for ≈55% and 25% of global SO_2 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 SO_2 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–SO_2 coupling illustrated above is consistent with a more quantitative modeling study (24). This study showed that when fossil fuel related CO_2 emission is considered along with fossil fuel-related SO_2 emission, Organization for Economic Cooperation and Development countries emerged as the "dominant contributor" to recent global warming, because of their great success in reducing SO_2 emissions (see Fig. 3 and refs. 25–32).

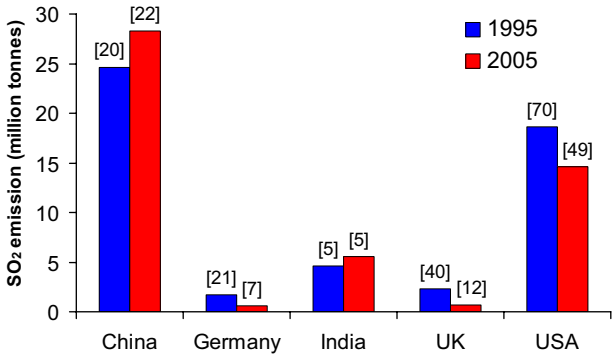

Fig. 3. Total SO_2 emission by nation (China, Germany, India, United Kingdom, and United States), for 1995 and 2005. The per-capita emissions (in kg) are indicated by the numbers in brackets on top of each bar. For 1995 emission in China, the mean value is calculated from refs. 25–27, and for 2005, the 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.

Switching from coal to "cleaner" natural gas will reduce CO_2 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 SO_2 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 Indian Ocean. On the other hand, the situation juxtaposed above demonstrates that, as we curb air pollution, the need for reducing CO_2 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, SO_2, BC, etc. are scrubbed out and CO_2 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 SO_2 from 1995 to 2005, the period that experienced the largest warming trend, is instructive (Fig. 3). SO_2 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 SO_2 emissions and the ABC masking effect in the coming decades.

CO_2 mitigation policies are aimed mainly at stabilization of the CO_2 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 CO_2 mitigation polices 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, CO_2 emission reduction actions and proposals are aimed at containing CO_2 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 climate 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 SO_2 emission without warming-offsetting emission reductions in black carbon, NO_x, and CO_2. 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.ccrc.unsw.edu.au/news/2007/Bali.html).

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