

# IPCC reasons for concern regarding climate change risks

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**The reasons for concern framework communicates scientific understanding about risks in relation to varying levels of climate change. The framework, now a cornerstone of the IPCC assessments, aggregates global risks into five categories as a function of global mean temperature change. We review the framework's conceptual basis and the risk judgments made in the most recent IPCC report, confirming those judgments in most cases in the light of more recent literature and identifying their limitations. We point to extensions of the framework that offer complementary climate change metrics to global mean temperature change and better account for possible changes in social and ecological system vulnerability. Further research should systematically evaluate risks under alternative scenarios of future climatic and societal conditions.**

The reasons for concern (RFC) framework was developed in the IPCC Third Assessment Report (AR3) to inform discussions relevant to implementation of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC). Article 2 presents the Convention's long-term objective of avoiding "dangerous anthropogenic interference with the climate system". The RFC framework and the associated Burning Embers diagram illustrating authors' risk judgments have since been widely discussed and used to inform policy decisions. For example, they informed a recent dialog between Parties to the UNFCCC and experts<sup>1,2</sup> on the adequacy of the long-term goal of avoiding a warming of 2 °C relative to pre-industrial temperatures, contributing to a strengthening of that goal in the recent Paris Agreement<sup>3</sup>. Elaborations of the Burning Embers diagram have been used to represent climate impacts and risks at the regional level<sup>4</sup> and for specific systems (for example, ocean systems<sup>5</sup>).

This Review summarizes the conceptual basis for the RFCs (Box 1) and offers an explanation of the reasoning behind associated risk judgments that is complementary to, but goes beyond, the treatment in the IPCC Fifth Assessment Report<sup>6</sup> (AR5). We focus explicitly on the evidence base for transitions from one risk level to the next, incorporate post-AR5 literature in those discussions, and offer thoughts about limitations of the subjective judgments behind each RFC. We also improve the synthesis of RFC-related material across AR5, and in turn provide both a clearer connection to evidence from AR5 that supports the RFC judgments, as well as a comparison of the RFCs to similar approaches employing metrics other than global mean temperature change (GMT) for characterizing

risk. Perhaps most importantly, we consider improvements in the framework, particularly emphasizing the dynamic nature of exposure and vulnerability, two key components of risk not sufficiently covered in the current approach.

## Reasons for concern

Risk judgments for each RFC are based on the key risk criteria (Box 1) but the relative importance of each varies across RFCs depending on the quality and quantity of information available in the literature. It is also not possible to rely on a single quantitative metric of risk for a given RFC since each one aggregates over a number of different risks. An enhanced Burning Embers diagram (Fig. 1) summarizes the evidence, indicating both individual risks that play important roles in identifying particular risk transitions, as well as overarching key risks relevant in broader terms to each RFC (Table 1). These overarching key risk categories were developed in AR5<sup>6</sup> from risks identified as being of high concern by chapter authors from across IPCC Working Group (WG) II (Supplementary Section 1). Unless otherwise specified, we refer to GMT relative to pre-industrial temperatures (1850–1900). Note that conversions from units used in AR5 can give the appearance of overly precise temperature levels (Supplementary Section 2).

**RFC1: Risks to unique and threatened systems.** Unique and threatened systems encompass ecological and human systems that (i) have restricted geographic ranges constrained by climate-related conditions and (ii) have high endemism or other distinctive properties. Many of these systems also face exceptional

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**Box 1 | Conceptual basis.**

The reasons for concern (RFCs) reported in AR5 are:

- Risks to unique and threatened systems (indicated by RFC1)
- Risks associated with extreme weather events (RFC2)
- Risks associated with the distribution of impacts (RFC3)
- Risks associated with global aggregate impacts (RFC4)
- Risks associated with large-scale singular events (RFC5)

Types of risk included in each category are discussed in the section on reasons for concern. The categories share an emphasis on going beyond changes in biophysical systems to possible consequences for society and ecosystems, including their interdependencies (henceforth ‘socio-ecological systems’). Risk is the potential for negative consequences, whereas impacts are the manifestation of that potential<sup>97,98</sup>. Climate-related risk depends on the probability of hazardous events or trends and on the consequences manifested when a physical, climate-related hazard interacts with the exposure and vulnerability of society and ecosystems. Hazards related to climate change include altered occurrence of extreme events, trends in precipitation or temperature, sea-level rise, and oceanic changes such as acidification, deoxygenation or circulation changes. Exposure is the presence of people, ecosystems, or assets in places and settings that could be adversely affected, and vulnerability is their susceptibility and predisposition to harm<sup>99,100</sup>. These definitions follow those laid out in AR5, although alternatives can be found in the literature<sup>101</sup>.

The process of making judgments about levels of risk for each RFC (Supplementary Section 1) was underpinned by the

identification of key risks. Key risks reflect potentially severe adverse consequences for socio-ecological systems that could be used to inform the interpretation of “dangerous” in the UNFCCC Article 2 objective. Criteria for identifying key risks include<sup>6,102,103</sup>: high probability of significant risk materializing, taking into account its timing; large magnitude of associated consequences, taking into account the importance of affected systems; persistent vulnerability or exposure contributing to risks, or the irreversibility, at least on human timescales, of associated impacts; and limited potential to reduce risks through adaptation or mitigation.

AR5 authors drew on these criteria to characterize climate-related risk for each RFC as a function of GMT as Undetectable, Moderate, High, or Very High. The transition from Undetectable to Moderate is defined by the GMT at which there is at least medium confidence that impacts associated with a given RFC are both detectable and attributable to climate change (based on the analysis in ref. 9, section 18.6.4), while also accounting for the magnitude of the risk and the other criteria noted above. The transition from Moderate to High risk is assigned to the GMT at which associated impacts become severe and widespread. The transition from High to Very High is set at the GMT at which risk is high according to all criteria and in particular the ability to adapt is limited. In each case, variations in regional climate outcomes for a given GMT are accounted for and the likelihood of the associated hazardous event or trend is judged.

Defining the risk levels this way enables integration within each RFC across different but related risks and many different types of evidence. The scale is inherently nonlinear and qualitative, even if quantified evidence enters the judgments.

human-driven threats. Examples include tropical glacier systems, coral reefs, mangrove ecosystems, biodiversity hotspots<sup>7</sup>, and unique indigenous communities<sup>8</sup>.

AR5 located the transition from Undetectable to Moderate risk below recent temperatures based on the detection and attribution (with at least medium confidence) of impacts on Arctic, mountain, and warm-water coral reef systems (ref. 9, section 18.6.4), with indirect support from impacts on other systems (Supplementary Section 3.1). In the Arctic, impacts include the observed decline in sea ice extent<sup>10</sup>, warming and thawing of permafrost in Alaska and associated land-sliding<sup>9,11,12</sup>, substantial changes in ecosystems and ecological dynamics — including signs of broad-scale boreal forest encroachment into tundra<sup>13–15</sup> — and livelihood impacts on indigenous Arctic peoples<sup>9</sup>. In mountain systems, there is evidence of shrinking or receding glaciers from all continents<sup>9</sup>. There is also high confidence that climate change has contributed to widespread and frequent coral bleaching and mortality due to high temperatures<sup>16–19</sup>.

A transition from Moderate to High risk occurs over the range ~1.1–1.6 °C. In broad terms, this transition is placed halfway between the Undetectable/Moderate transition and High/Very High transition (discussed next) to reflect the generally increasing risks over this range. However, specific projected impacts for Arctic and coral reef systems also informed the judgment (Supplementary Section 3.2).

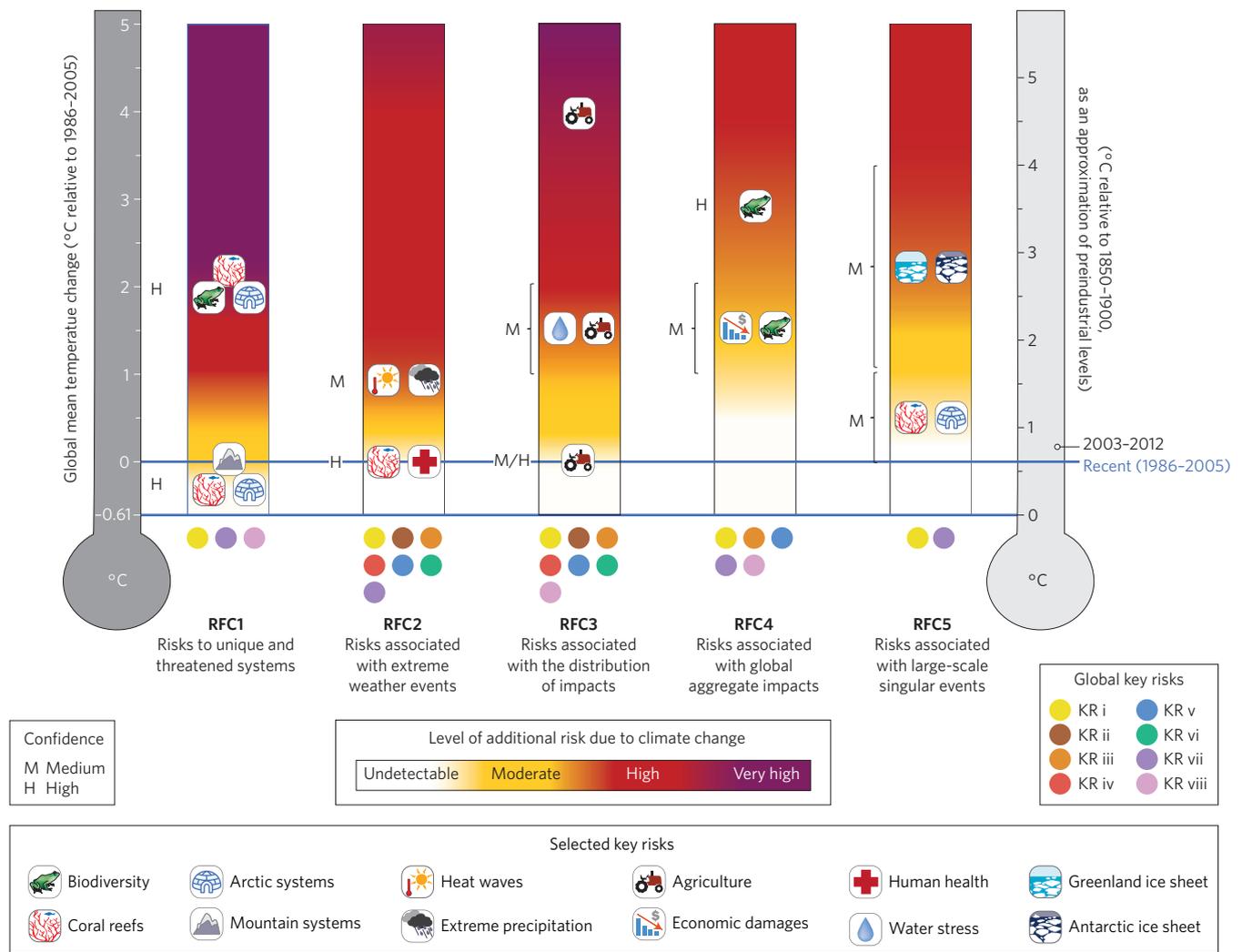
A transition to Very High risk is located around 2.6 °C to reflect very high risks and limited ability to adapt for a wide range of unique and threatened ecosystems<sup>20,21</sup> (Supplementary Section 3.3.1). Substantial impacts to unique and threatened systems are projected at or even below this level of warming<sup>22,23</sup>. These systems include both major ecoregions and biodiversity hotspots containing unique (including endemic) and threatened systems. They include the Cerrado in South America, the Fynbos and Succulent

Karoo ecoregions in South Africa, Australian rainforest ecoregions, the Caribbean, Indo-Burma, Mediterranean Basin, Southwest Australia, and the Tropical Andes<sup>23–25</sup>. Risks to Arctic, coral reef, and mountain systems also escalate above this level of warming (Supplementary Section 3.3.2). For example, large-scale coral reef dissolution may occur if CO<sub>2</sub> concentrations reach approximately 560 ppm due to the combined effects of warming and ocean acidification (ref. 26, section 5.4.2.4; ref. 18), consistent with a warming of approximately 2.5 °C (ref. 27, Fig. 3 and Table 2).

More comprehensive impact assessments are needed that consider more fully the human dimensions of impacts on unique and threatened systems. Most projections of impacts on species and ecosystems fail to consider how adaptation may ameliorate or exacerbate existing pressures and threats and introduce new ones<sup>28</sup> (Supplementary Section 3.3.3). Also, whether species will be able to adapt or move fast enough to keep up with their changing environments will be crucial to the resilience of ecological systems<sup>29</sup> but remains poorly studied<sup>30</sup>.

**RFC2: Risks associated with extreme weather events.** RFC2 encompasses risk to human health, livelihoods, assets, and ecosystems from extremes such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding.

The transition from Undetectable to Moderate risk is located at recent temperatures based primarily on evidence for the detection and attribution of impacts of extreme events on coral reefs and human health (Supplementary Section 4.1). Bleaching of warm-water corals has resulted from periods of elevated near-surface ocean temperature where these levels of warming are attributed to climate change (ref. 31; ref. 9, section 18.6.4 and Tables 18–10; ref. 6, section 19.6.3.2). For human health impacts, there has been detection and attribution of mortality impacts of temperature extremes in some regions (ref. 32, section 11.4.1). Additional support for this



**Figure 1 | The enhanced burning embers diagram, providing a global perspective on climate-related risks.** Levels of risk associated with 5 different reasons for concern are illustrated for increasing global mean temperature and are the same as those presented in the IPCC Working Group II report. Icons indicate selected risks that played an important role in locating transitions between levels of risks. Coloured dots indicate overarching key risk categories that were considered in the assessment for each RFC (see Table 1). Confidence in the judgments of risk transitions is indicated as medium (M) or high (H) as provided in ref. 93 and supplemented here, and the range over which transitions take place is indicated with brackets. For example, RFC1 is underpinned by overarching key risks (i), (vii), and (viii) from Table 1; there is high confidence in the location of the transition from Undetectable to Moderate risk, which is informed by impacts to coral reef, Arctic and mountain systems; and there is high confidence in the location of the transition from High to Very High risk, which is informed by impacts to coral reef and Arctic systems as well as to species associated with unique and threatened systems.

transition comes from the detection and attribution of extreme heat and precipitation events, including post-AR5 analyses at the global scale<sup>33</sup>, along with the widespread occurrence of high vulnerability and exposure and abnormal levels of mortality in some events<sup>34</sup>.

The transition to High risk is located at ~1.6 °C, relying primarily on projections of large, near-term changes in the magnitude and likelihood of extremes of temperature and precipitation. The choice is subjective due to the paucity of literature projecting the impacts of changes in heat extremes. By about 2035 (during which time the increase in model-averaged and scenario-averaged GMT remains below ~1.6 °C), 25–30% of daily maximum temperatures are projected to exceed the historical (1961–1990) 90th percentile value (ref. 35, Figs 11–17). Duration, intensity and spatial extent of heat waves and warm spells also increase in the near term. We choose 2035 as a benchmark for the transition to high risk because the potential impacts from changes in temperature extremes are large and AR5 indicates such changes are likely<sup>35</sup>. Furthermore, there is high confidence in projected mean changes through 2035

because they are not strongly dependent on future emissions. In addition, on average, the frequency and intensity of heavy precipitation events over land will likely increase over much of the world (Supplementary Section 4.2). A reduction in return period for historical once-in-20-year precipitation events globally (land only) to about once-in-14-year or less by 2046–2065 is also expected<sup>36</sup>.

A key limitation is that changing exposure has been quantified for very few types of events, for example, exposure to tropical cyclones<sup>37,38</sup> or heat waves<sup>39,40</sup>, and quantification of future vulnerability is also rare<sup>44,42</sup>. Lower mean age, greater wealth, and increased penetration of air conditioning could ameliorate risk. Recent experience in France<sup>43</sup> and Bangladesh (ref. 36, section 9.2.5) provides evidence for the potential for reductions in vulnerability in both developed and developing countries. In contrast, risks could increase in the future even if the temperature change remains moderate, since exposure to climate-influenced hazards is increasing significantly in various world regions<sup>41</sup>, particularly in Asia and Africa due to population-growth, urbanization<sup>44,45</sup>, and migration.

**Table 1 | Eight overarching key risks representative of the range of key risks identified by WG II authors as of highest concern to their chapters (ref. 6, section 19.6.2.1, based on Table 19-4). These risks inform judgments regarding the indicated RFCs.**

Overarching key risk	Reason for concern				
	1	2	3	4	5
(i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands due to storm surges, coastal flooding, and sea-level rise	✓	✓	✓	✓	✓
(ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions		✓	✓		
(iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services		✓	✓	✓	
(iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas		✓	✓		
(v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings		✓	✓	✓	
(vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions		✓	✓		
(vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic	✓	✓		✓	✓
(viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods	✓		✓	✓	

**RFC3: Risks associated with the uneven distribution of impacts.**

This category of risk reflects climate change impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. Unevenness can be with respect to geographic location, income and wealth, gender, age, or other physical and socioeconomic characteristics.

The transition from Undetectable to Moderate risk is located at recent temperatures based primarily on the detection and attribution with at least medium confidence of negative impacts on wheat yields in Europe and South Asia (ref. 9, Table 18.9) and evidence of negative agricultural impacts in other regions as well (ref. 46, Figs 7.2,7.7; ref. 47; Supplementary Section 5.1). Some positive impacts on crop yield have also been detected, for example in Northern Europe and South America (ref. 9, Table 18.9). AR5 authors took yield impacts as an early warning sign of attributable risk to food security<sup>6</sup>.

The transition to High risk occurs between ~1.6 and ~2.6 °C based on risks of increased water stress and reductions in crop production in some regions (Supplementary Section 5.2). Without adaptation, losses in production of wheat, rice and maize are expected by 2.6 °C of local warming (and therefore typically a lower level of global warming) although individual locations may benefit<sup>46,48</sup>. Projections of yield loss are greatest in low latitudes and tropical regions such as Africa, South Asia and Central and South America<sup>46,48–50</sup>. Substantial decreases in water resources are projected for warming of 2.3 °C<sup>51,52</sup>.

A transition to Very High risk occurs around 4.6 °C based primarily on projected large impacts on crop yields and water resources in many regions combined with limited scope for agricultural adaptation<sup>46,48,50–52</sup>, although other risks contribute (Supplementary Section 5.3). Poorer populations in less developed countries would be at highest risk of malnutrition, for example in sub-Saharan Africa<sup>53</sup> where food security is projected to be at risk even under high adaptation levels (ref. 54, section 22.5).

A principal limitation to the judgments for this RFC is the sparseness of literature on impacts that can be linked to levels of GMT in sectors beyond food and water (such as health, energy, civil conflict, urban areas, and migration<sup>55,56</sup>) that also have distributional consequences, especially for the poor<sup>57</sup> (Supplementary Section 5.4). In addition, the food and water literature focuses primarily on biophysical impacts (such as crop yields or water supply) as opposed to societal impacts (such as food and water security). The agronomic limits to adaptation considered in the judgment of Very High Risk do not account for additional means of offsetting yield changes<sup>58</sup>

such as changes in cropland and pasture area, reductions in food waste<sup>59,60</sup>, and changes in diet<sup>61</sup> or international trade. Biophysical impact studies are also subject to substantial uncertainties, including the strength of the CO<sub>2</sub> fertilization effect on crop yields<sup>46</sup>, and the yield effects of extreme events, neither well accounted for (Supplementary Section 5.4).

**RFC4: Risks associated with global aggregate impacts.** This category of risk reflects impacts to socio-ecological systems that can be aggregated globally according to a single metric such as lives affected, monetary damage, number of species at risk of extinction, or degradation and loss of a number of ecosystems at a global scale. Ecosystem degradation may be caused by wholesale transformation of biomes, large scale extirpation of species induced by climatic range loss, and the disruption of ecosystem functioning as interacting species respond differently to climate change<sup>22</sup>.

AR5 concluded that global aggregate impacts on socio-ecological systems by any of the metrics listed above have not yet been detected and attributed to climate change with sufficient confidence to locate the transition from Undetectable to Moderate risk at recent temperatures<sup>9</sup> (Supplementary Section 6.1).

A Moderate risk level occurs at warming of ~1.6–2.6 °C based on projected impacts to biodiversity and the global economy (and therefore a transition from Undetectable to Moderate risk between current temperatures and ~1.6 °C). A global assessment of 16,857 species of all birds, amphibians and corals found that with approximately 2 °C of warming above preindustrial (in scenario A1B, 2050s), 24–50% of birds, 22–44% of amphibians and 15–32% of corals were at increased risk of extinction (Supplementary Section 6.2.1) due to their vulnerability to climate change<sup>20</sup>. Other studies<sup>62</sup> found increasing extinction risks with warming and project range losses exceeding 50% for large fractions of species globally at 2 °C warming (Supplementary Section 6.2.2). Estimates of global economic damages transition from generally small, negative projected impacts around 1 °C warming<sup>63</sup> to central estimates of impacts ranging from 0 to 3% of global Gross Domestic Product for levels of warming between 1.9 and 3.0 °C (Supplementary Section 6.2.3).

The transition to High risk around 3.6 °C reflects an increase in the magnitude and likelihood of extensive loss of biodiversity (including losses in range, equating to local extirpations) and concomitant loss of ecosystem services (Supplementary Section 6.3). There are too few studies of aggregate economic damages to provide support for the judgment of risks above 3 °C.

**Box 2 | RFCs and the vulnerability of socio-ecological systems.**

The Burning Embers diagram does not explicitly account for differences in the exposure and vulnerability of socio-ecological systems over time, including those changes arising from adaptation. In AR5, judgments about risks reflected in the Burning Embers diagram were based on the varied assumptions in the underlying literature about future societal conditions that would affect vulnerability and exposure, including income, poverty, technology, demography, institutions, and other factors. These assumptions range from complete disregard of future societal conditions, to central or middle-of-the-road expectations, to differing societal futures across studies which were then aggregated by IPCC authors.

At the same time, a growing number of examples in the impact literature demonstrate the dependence of impacts on societal conditions, especially the differential vulnerability of people and ecosystems exposed<sup>104</sup> (Supplementary Section 9). AR5 concluded with high confidence that risks vary substantially across plausible alternative development pathways, and that both climate change and societal development are important to understanding possible future risks (ref. 6, section 19.6.2.2). AR5 also introduced an alternative version of a burning ember with an additional axis for exposure and vulnerability. However, the figure was conceptual, illustrating how risks for a particular RFC might vary by societal conditions as well as by the level of climate change.

Here we illustrate how a vulnerability-dependent version of a burning ember diagram could be developed, drawing on impact studies<sup>94–96</sup> that project the number of people at risk of hunger

under alternative assumptions about future vulnerability and climate change. There is substantial uncertainty about estimates of hunger risk for any given societal and climate future, due to, for example, uncertainties in crop modeling, the effects of CO<sub>2</sub> fertilization, economic models of food consumption, and factors affecting access to food. This uncertainty precludes judgments about the absolute level of risk for any given climate and vulnerability outcome, and therefore the production of a burning-ember style diagram. However, judgments about changes in risk if climate or vulnerability varies from a given outcome in the future are possible. Figure 3a shows changes in the number of people at risk of hunger due to climate change relative to the number at risk for a particular set of conditions used as a benchmark (medium vulnerability, and about 2.6 °C of GMT). The general pattern confirms that lower vulnerability development pathways minimize risk, while increases in the level of future warming result in a larger risk. Exceptions occur in studies in which relatively large CO<sub>2</sub> concentration increases improve access to food in scenarios with a further warming of 3 °C and high vulnerability (Fig. 3). As additional literature accumulates, it may be possible to use the type of approach illustrated here to produce a fuller assessment of vulnerability-dependent RFCs, including explicit treatment of adaptation (Supplementary Section 10.1).

A complementary view of future risks is provided by Fig. 3b, which shows that the total number of people at risk of hunger is much more sensitive to the development pathway than to the level of climate change.

Limitations of the judgments for this RFC include the limited number of studies that assess global aggregate economic impacts that can be associated with specific levels of warming. In addition, global estimates of economic damages are incomplete, generally inadequately represent the possibility of abrupt and irreversible changes, ignore some impacts that are difficult to monetize, and depend in part on value-based judgments that can mask differential impacts through space and time<sup>64</sup> (Supplementary Section 6.4). Finally, assessments of impacts on ecosystems insufficiently consider how biotic interactions between species may be disrupted by climatic change<sup>65</sup>.

**RFC5: Risks associated with large-scale singular events.** Large-scale singular events (sometimes called tipping points or critical thresholds) are relatively large, abrupt and sometimes irreversible changes in physical, ecological, or social systems in response to smooth variations in driving forces (accompanied by natural variability)<sup>66,67</sup>. AR5 focussed on two types of such events in assessing this risk: disintegration of the Greenland and West Antarctic ice sheets leading to a large and rapid sea-level rise, and major regime shifts in ecosystems such as degradation of coral reef and Arctic systems. In each case, there is low confidence in the precise temperature changes at which thresholds might exist for these phenomena (ref. 6, section 19.6.3.6; ref. 68, sections 12.4.5 and 12.5.5; ref. 69, section 13.4). For coral reefs, the distinction between the ‘regime shift’ criterion here and the systematic degradation indicated under RFC1 resides in the likelihood of abrupt change. While the long term outcome for coral reefs under each of the two categories of risk may be similar, RFC5 is concerned with a rapid undermining of system function (where “rapid” and “abrupt” are relative terms; see discussion below and Supplementary Section 7.2).

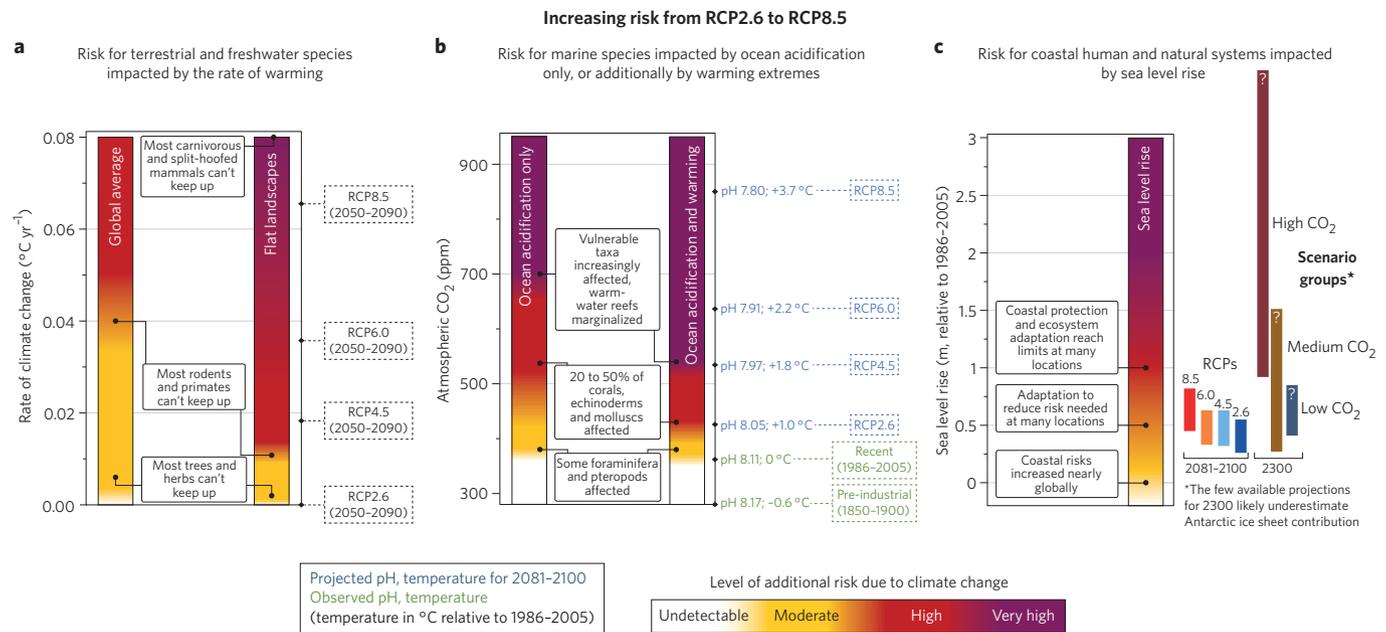
The transition from Undetectable to Moderate risk between ~0.6 and ~1.6 °C warming is based on potential regime shifts in the Arctic and in coral reef systems. Impacts on the Arctic and on

warm water coral reef systems are already observed (see RFC1), but for RFC5, the detection and attribution criterion applies to a large and sudden change. There is robust evidence of early warning signals that a biophysical regime shift already may be underway in Arctic ecosystems, including impacts on human livelihoods (ref. 9, section 18.6.4), and observed increases in mass coral bleaching are considered to be a strong warning signal for the irreversible loss of an entire biome (ref. 9, section 18.6.4).

The transition to High risk over the ~1.6–4.0 °C warming range (slightly revised from AR5) is based on ice sheet responses and the resulting sea-level rise. The warming level associated with eventual, near-complete loss of the Greenland ice sheet is greater than about 1 °C (low confidence) but less than about 4 °C (medium confidence) (ref. 70, based on ref. 71, section 5.8, and ref. 69, sections 13.4 and 13.5). The difference between the risk range and the ice sheet loss range arises because the risk range implicitly incorporates a quantification of the implications of the qualitative confidence levels presented by IPCC WG I<sup>70</sup>. Within this range, a more rapid increase in risk is judged to occur as temperature rises between ~1.6 °C and ~2.6 °C, reflecting additional risk of a very large sea-level rise due to ice loss from both ice sheets as occurred during the last interglacial (Supplementary Section 7.1), when GMT was no more than 2 °C warmer than preindustrial levels<sup>72</sup>.

Due to the large uncertainty in timing of ice sheet loss (which affects the probability of it occurring sufficiently slowly to allow effective adaptation, for example, over a millennium, as well as the probability that action during the next centuries may reduce the warming sufficiently early to limit the melting), RFC5 is not judged to attain Very High risk in the temperature range below ~5.6 °C, the maximum warming considered in Fig. 1.

Improved prognostic modeling of continental ice sheets is a necessity for significantly sharpening this risk assessment. Post-AR5 literature on such models<sup>73–76</sup>, observations<sup>77</sup>, and additional lines of evidence<sup>78</sup> indicate the possibility of large, very fast (decade or



**Figure 2 | Additional burning embers diagrams.** These figures from the AR5 Synthesis Report<sup>74</sup> use (i) rate of climate change, (ii) atmospheric CO<sub>2</sub> and associated ocean acidification as well as (iii) sea-level rise as the metric of climate-related hazard, rather than global mean temperature (for further explanations see text).

century scale) responses providing further support for a tipping point (Supplementary Section 7.2).

**Additional metrics**

The RFCs and associated Burning Embers diagram use GMT as the proxy indicator for climate-related hazards. This approach has the benefit of simplifying the communication of risk. However, there are important climate-related hazards that are inadequately captured by the temperature indicator alone. We discuss three metrics that were incorporated in complementary ember diagrams in the AR5 Synthesis Report<sup>74</sup> as illustrations of ways in which the analysis of key risks could be extended (Fig. 2). These metrics informed a recent UNFCCC policy dialog on long-term targets<sup>1</sup>.

**Rate of climate change.** For many socio-ecological systems, the rate of climate change determines the success or failure to adapt. Theory as well as paleo-ecological and paleo-climatic data indicate that adaptation of organisms to climate change through geographic movement has limits (Supplementary Section 8.1). The ‘rate of climate change’ ember (Fig. 2a) assigns risk levels as a function of the rate of climate change during the twenty-first century, translated into a velocity at which climate zones move across the landscape. A range of species movement rates was estimated for a number of groups of species<sup>79</sup>, using data from fossil records, dispersal studies, and models of species movement (see listing of the primary sources in the caption of Fig. 4.5 in ref. 79).

The relationship between ‘climate velocity’ (the rate of movement of climate zones) and the rate of GMT change depends on topography (Supplementary Section 8.2). Thus, at a given rate of GMT change, risks to species vary depending on location. In addition, there are geographical barriers to species-range shifts, such as coasts, mountaintops, or habitat fragmentation breaking connections to cooler areas<sup>81</sup>. Rate of change considerations supplement amount of change rather than replacing it; for instance there are situations (such as mountaintops) where potentially fast-moving species have nowhere to go.

Authors of the IPCC Synthesis Report compared the estimated rates of species movement with estimates of the climate velocity

during past<sup>81–83</sup> and projected future<sup>84–86</sup> climate change. Since trees and herbaceous plants form the productive basis of most terrestrial ecosystems, and flat landscapes occupy a large part of the land surface, moderate risk was assigned to commence when the climate velocity exceeded the lower end of the range of observed movement rates (trees in flat landscapes) and end at the median movement rate for rodents and primates. The risk was assessed as High beginning where the movement rate exceeded the upper end of the range for trees and ending at the upper limit for herbs and rodents, beyond the upper limit for primates, and at the median for freshwater molluscs. Substantial biotic community and ecosystem disruption over large areas could be anticipated in this range. Very High risks were assigned when the median movement rate was exceeded in all assessed groups (which included carnivores and split-hoofed animals in addition to the groups described above). The impact on species assemblages and thus ecosystem function would, with high likelihood, be large, persistent and difficult to adapt to for this rate of climate change.

**Anthropogenic CO<sub>2</sub> causing ocean acidification.** This ember diagram (Fig. 2b) depicts the increasing risk for the well-being and survival of marine organisms due to accumulating CO<sub>2</sub> in seawater causing ocean acidification (OA). Since pre-industrial times, atmospheric CO<sub>2</sub> levels have risen from 280 ppm to presently (2016) about 400 ppm, paralleled by a drop in ocean pH of approximately 0.1 units<sup>87</sup>. Anthropogenic OA occurs on a background of natural temporal and spatial variability of pH, CO<sub>2</sub>, and aragonite and calcite saturation levels, for example in upwelling areas, where oxygen-deficient and CO<sub>2</sub>-enriched deep water is brought to the surface.

Risks of harmful ecosystem effects of OA are considered Moderate around CO<sub>2</sub> levels of 380 ppm. This judgment is based on observed declines in calcification of foraminifera and pteropods attributed to anthropogenic OA<sup>88</sup>. In addition, negative impacts on pteropods and oyster cultures along the west coast of North America have been attributed to upwelling of acidified water shifted closer to shore combined with anthropogenic acidification<sup>89</sup>.

Under OA only, warming excluded, the transition to High risk occurs at a CO<sub>2</sub> level of about 500 ppm, beyond which studies reflect

onset of significantly negative effects and High risk in 20–50% of extant calcifying taxa (corals, echinoderms and molluscs). The negative effects comprise declines in physiological performance, indicated by changes in characteristics such as standard metabolic rate, aerobic scope, growth, morphology, calcification, acid-base regulation, immune response, fertilization, sperm motility, developmental time, changes in gene expression patterns, behavioural changes and abundance<sup>74,88,90</sup>. Risks are judged to be Very High with limited capability to adapt beyond about 700 ppm, based on a rising percentage of the calcifying taxa being negatively affected. For the calcifying invertebrate taxa, these conclusions are confirmed by observations at natural analogues (volcanic CO<sub>2</sub> seeps, upwelling systems) and by the similarity of sensitivity distributions among taxa during paleo-periods<sup>90</sup>.

Current knowledge indicates that the combined pressures of ocean warming extremes and acidification lead to a shift in sensitivity thresholds to lower CO<sub>2</sub> concentrations, as seen in corals and crustaceans<sup>88</sup>. For corals this comes with the risk that OA will increasingly contribute to the reduction in areal extent of coral ecosystems, already underway as a result of interacting stressors (extreme events, increased predation, bleaching<sup>91</sup>). Knowledge on the long-term persistence of acidification impacts presently relies on findings in the paleo-records. Therefore, evidence that changes in extant ecosystems will persist is limited, especially for fishes. Additionally, knowledge is scarce on compensatory mechanisms and their capacity for and associated limits to long-term evolutionary adaptation under ocean warming and acidification.

**Sea-level rise.** While sea-level change is driven by temperature change, the relationship is uncertain and involves delays — so that coastal risks are not directly and linearly related to temperature. Accounting for variability in sea level is also important, because a change in average sea level can disproportionately increase the likelihood of water levels that exceed the coping capacity of socio-ecological systems.

For this ‘sea-level rise’ ember (Fig. 2c), the detection and attribution of impacts on society or ecosystems was not used for judging risk levels due to the difficulty of attributing such impacts. Impact attribution is difficult because observed increases in impacts are overwhelmingly due to population and socio-economic changes (ref. 26, section 5.4.4) or non-climatic, anthropogenic stress (ref. 26, section 5.2), and also influenced by historical investments in coastal protection for which data are lacking. Therefore attribution of sea level rise itself was used.

The transition to Moderate risk starts before the recent period, given that global sea-level rise over the past several decades is attributable to climate change (ref. 10, section 10.4.3) and increases the risk of coastal flooding, soil salinization, and saltwater intrusion. The risk is judged to reach the Moderate level at about 10 cm above the 1986–2005 level, which authors of the Synthesis Report estimated to be the level at which increased flood risks become significant and require changes in coastal management.

At this level, the transition to High risks starts and risks are expected to become High at around 100 cm above the same reference level. High risk is defined for this RFC as the risk of losses that, in the absence of adaptation, would reach levels that are at least an order of magnitude higher than today, and cause coastal ecosystem losses that are visible and widespread. High risks may occur before the 100 cm level is reached, since some evidence suggests the risk would increase rapidly even before this value (Supplementary Section 8.3). For example, for sea-level rise of 40–130 cm, 1.3–2.9% of the world population could be flooded every year<sup>92</sup>.

The transition to Very High risk is expected over the range of 100–200 cm above the 1986–2005 level. This transition starts where adaptation limits for ecosystems and human systems are reached in many places. Limited evidence suggests that only a small number of

adaptation options are available for specific coastal areas if sea-level rise exceeds 100 cm at the end of the century (ref. 26, section 5.5.6). There are also biophysical limits to the adaptation of ecosystems and natural areas, which vary greatly depending on the rate of change, location and other stressors (ref. 26, section 5.2).

## Discussion and future directions

The RFCs were designed to categorize and depict increasing risks from warming of the climate system and thereby inform (but not determine) judgments about danger from climate change. Within the current limits of the framework, the RFC assessment provides a number of insights relevant to Article 2. First, continued high emissions would lead to High or Very High risk of severe, widespread, and in some cases irreversible impacts globally within this century. Risks to unique and threatened systems, among the most sensitive natural and human systems, increase most quickly with additional warming. Risks associated with global aggregate impacts increase most slowly.

In addition, the RFCs can communicate the specific nature of current and future risks. For RFCs 1–3, risks from anthropogenic climate change are currently Moderate, based primarily on detection and attribution of associated impacts on Arctic ecosystems and coral reefs (RFC1); extreme heat and precipitation events and their impacts on human health and coral reefs (RFC2); and impacts on crop production in some regions (RFC3). In terms of future risk, at 2 °C above preindustrial, High risks are based on increasing risks to Arctic systems and coral reefs, as well as increasing species extinction risks (RFC1), and projected increasing magnitude and likelihood of extreme weather events (RFC2). Moderate to High risks are based on projections of increasing risks to crop production and water resources (RFC3), and on the risks associated with ice sheet disintegration and very large sea-level rise (RFC5). Limiting warming to 1.5 °C would reduce the risks for RFCs 1 and 2 from High to the Moderate/High transition.

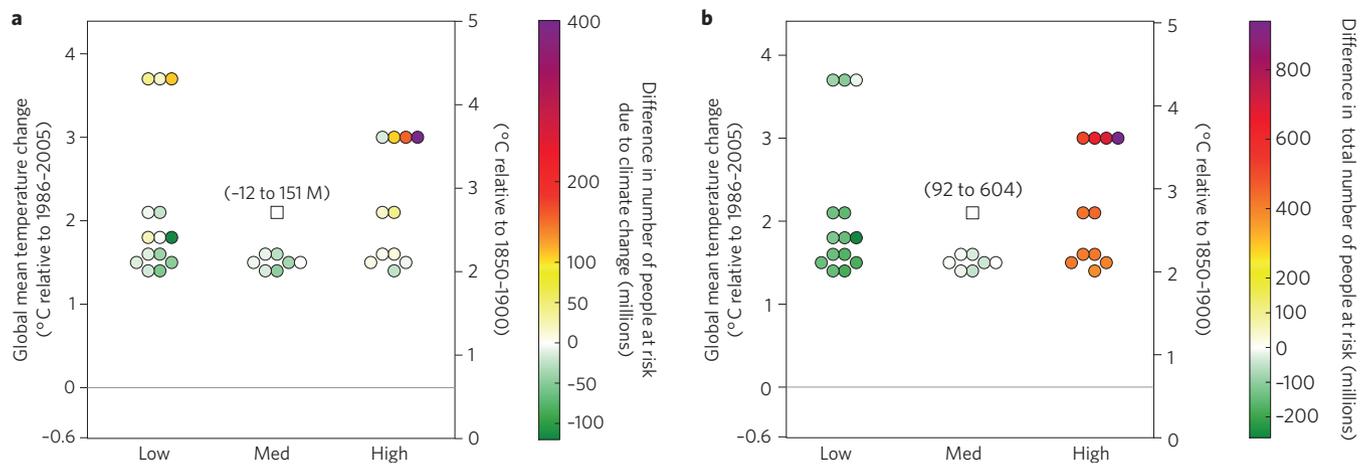
At 3 °C above pre-industrial temperatures, risks are at least High, or nearly so, for all RFCs. In addition to the basis for High risk judgments that apply to 2 °C, additional factors include a higher risk of species extinction (RFCs 1 and 4), limited ability to adapt to impacts on coral reefs and Arctic systems (leading to Very High risk for RFC1), and the higher risk of very large sea-level rise associated with eventual ice sheet loss (RFC5).

Judgments, choices, and decisions informed by the RFCs should take into account key challenges faced by this framework. First, the assessment of risk levels across the RFCs has been based primarily on impacts to physical and ecological systems, given a literature on consequences for society that is either thin or difficult to relate to specific levels of climate change and future societal conditions. Extensions to the framework to explicitly account for the vulnerability of socio-ecological systems (Fig. 3) offer a means of incorporating new knowledge of this type.

Second, aggregating risks across affected sectors and systems necessarily suppresses the detail and variation of associated risks. Communicating the specific key risks informing the RFC assessment is important to prevent misinterpretation of risk judgments and to better inform discussion of response options. It may also be possible to extend the Burning Embers diagram to better represent individual risks (Supplementary Fig. 2).

Third, the perceived seriousness of risks will vary by stakeholder and among authors carrying out the assessment. Some may value the existence of species and ecosystems — beyond their role in providing ecosystem services — more highly than others, and therefore perceive particular RFCs (such as RFC1) as more important. Others may prioritize aggregate damages or may consider equity and distributional impacts as paramount.

Finally, additional dimensions of climate change beyond GMT, such as the rate of climate change, ocean acidification, and sea-level



**Figure 3 | Illustrative version of a vulnerability-dependent burning embers diagram. a**, The figure uses results for one type of climate change impact (additional population at risk of hunger) based on three studies<sup>94–96</sup>. The x-axis categorizes scenarios of societal development by trends in exposure and vulnerability based on ref. 34. Each coloured circle indicates the difference between the number of people at risk of hunger due to climate change according to one scenario and the number at risk as calculated under benchmark outcomes. Benchmark conditions are defined as those associated with a medium vulnerability scenario with about 2.6 °C warming relative to preindustrial (Box 2, and Supplementary Section 10 for further description). Results for this benchmark outcome are plotted as zero (a white square) in the figure, with the underlying range of results given in parentheses. Green circles indicate lower risk than this benchmark outcome (values <0), and generally occur for lower levels of climate change and/or lower levels of societal vulnerability. Yellow, red and purple circles indicate greater risk (values >0), and generally occur for more climate change and/or higher societal vulnerability. The figure incorporates 40 scenarios with a range of economic, crop and climate models and assumptions about CO<sub>2</sub> fertilization and adaptation (Supplementary Table 1). In panel **a**, the medium vulnerability, 2.6 °C (benchmark) outcomes span a range of -12 million to 151 million additional people at risk of hunger, illustrating the relatively large uncertainty in estimates of this risk. The exposure and vulnerability (E&V) axis indicates relative trends over time rather than absolute levels, with current conditions defined as ‘Medium’ E&V. For example, a future development path in which E&V remains ‘Medium’ is assumed to change over time (and therefore also with changes in GMT along the y-axis) at a moderate rate, driven by trends in socioeconomic conditions that are in the middle of the range of future scenarios. ‘Low’ and ‘High’ E&V indicate futures that are substantially more optimistic or pessimistic, respectively, regarding trends in exposure and vulnerability. **b**, Same as panel **a**, but for the total population at risk of hunger rather than the additional population at risk due only to climate change. As for panel **a**, the exposure and vulnerability (E&V) axis is relative rather than absolute.

rise, can be important metrics of hazard, sometimes more directly linked to impacts than GMT.

These caveats, and the review of the RFCs as a whole, suggest a number of research needs. More systematic evaluation of key risks and impacts at varying levels of climate change is needed to inform a more complete, specific and quantitative understanding of the differential impacts across possible climate futures for a larger number of key risks. A deeper literature of this kind would avoid imbalances in the role of specific risks, such as the large role of agricultural risks in RFC3 and the role of risks to coral reefs across several RFCs. It would also improve understanding of the uncertainty in the level of GMT associated with risk transitions. There is an equally strong need for research on socioeconomic dimensions of risks, to improve on the current common use of physical climate system outcomes as a proxy for societal impacts. In particular, more work is needed on how alternative societal development pathways, implying different levels of vulnerability to climate change and possibilities for adaptation, affect the risks of any given level of warming.

Beyond improving the research base, modifications to or extensions of the RFC framework itself may be called for, especially as new evidence accumulates, while also recognizing the value of simplicity in communicating risk. Efforts should be continued to make the methods for producing the RFCs and the associated Burning Embers diagram more systematic, transparent and comparable across generations. Improvements in these aspects of the RFCs will also make them more effective tools for informing decisions related to avoiding dangerous climate change.

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## Author contributions

B.C.O. and M.O. led the design of the study. B.C.O. led, and M.O. contributed to, the coordination of the paper. M.O., R.W., S.H., R.E.K., B.C.O., H.O.P., and B.S. led the drafting of subsections of the paper. B.C.O., P.M., R.L., K.J.M., M.M., and K.T. led the development of figures. All authors contributed to writing and/or editing the paper.

## Additional information

Supplementary information is available in the [online version of the paper](#). Reprints and permissions information is available online at [www.nature.com/reprints](http://www.nature.com/reprints). Correspondence should be addressed to B.C.O.

## Competing financial interests

The authors declare no competing financial interests.

## Erratum: IPCC reasons for concern regarding climate change risks

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In the print version of this Review, references 6, 9, 10, 19, 22, 26, 32, 35, 36, 46, 54, 68–71, 74, 79, 100, 101 and 102 contained errors. These errors have been corrected in the online version.