Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern"

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Article 2 of the United Nations Framework Convention on Climate Change [United Nations (1992) http://unfccc.int/resource/docs/convkp/conveng.pdf. Accessed February 9, 2009] commits signatory nations to stabilizing greenhouse gas concentrations in the atmosphere at a level that "would prevent dangerous anthropogenic interference (DAI) with the climate system." In an effort to provide some insight into impacts of climate change that might be considered DAI, authors of the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) identified 5 "reasons for concern" (RFCs). Relationships between various impacts reflected in each RFC and increases in global mean temperature (GMT) were portrayed in what has come to be called the "burning embers diagram." In presenting the "embers" in the TAR, IPCC authors did not assess whether any single RFC was more important than any other; nor did they conclude what level of impacts or what atmospheric concentrations of greenhouse gases would constitute DAI, a value judgment that would be policy prescriptive. Here, we describe revisions of the sensitivities of the RFCs to increases in GMT and a more thorough understanding of the concept of vulnerability that has evolved over the past 8 years. This is based on our expert judgment about new findings in the growing literature since the publication of the TAR in 2001, including literature that was assessed in the IPCC Fourth Assessment Report (AR4), as well as additional research published since AR4. Compared with results reported in the TAR, smaller increases in GMT are now estimated to lead to significant or substantial consequences in the framework of the 5 "reasons for concern."

Article 2 | UNFCCC | climate change impacts

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) commits signatory nations to stabilizing greenhouse gas concentrations in the atmosphere at a level that "would prevent dangerous anthropogenic interference (DAI) with the climate system." The UNFCCC also highlights 3 broad metrics with which decision-makers are to assess the pace of progress toward this goal: allow "ecosystems to adapt naturally to climate change," ensure that "food production is not threatened," and enable "economic development to proceed in a sustainable manner." In an effort to provide some insight into impacts that might be considered DAI, authors of the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) identified 5 "reasons for concern" (RFCs) in (1). Each RFC categorizes impacts of a similar type, providing a set of metrics reflecting severity of risk. Relationships between various impacts reflected in each RFC and increases in global mean temperature (GMT) were portrayed in what has come to be called the "burning embers diagram"; the image was also included in the Summary for Policy Makers of the contribution of Working Group II to the TAR and highlighted in the Synthesis Report.

In presenting the "embers" in the TAR, IPCC authors did not assess whether any single RFC was more important than any other; nor, as they noted, did they conclude what level of impact or what atmospheric concentrations of greenhouse gases would constitute DAI, a value judgment that would be policy-prescriptive. The "embers" were designed primarily to communicate the associations of impacts with increases in GMT and facilitate examination of the underlying evidence for use by decision-makers contemplating responses to these concerns.

The IPCC Fourth Assessment Report (AR4) states that "the 'reasons for concern' identified in the TAR remain a viable framework for assessing key vulnerabilities" (2). In this article, we revise sensitivities of the RFCs to increases in GMT, based on our expert judgment about new findings in the growing literature since the publication of the TAR in 2001.* Furthermore, our judgments are supported by a more thorough understanding of the concept of vulnerability that has evolved over the past 8 years,† as well as a more careful articulation of the criteria by which any specific vulnerability can be labeled "key," and thus contribute to a reason for concern (3).‡

Section 1 defines and reviews the RFCs and "burning embers" figure as presented in the IPCC TAR. Section 2 presents the

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*These judgments were vetted by 3 rounds of IPCC review and were approved in the Summary for Policymakers of both the AR4 Working Group 2 and Synthesis Reports by the IPCC Plenary.

†Vulnerability to climate change is the degree to which geophysical, biological and socioeconomic systems are susceptible to and unable to cope with adverse impacts of climate change.

‡The criteria are: (*i*) magnitude of impacts; (*ii*) timing of impacts; (*iii*) persistence and reversibility of impacts; (*iv*) potential for adaptation; (*v*) distributional aspects of impacts and vulnerabilities; (*vi*) likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates; and (*vii*) importance of the system(s) at risk. IPCC authors applied only the first 6 criteria in its assessment, because "importance" is really a subjective judgment by a potential decision-maker and thus crosses too far into the realm of being "policy prescriptive"; we follow the same convention.

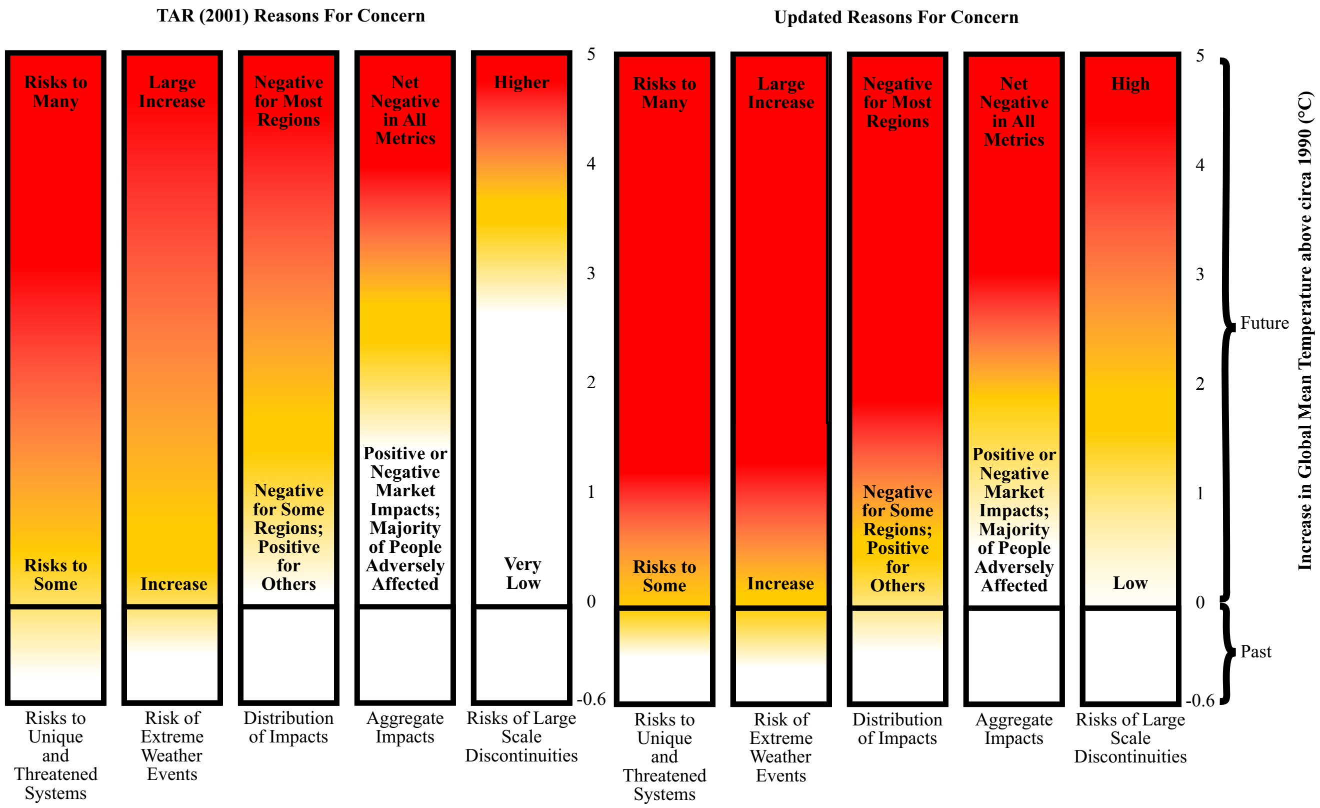

Fig. 1. Risks from climate change, by reason for concern—2001 compared with updated data. Climate change consequences are plotted against increases in global mean temperature (°C) after 1990. Each column corresponds to a specific RFC and represents additional outcomes associated with increasing global mean temperature. The color scheme represents progressively increasing levels of risk and should not be interpreted as representing ''dangerous anthropogenic interference,'' which is a value judgment. The historical period 1900 to 2000 warmed by ≈0.6 °C and led to some impacts. It should be noted that this figure addresses only how risks change as global mean temperature increases, not how risks might change at different rates of warming. Furthermore, it does not address when impacts might be realized, nor does it account for the effects of different development pathways on vulnerability. (*A*) RFCs from the IPCC TAR as described in section 1. (*B*) Updated RFCs derived from IPCC AR4 as supported by the discussion in section 2. (Reproduced with permission from Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Figure SPM-2. Cambridge University Press.)

update of the RFCs and the "burning embers" figure derived from the recently released IPCC AR4 and subsequent literature. The final section compares the earlier representation with the updated version.

The IPCC TAR and Reasons for Concern. Fig. 1 *Left* replicates the version of the "burning embers" diagram that was offered as figure SPM-2 in the Summary for Policymakers of the contribution of Working Group II to the TAR (4). IPCC AR4 projected a range of 1.1 °C to 6.4 °C increase in GMT from 1990 to 2100 (5) based on 6 IPCC Special Report on Emissions Scenarios (SRES) nonmitigation scenarios (6). Although uncertainty in the response of the climate system to increasing greenhouse gas concentrations contributes to this very broad spread in projections of increase in GMT, the magnitude of future emissions driven by alternative development pathways plays a comparable role. The assessed "likely range" (66–90%) of global temperature increase by 2100 for the lowest emissions scenario (SRES B1) is 1.1 °C to 2.9 °C, whereas the likely range for the highest scenario (SRES A1FI) is 2.4 °C to 6.4 °C. Since 2000, the trajectory of global emissions is above the highest SRES scenario (5). The observed temperature change, reflecting the response to date of the climate system to historical emissions, is also at the top of the projected range of temperature increase (7). The temperature increases in Fig. 1 go up to 5 °C although, as the IPCC projects, the increase in GMT could exceed 5 °C by 2100. An increase in GMT >5 °C by 2100 would have even more adverse effects within each RFC than has been analyzed.

The right side of Fig. 1 tracks the updated 5 RFCs against increases in GMT above 1990.[§]

Risk to Unique and Threatened Systems. This RFC addresses the potential for increased damage to or irreversible loss of unique and threatened systems, such as coral reefs, tropical glaciers, endangered species, unique ecosystems, biodiversity hotspots, small island states, and indigenous communities.

Risk of Extreme Weather Events. This RFC tracks increases in extreme events with substantial consequences for societies and natural systems. Examples include increase in the frequency, intensity, or consequences of heat waves, floods, droughts, wildfires, or tropical cyclones.

Distribution of Impacts. This RFC concerns disparities of impacts. Some regions, countries, and populations face greater harm from climate change, whereas other regions, countries, or pop-

§It is recognized that vulnerability can also be partly a function of the expected rate of climate change, but this assessment focuses on the magnitude of change. These magnitudes are, however, projected to occur over time frames that imply rates of change that are very likely to exceed the abilities of natural and human systems to adapt completely.

ulations would be much less harmed—and some may benefit; the magnitude of harm can also vary within regions and across sectors and populations.

Aggregate Damages. This RFC covers comprehensive measures of impacts. Impacts distributed across the globe can be aggregated into a single metric, such as monetary damages, lives affected, or lives lost. Aggregation techniques vary in their treatment of equity of outcomes, as well as treatment of impacts that are not easily quantified. This RFC is based mainly on monetary aggregation available in the literature.

Risks of Large-Scale Discontinuities. This RFC represents the likelihood that certain phenomena (sometimes called singularities or tipping points) would occur, any of which may be accompanied by very large impacts. These phenomena include the deglaciation (partial or complete) of the West Antarctic or Greenland ice sheets and major changes in some components of the Earth's climate system, such as a substantial reduction or collapse of the North Atlantic Meridional Overturning Circulation (8).

The RFCs were selected based on literature and judgments of the authors about risks from climate change. As indicated in the caption to Fig. 1, the authors made judgments for each RFC about what increases in GMT above 1990 would be associated with neutral or low impacts or risks (Fig. 1, white regions), negative impacts for some systems or more significant risks (Fig. 1, yellow regions), and substantial negative impacts or risks that are more widespread and/or severe (Fig. 1, red regions). In every case, the number of impacts and the harm implied depended on the rate of climate change, the amount of climate change, and the vulnerability of the affected systems. However, no single metric could adequately describe the diversity of impacts and associated risks for any one RFC, let alone aggregate across all of them into a single "dangerous" global temperature threshold. Within each RFC, therefore, multiple metrics were aggregated through expert judgment, and no aggregation was attempted across the RFCs. Moreover, it was clear that an objective ranking of relative importance across the RFCs would be impossible.

The various shadings and the judgments they depict only took autonomous adaptation into account (i.e., adaptation that might be expected to occur in the absence of anticipatory policies and measures), to the extent that such responses were captured by the underlying literature. The impacts literature, however, often makes simplifying assumptions about adaptation which can result in overestimates or underestimates of the magnitude of negative or beneficial impacts. Furthermore, there is little information on the effects of proactive adaptation (i.e., adaptations implemented to anticipate and lessen the adverse impacts of climate change, such as breeding new crop varieties or planning for coastal protection) in reducing vulnerability. Thus, it is uncertain how the relationship between the RFCs and increase in GMT would be affected by consideration of proactive adaptation.

In summary, the first 2 RFCs—Risks to Unique and Threatened Systems and Risks to Extreme Events—were judged in the TAR to imply substantial impacts or risks (transition from yellow to red) between 1 °C and 2 °C above 1990 levels. The third and fourth RFCs—Distribution of Impact and Aggregate Impacts—reflected substantial risks beginning in the range between 2 °C and 3 °C. The fifth RFC—Risks of Large-Scale Discontinuities—was not judged to be a source of substantial risk until GMT climbed more than 4 °C or 5 °C above the 1990 mean.

Updating the Reasons for Concern After the IPCC AR4. Fig. 1 *Right* shows the results of our assessment based on literature since the TAR. In updating the "embers," we retained the same color scheme and structure as the TAR. The same scale for temperature change frames the update. Transitions between colors remain fuzzy because there was (and there still is) uncertainty about the increase in GMT associated with a transition from little or no risk to some risk and from some to substantial and/or widespread risk for any specific system or sector. As was true in the TAR, the aggregation of risk across many different sectors, regions, or populations under a particular RFC is subjective, and thereby introduces another source of uncertainty. The width and placement of the transitions in each bar can nonetheless still be interpreted as visual representations of aggregated damage functions for each RFC, with narrower and lower transitions representing rapidly changing levels of risk as a function of temperature.

We take each RFC in turn in this update. Our assessment of risk for each is based on not only new information about impacts and vulnerabilities assessed in the AR4 and since, but also more clearly established criteria for identifying "key vulnerabilities" (3).

Risks to Unique and Threatened Systems. There is new and stronger evidence since the TAR of observed impacts of climate change on unique and threatened systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase further. An increasing risk of species extinction and coral reef damage is projected with higher confidence than in the TAR. There is medium confidence that ≈20–30% of known plant and animal species are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5 °C to 2.5 °C over 1980–1999 levels ("1990 levels" hereafter), a finding not made in the TAR (9). Confidence has increased that a 1 °C to 2 °C increase in GMT above 1990 levels poses significant risks to many unique and threatened systems, including many biodiversity hotspots. Corals are vulnerable to thermal stress and may have limited adaptive capacity. Increases in sea surface temperature of ≈1 °C to 3 °C are projected to result in more frequent coral bleaching events and widespread mortality unless there is substantial thermal adaptation or acclimatization by corals (10, 11). Increasing vulnerability of Arctic indigenous communities and small island communities to warming has been observed and is projected to accelerate (12). Kurz *et al.* (13) found that outbreaks of mountain pine beetle in British Columbia linked to climate change have resulted in net loss of forest biomass.

On the basis of this evidence, particularly the emergence of a number of adverse impacts that are clearly linked to anthropogenic climate change, the yellow shading in the leftmost bar of Fig. 1 *Right* begins the transition to red slightly above 0 °C, indicating substantial impacts and/or moderate risks at current temperature levels. The darker red shading, indicating potentially severe and/or widespread impacts and associated increases in risks, begins to appear ≈1 °C.

Risks of Extreme Weather Events. It is now more likely than not that human activity has contributed to observed increases in heat waves, intense precipitation events, and the intensity of tropical cyclones (2). There are, as well, more observations of climate change impacts from extremes than in the TAR (5, 14). Responses to some recent extreme climate events have also revealed higher levels of vulnerability across the globe, producing significant loss of life and property damage in both developing and developed countries. The large and unexpected health impacts due to a heat wave of unprecedented magnitude in 2003 in Europe provide one such example (15).[¶] Projected increases

[¶]Schär *et al.* (15) found that the likelihood of the 2003 heat wave in Europe, which led to the death of tens of thousands of people, was substantially increased by increased greenhouse gas concentrations compared with preindustrial levels and associated regional mean temperature increase. Luterbacher *et al.* (31) come to a similar conclusion based on a complementary line of inquiry despite working with a shorter estimated return period.

in the intensities of tropical cyclones, droughts, extreme heat waves, and floods would further increase risks to human life, damage to property and infrastructure, and damage to ecosystems, and there is now higher confidence than in the TAR in the projected increases in these events as well as their adverse impacts. More specifically, increases in drought, heat waves, and floods are projected in many regions and would have adverse impacts, including increased water stress, wildfire frequency, and flood risks (starting at less than 1 °C of additional warming above 1990 levels) and adverse health effects (slightly above 1 °C) (2).

Risk is the product of probability and consequence. The more extensive projections of increasing frequency and intensity of extreme weather events with warming (5), combined with the conclusions that severe impacts from such extreme weather events are already apparent (12), suggest that the temperature levels associated with yellow and red gradations of risk begin ≈0 °C and just below 1 °C in the second bar of Fig. 1 *Right*, respectively. Lowering the yellow-to-red transition is justified in some cases by increases in the likelihood of extreme events, by the increased impacts at a given GMT in other cases, and by a combination of these in other examples.

Distribution of Impacts (and Vulnerabilities). As in the TAR, the AR4 found that vulnerability is distributed unevenly across the globe. There is increased evidence that low-latitude and less-developed areas generally face greater risk than higher-latitude and more-developed countries, because of both higher sensitivity and lower adaptive capacity; for example, in dry regions and mega-deltas (2, 16). There is new evidence, some of it coming from observed impacts, that vulnerability to climate change is also highly variable within individual countries, including developed countries (17). There is increasing evidence of greater vulnerability of specific populations, such as the poor and elderly, to climate variability and change in not only developing but also developed countries, and that high levels of adaptive capacity may not be realized in practice in the face of stress. For example, events such as Hurricane Katrina‖ and the 2003 European heat wave have shown that the capacity to adapt to climate-related extreme events is lower than expected and, as a result, their consequences and associated vulnerabilities are higher than previously thought.

It is also now possible to better identify specific systems, sectors, and regions across the globe that are particularly vulnerable. There are sharp differences across the globe, in large measure because those in the weakest economic position are often the most vulnerable to climate change and are frequently the most susceptible to climate-related damages. This is especially true when they face multiple stresses; it is also now recognized that climate change can, itself, be the source of multiple stresses. New studies confirm that Africa is one of the most vulnerable continents because of the range of projected impacts, multiple stresses, and low adaptive capacity (18). For these reasons, and because IPCC AR4 (12) show many of the noted vulnerabilities begin or continue to grow with increases in GMT of less than 1 °C, the yellow shading begins below 1°C in the third bar of Fig. 1 *Right*, and the red shading emerges between 1 °C and 2°C.

Net Aggregate Impacts. Initial net market-based benefits from climate change are now projected to peak at lower magnitudes of temperature increase than in the TAR. It is likely that there will be higher damages for larger magnitudes of increased GMT, and the net costs of impacts of warming are projected to increase over time. Recent studies have estimated potential damages from increased extreme weather events (19, 20, 32). Inclusion of these impacts in aggregation could substantially reduce net aggregate benefits and lower the GMT increase at which net aggregate benefits peak (i.e., marginally decline) or at which they become negative. In addition, different analytic techniques (21) result in estimates of higher net damages, and inclusion of indirect effects can increase the magnitude of impacts (22, 23).

Aggregate impacts have also been quantified in nonmonetary metrics. For example, climate change over the next century is likely to adversely affect hundreds of millions of people through increased coastal flooding after a further 2 °C warming from 1990 levels (16); reductions in water supplies (0.4 to 1.7 billion people affected with less than a 1 °C warming from 1990 levels; ref. 24); and increased health impacts (that are already being observed; ref. 25).

As a result of uncertainties and use of different metrics, it is difficult to place transitions between the colors for aggregate impacts in the figure. In the revision of the figure, the fourth bar in Fig. 1 *Right* shows the yellow shadow beginning just ≈1 °C because of projections of the number of people adversely affected by climate change. The transition to red is difficult to place because it can vary depending on the metrics that are used. The transition should be no higher than just above 2 °C because of our conclusion about lower net market-based benefits. Application of nonmonetary metrics could justify a transition to red at a lower GMT.

Risks of Large-Scale Discontinuities.** There is very high confidence that global warming over many centuries would lead to a sea level rise contribution from thermal expansion alone (with associated loss of coastal area and other impacts) that is projected to be much larger than the observed contribution from expansion over the 20th century (26). There is now better understanding that the risk of additional contributions to sea level rise from melting of both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models assessed in the AR4, and that several meters of additional sea level rise could occur on century time scales (2, 7, 27, 28). Such risk arises in part from ice dynamical processes apparent in observations since the TAR but not fully included in ice sheet models assessed in AR4. New insights also come from recent paleoclimate studies (29). Complete deglaciation of the Greenland ice sheet would raise sea level by 7 m and could be irreversible. There is medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet, would occur over a period ranging from centuries to millennia for a global average temperature increase of 1–4 °C (relative to 1990 levels); this may cause an additional contribution to sea level rise of 4–6 m or more. The AR4 also discusses the consequences of ocean acidification due to increasing CO_2 concentration. However, impacts of acidifaction and other direct effects of higher CO_2 concentration on calcifying organisms have yet to be confidently observed in situ, and the CO_2 concentration thresholds for such impacts, if any, are uncertain. Finally, compared with the TAR, there is now more confidence in projections of the climate consequences of amplifying feedbacks in the carbon cycle (26, 30).

Taken together, the updated evidence on large-scale discontinuities is reflected by beginning the yellow shading ≈1 °C in the rightmost bar of Fig. 1 *Right*. Red shading begins ≈2.5 °C, the midpoint of the warming range cited above for partial deglaciation and the possible trigger for commitment to large-scale global impacts over multiple-century time scales. Given the

‖Although not attributed in the literature in whole or in part to anthropogenic climate change, Hurricane Katrina demonstrated that even developed nations face significant and inequitable risks from extreme events.

**The TAR assessed the risk of abrupt and/or irreversible changes under the rubric of large scale singularities or discontinuities, and this usage is retained here.

uncertainties over the impacts of ocean acidification and also in the relationship of temperature to CO_2 concentration, the lower limit could arguably be placed lower.

Comparisons of the Reasons for Concerns 8 Years After the IPCC TAR. Compared with results reported in the TAR, smaller increases in GMT are now estimated to lead to significant or substantial consequences in the framework of the 5 "reasons for concern." This conclusion is displayed most vividly by side-by-side comparison of the "embers" from the TAR and the updated assessment displayed in the 2 panels of Fig. 1. The transitions from yellow (moderately significant risks) to red (substantial or severe risks) for all of the RFCs are at lower GMT increases above 1990 compared with the location of the transitions in the TAR. In addition, for 3 RFCs—distribution of impacts, aggregate impacts, and large-scale discontinuities—the transition from white to yellow (i.e., no or little risk to moderately significant risk) also occurs at a lower GMT increase. The transition from white to yellow in the unique and threatened systems and extreme events RFCs occurs at a lower increase in GMT because there are more and stronger observations of climate change impacts. The temperature range that is in yellow and red on large-scale discontinuities is now much wider than in the TAR. In general, the figure provides a visual portrait of the conclusion that the temperature range from which a consensus definition of "dangerous anthropogenic interference" might be drawn is getting lower.

In summary, the shifting of risk transitions to lower GMTs is derived from assessment of (*i*) strengthened observations of impacts already occurring because of warming to date, (*ii*) better understanding and greater confidence in the likelihood of climatic events and the magnitude of impacts and risks associated with increases in GMT, (*iii*) more precise identification of particularly affected sectors, groups, and regions, and (*iv*) growing evidence that even modest increases in GMT above levels circa 1990 could commit[††] the climate system to the risk of very large impacts on multiple-century time scales.

[††]The term "commit" is used as in AR4 WGII and is derived from the possibility of crossing thresholds of irreversible change, but ones for which the actual impact may be substantially delayed.

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