The human imperative of stabilizing global climate change at 1.5°C.

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Abstract (150 words):

Global mean surface temperature is now 1.0°C higher than the pre-industrial period due to increasing atmospheric greenhouse gases. Significant changes to natural and human (managed) systems have already occurred emphasizing serious near-term risks. Here, we expand on the recent IPCC Special Report on global warming of 1.5ºC as well as additional risks associated with dangerous and irreversible states at higher levels of warming, each having major implications for multiple geographies, climates and ecosystems. Limiting warming to 1.5ºC rather than 2.0ºC is very beneficial, maintaining significant proportions of systems such as Arctic summer sea ice, forests and coral reefs as well as having clear benefits for human health and economies. These conclusions are relevant for people everywhere, particularly in low- and middle-income countries, where climate related risks to livelihoods, health, food, water, and economic growth are escalating with major implications for the achievement of the United Nations Sustainable Development Goals.

One Sentence Summary: Climate change is already driving dangerous impacts that will be progressively less manageable at 1.5°C of global warming or higher.

Main text:

Climate change is one of the greatest challenges for humanity. Global mean surface temperature (GMST) is increasing at the rate of 0.2°C ±0.1°C per decade, reaching 1.0°C above the pre-industrial period (reference period 1850–1900) in 2017 (*1*). GMST is projected to reach 1.5°C above the pre-industrial period between 2030 and 2052, depending on the model and assumptions regarding projected changes to atmospheric greenhouse gas (GHG) levels and climate sensitivity (*1*). At the same time, growing awareness of impacts beyond 1.5°C has focused international attention on the feasibility and implications of stabilizing temperatures at this level (*2*).

In broad terms, limiting warming to 1.5°C will require a total investment in the energy sector of 1.46-3.51 trillion (US$2010) in energy supply and 0.64-0.91 trillion (US$2010) in energy demand measures in order to reach net zero GHG emissions by 2050 (*3*)(p154). On the other hand, the mean net present value (in 2008) of the avoided damages resulting from this action is estimated as totalling $496 trillion (US$2010) by the year 2200 (*3*–*5*). This, together with other damages that are difficult to fully cost and include (e.g. disruption and migration of human communities; reductions in ecosystem services associated with biodiversity loss), suggests that potential economic benefits arising from limiting warming to 1.5°C may be four or five times larger than the investments needed to stabilize GMST to 1.5°C (SM1)(*3*).

Here, we explore the near-term mostly unmonetized impacts projected for 1.5°C of global warming, and the associated risks and adaptation options for natural and human (managed) systems. In order to understand the implications of reaching 1.5°C, we compare it to recent conditions (i.e. 1.0°C warming above the pre-industrial period, Fig 1), and to those that are projected to emerge as we approach 2.0°C of warming. This comparison helps understand the benefits or not of stabilizing GMST at 1.5°C as compared to 2.0°C or higher, as well as providing a framework for societal responses and consequences.

[Insert Figure 1 here]

Crossing the 1.0°C threshold has already severely impacted natural and human systems

The incidence of extremes has increased sharply as GMST has warmed from 0.5^{o}C to 1.0^{o}C (~1980 – 2018) relative to the Pre-industrial period, with the intensity and/or frequency of extremes projected to change further with another 0.5°C of warming (*5*). As GMST has increased, for example, the average temperature of cold days and nights (i.e. the coldest 10%) has also increased overall, as has the average temperature of warm days and nights (i.e. the warmest 10%) globally (*5*). These changes have also been accompanied by increases in the frequency and/or duration of heatwaves for large parts of Europe, North America and Australia. Increases in GMST have been accompanied by increases in the frequency, intensity and/or amount of heavy precipitation in more regions than those with decreases, especially in North-Hemisphere mid-latitude and high-latitude areas (*5*, *6*). There is also evidence of increasing rainfall associated with recent tropical cyclones (*6*, *7*) and increasingly heavy precipitation during storms in the Central Sahel (*8*, *9*). The number of tropical cyclones has decreased, while the number of very intense cyclones has increased, for many areas (*5*). There is less confidence regarding trends in the length of drought, although a significant increasing trend has been detected in the Mediterranean region (particularly Southern Europe, North Africa and the near-East) (*10*–*12*).

As on land, coastal and marine habitats have also experienced an increased frequency, intensity and duration of underwater heatwaves, with a threefold increase in the number of marine heatwave days globally since 1980 (*13*). The differential heating of the water column has also led to increased thermal stratification in some coastal and oceanic regions which decreases ocean-atmosphere gas exchange as well the turnover of nutrients between the photic layer and deeper layers of the ocean. The annual mean Arctic sea ice extent decreased by 3.5 - 4.1% per annum from 1979 to 2012 (*6*). The melting of land-based ice includes potentially unstable regions such as the Western Antarctic Ice Sheet (WAIS, Fig 1B), which contributed 6.9 $\pm$ 0.6 mm over 1979-2017 to global mean sea level (GMSL). Together with glacial melt water, thermal expansion of the ocean has accelerated the rate of GMSL increase by up to 0.013 [0.007-0.019] mm yr^{-2} since the early 20th Century (*14*). Changes in ocean temperature have also decreased the oxygen concentration of the bulk ocean, interacting with coastal pollution to increase the number and extent of low oxygen dead zones in many deep-water coastal habitats (*15*). In addition to increasing GMST, anthropogenic CO_2 also enters the ocean causing a reduction in pH (ocean acidification) which negatively impacts processes such as early development, calcification, photosynthesis, respiration, sensory systems, and gas exchange in organisms from algae to fish (*5*).

Changing weather patterns (e.g. temperature, rainfall, dryness, storms) have increased negative impacts on natural and managed systems (Fig 1A-D). Changes to coral reefs (*5*), forests (e.g. changing drought/fire regimes) (*16*, *17*), low-lying islands and coasts (*5*), and impacts on agriculture production and yield (*18*, *19*) are threatening resources for dependent human communities. There are also many gradual changes that have occurred as GMST has increased, with many being no less important than the more abrupt changes. Land-based biomes (i.e. major natural and agricultural ecosystem types) have also shifted to higher latitudes and elevation in boreal, temperate and tropical regions (*5*, *15*)., with similar shifts reported for marine and freshwater organisms. Marine organisms and some ecosystems have also shifted their biogeographical ranges to higher latitudes at rates up to 40 km yr^{-1}. Rates are highest for pelagic organisms and ecosystems such as plankton, and are lowest for more sedentary benthic organisms and ecosystems such as seaweeds and kelp forests (*5*, *15*). These types of changes (e.g. temperature, storms, circulation) have also affected the structure and function of ocean ecosystems with respect to its biodiversity, food-webs, incidence disease and invasive species (*5*).

Other changes to biological systems include changes to the phenology of marine, freshwater and terrestrial organisms (e.g. timing of key events such as reproduction and migration) (*5*, *15*). The phenology of plants and animals in the Northern-Hemisphere, for example, has advanced by 2.8 $\pm$ 0.35 days per decade due to climate change, with similar changes in the flowering and pollination of plants and crops, and the egg-laying and migration times of birds (*5*, *20*). There are indications that climate change has already contributed to observed declines in insects and arthropods in some regions (*21*, *22*). Variations in these types of changes have also been observed in the phenology of tropical forests, which have been more responsive to changes in moisture stress rather than to the direct changes in temperature (*5*). While the intention here is not to catalogue all of the changes that have occurring in natural systems, it is important to acknowledge that deep and fundamental changes are underway in biological systems with just 1°C of global warming so far (*5*).

Changes in GMST of 1.0°C have also directly and indirectly affected human communities, many of which depend on natural and managed systems for food, clean water, coastal defence, safe places to live, and livelihoods among many other ecosystem goods and services (*5*). Coral reefs clearly illustrate the linkage between climate change, ecosystem services and human well-being. At 1.0°C, large-scale mortality events driven by lengthening marine heatwaves have already reduced coral populations in many places (*5*), with prominent coral reef ecosystems such as the Great Barrier Reef in Australia losing as much as 50% of their shallow water corals in the last four years alone (*5*, *23*, *24*). These changes have potential implications for millions of people given their dependency on coral reefs for food, livelihoods and well-being (*5*).

Understanding climate change over the next few decades: methods and assumptions

There are a range of strategies for quantifying risks for natural and human systems at 1.5°C and 2.0°C above the pre-industrial period. This requires calculating the future exposure of systems to changes in climatic hazards. Some methods rely on the fact that an equivalent amount of warming (e.g. 0.5°C) occurred in the recent past (e.g. ca. 1950 to 2000, or ca. 1980 to 2018, Fig 2A; (*3*)) potentially providing insights into how risks might change in the near future. In this case, the associated risks of the next 0.5°C of global warming (Fig 2A) are linearly extrapolated from the impacts associated with the previous 0.5°C increase (ca. 1980-2018). This method of projecting future risk is likely to be conservative given (a) the pace of climate change is increasing (*25*) and (b) the impacts per unit of temperature are likely to increase as conditions are pushed increasingly beyond the optimal conditions for a particular organism or physiological process (Fig 2B)(*26*). Responses by natural and human systems are likely to also differ if temperature pathways involve a gradual increase to 1.5ºC above the pre-industrial period (no ‘overshoot’) as opposed to pathways that first exceed 1.5°C before later declining to 1.5°C, which is referred to as an 'overshoot' (*5*) (Fig 2A). High levels of overshoot involve exceeding 1.5ºC by 0.1ºC (Figure 2A) (*3*).

[Insert Figure 2 here]

Other approaches for understanding how the world may change at 1.5°C and 2.0°C of global warming draw on laboratory, mesocosm, and field experiments. These approaches simulate projected conditions for different levels of warming and, in the case of marine systems, levels of acidification (e.g. changes in pH, carbonate, pollution levels (*5*, *26*, *27*). These experimental approaches also provide calibration as well as insight into future conditions and responses (i.e. 1.5°C versus 2.0°C). Some caution is also required given that global increases of 1.5°C or 2.0°C may involve a broad range of regional responses. This arises due to uncertainties in (for example) the likelihood of overshoot, land-atmosphere interactions, biophysical effects of land use changes, and interannual climate variability (*28*). Several lines of evidence for understanding these complex problems include the analysis of the frequency and intensity of extremes as well as projections based on existing climate simulations and empirical scaling relationships for 1.5°C and 2.0°C of global warming (*5*). Lines of investigation may also include dedicated experiments prescribing sea surface conditions consistent with these levels of warming, as done in the HAPPI (Half a degree Additional warming, Prognosis and Projected Impacts) project (*5*). Furthermore, fully-coupled climate model experiments can be achieved using GHG forcing consistent with 1.5°C or 2.0°C scenarios (*5*). These multiple yet different lines of evidence (above) underpin the development of qualitatively consistent results regarding how temperature means and extremes could change at 1.5°C as compared to 2.0°C of global warming.

Projected changes in climate at 1.5°C versus 2.0°C of global warming

Understanding the potential advantages of restraining global warming to 1.5ºC requires an understanding of the risks associated with the exposure of natural and human systems to climatic hazards, and how they change at 1.5°C relative to 2.0ºC (Fig 3)(*29*). Increases of GMST to 1.5°C will further increase the intensity and frequency of hot days and nights, and decrease the intensity and frequency of cold days and nights (Fig 3 C.D.E). Warming trends are projected to be highest over land, in particular for temperature extremes, with increases of up to 3°C in the mid-latitude warm season and up to 4.5°C in cold seasons at high latitudes. These increases are projected to be greater at 2.0°C of global warming, with increases of up to 4°C in the mid-latitude warm season and up to 6°C in the high-latitude cold season (e.g. Fig 3 A.C.D.E.) (*29*). Heatwaves on land, which are already increasing pressure on health and agricultural systems, are projected to become more frequent and longer (Fig 3 C.D.).

There is considerable evidence that dryness will increase in some regions, especially the Mediterranean as well as southern Africa (*5*, *30–32*). Risks of drought, dryness and precipitation deficits are projected to increase at 1.5°C and even further at 2.0°C for some regions relative to the pre-industrial period (Fig 3B,F)(*5*, *33*). Recent studies also suggest similar projections for the western Sahel and southern Africa, as well as the Amazon, north-eastern Brazil, and Central Europe (*5*, *34*). Projected trends in dryness are uncertain in several regions, however, and some regions are projected to become wetter(Fig 3 B,F) (*5*). Reaching GMST of 1.5°C and 2.0°C, for example, would lead to a successive increase in the frequency, intensity and/or amount of heavy rainfall when averaged over global land area (Fig 3 B,F). Global warming of 2.0°C versus 1.5°C increases exposure to fluvial flood risk particularly at higher latitudes and in mountainous regions, as well as in East Asia, China (*35*) and eastern North America overall (*5*). The prevalence of subsequent intense wet and dry spells, in which a prolonged drought is immediately followed by heavy precipitation at the same location (potentially leading to flooding) or vice versa, is projected to be greater at 2.0°C global warming versus 1.5°C (*36*). These large changes between coupled wet and dry conditions represent a major challenge for adaptation as they will affect water quality and availability as well as increased soil erosion along many coastal areas. Sea level rise can also amplify problems through damage to coastal infrastructure and the salinization of water supplies for drinking and agriculture (*5*).

Relatively few studies have directly explored the effect of 1.5°C versus 2.0°C of global warming on tropical cyclones (*5*). These studies consistently reveal a decrease in the global number of tropical cyclones at 1.5°C vs 1.0°C of global warming, with further decreases under 2.0°C vs 1.5°C of global warming. Simultaneously, very intense cyclones are likely to occur more frequently at 2.0°C vs 1.5°C of global warming, with associated increases in heavy rainfall and damage, further emphasizing the advantages of not exceeding 1.5°C (*5*).

[Insert Figure 3 here]

Coastal and oceanic regions are also projected to increase in temperature as GMST increases to 1.5°C, and further to 2.0°C, above the pre-industrial period. Absolute rates of warming are only slightly lower in the ocean than on land although the shallower spatial gradient of ocean temperature will mean that the velocity of climate change may be higher in many regions of the ocean (*5*, *37*). Increases in ocean temperature associated with 1.5°C and 2.0°C of global warming will increase the frequency and duration of marine heatwaves, as well as reducing the extent of ocean mixing due to the greater thermal stratification of the water column (*13*, *15*). Sea ice is projected to continue to decrease in the Arctic, although restraining warming to 1.5°C will mean an ice free Arctic summer will only occur every 100 years, while warming to 2.0°C above the pre-industrial period will mean an ice free Arctic summer is likely to occur every 10 years by 2100 (*5*, *38*). These and other models indicate that there will be no long-term consequences for sea ice coverage in the Arctic (i.e. no hysteresis)if GMST is stabilised at or below 1.5°C (*3*).

Impacts on ecosystems at 1.5°C versus 2.0°C of global warming

Multiple lines of evidence (*5*) indicate that reaching and exceeding 1.5°C will further transform both natural and human systems, leading to reduced ecosystem goods and services for humanity. Importantly, risks for terrestrial and wetland ecosystems such as increasing coastal inundation, fire intensity and frequency, extreme weather events, and the spread of invasive species and diseases are lower at 1.5°C as compared to 2.0°C of global warming (*5*). In this regard, the global terrestrial land area that is predicted to be affected by ecosystem transformations at 2.0°C (13%, interquartile range 8-20%) is approximately halved at 1.5°C (4%, interquartile range 2-7%). Risks for natural and managed ecosystems are higher on drylands as compared to humid lands (*5*). The number of species that are projected to lose at least half of their climatically determined geographic range at 2.0°C of global warming (18% of insects, 16% of plants, 8% of vertebrates) would be significantly reduced at global warming of 1.5°C (i.e. to 6% of insects, 8% of plants, and 4% of vertebrates)(*5*). In this regard, species loss and associated risks of extinction are much lower at 1.5°C than 2°C. Tundra and boreal forests at high latitudes are particularly at risk, with woody shrubs having already encroached on tundra, which will increase with further warming (*5*). Constraining global warming to 1.5°C would reduce risks associated with the thawing of an estimated 1.5-2.5 million km² of permafrost (over centuries) compared to the extent of thawing expected at 2.0°C (*5*).

Ecosystems in the ocean are also experiencing large-scale changes, with critical thresholds projected to be increasingly exceeded at 1.5°C and higher global warming. Increasing water temperatures are driving the relocation of many species (e.g. fish, plankton) while sedentary organisms, such as kelp and corals, are relatively less able to move. In these cases, there are multiple lines of evidence that indicate that 70-90% of warm water tropical corals present today are at risk of being eliminated even if warming is restrained to 1.5°C. Exceeding 2.0°C of global warming will drive the loss of 99% of reef-building corals (*5*). These non-linear changes in survivorship are a consequence of the increasing impact of changes as they move away from optimal conditions (Fig 2B) (*26*). Impacts on oceanic ecosystems are expected to increase at global warming of 1.5°C relative to today, with losses being far greater at 2.0°C of global warming. Significant compound or secondary risks exist with respect to declining ocean productivity, loss of coastal protection, damage to ecosystems, shifts of species to higher latitudes, and the loss of fisheries productivity (particularly at low latitudes)(*15*). There is substantial evidence that these changes to coastal risks will increasingly threaten the lives and livelihoods of millions of people throughout the world (*5*).

Increasing risks for human (managed) systems at 1.5ºC and 2.0ºC of global warming

Many risks for society will increase as environmental conditions change. Water, for example, is often central to the success or failure of human communities. The projected frequency and scale of floods and droughts in some regions will be smaller under 1.5°C global warming as opposed to 2°C, with risks to water scarcity being greater at 2.0°C than at 1.5°C of global warming for many regions (*5*). Salinization of freshwater resources on small islands and along low-lying coastlines is a major risk that will become successively more important as sea levels rise, particularly as they will continue to increase even if temperatures stabilise. (*5*). Depending on future socio-economic conditions, limiting warming to 1.5°C is projected to reduce the proportion of the world's population exposed to climate induced water stress by up to 50% as compared at 2ºC (*5*), although there is considerable variability among regions as already discussed. Most regions, including the Mediterranean and Caribbean regions, are projected to experience significant benefits from restraining global warming to 1.5°C (*39*), although socio-economic drivers are expected to play a dominant role relative to climate change for these communities over the next 30-40 years.

Limiting global warming to 1.5°C is projected to result in smaller reductions in the yield of maize, rice, wheat and potentially other cereal crops than at 2.0°C, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America (*40–42*). A loss of 7-10% of rangeland stock globally is also projected to occur at an increase of 2.0°C above the pre-industrial period, which will have considerable economic consequences for many communities and regions. Reduced food availability at 2.0°C as compared to 1.5°C of global warming is projected for many regions including the Sahel, Southern Africa, the Mediterranean, Central Europe and the Amazon. Few examples exist where crop yields are increasing and hence food security is at increasing risk in many regions (*41*). Although food systems in future economic and trade environments may provide important options for mitigating hunger risk and disadvantage (*43*, *44*)(*5*), assuming that solutions are found to the decline in the nutritional quality of major cereal crops from higher CO_2 concentrations (*5*).

Food production from marine fisheries and aquaculture is of growing importance to global food security but is facing increasing risks from ocean warming and ocean acidification (*5*). These risks increase at 1.5°C of global warming and ocean acidification, and are projected to impact key organisms such as finfish, corals, crustaceans and bivalves (e.g. oysters) especially at low latitudes (*5*). Small-scale fisheries that depend on coastal ecosystems such as coral reefs, seagrass, kelp forests and mangroves, are expected to face growing risks at 1.5°C of warming as a result of the loss of habitat (*5*). Risks of impacts, and subsequent risks to food security, are projected to become greater as global warming reaches 1.5°C (*5*, *43*, *44*) Tropical cyclones have major impacts on natural and human systems, and are projected to increase in intensity in many regions, with the damage exacerbated by rapid sea level rise (*14*, *45*). The tropical cyclones in the North Atlantic basin in 2017 had significant and widespread effects on the small islands of Caribbean as well as the United States, resulting in many deaths, displacement of communities, elevated rates of morbidity and mental health issues, as well as the long-term loss of electricity generation and distribution. These impacts have resulted in significant economic damage, which has exceeded the annual GDP of some small island developing States (*46*, *47*).

Millions of people are already exposed to coastal flooding due to sea level rise and storms, particularly in cities. Projections of sea level rise remain uncertain (*5*), and may include significant non-linear responses, in part due to the contribution of land-based ice (*48*–*50*). Due to the time lag between increased emissions and higher sea levels, differences in mitigation at 1.5°C and 2.0°C, are relatively small compared with the uncertainty in the projections at 2050 or even 2100. Small differences can, however, have big impacts: an increase of 0.1m of sea level rise, for example, will expose an additional 10 million people to flooding (*5*) particularly those living in low-lying deltas and small islands (*5*, *51*). Even with mitigation, adaptation remains essential, particularly as multi-metre sea level rise remains possible over several centuries for higher levels of temperature rise (*5*). Estimates of the net present value in 2008 of global aggregate damage costs (which would be incurred by 2200 if global warming is limited to 2.0°C) reach $69 trillion (*5*). Damages from sea level rise alone contributes several trillion of dollars per annum (*52*). The net present value in 2008 of global aggregate damage costs associated with 1.5^{o}C warming which would be incurred by 2200 if global warming is limited to 1.5C are less than those at 2.0^{o}C, with comparable estimates around $54 trillion in total (*5*).

Warming of 1°C has increased the frequency and scale of impacts on human health through changes to the intensity and frequency of heatwaves, droughts, floods and storms, as well as impacts on food quantity and nutritional quality (through increasing CO_2 concentrations) resulting in undernutrition or malnutrition in some regions (*5*, *43*, *44*). Multiple lines of evidence indicate that any further increases in GMST could have negative consequences for human health, mainly through the intensification of these risks (*5*, *53*). Lower risks are projected at 1.5°C than 2.0°C of global warming for heat-related morbidity and mortality, and for ozone-related mortality if ozone precursor emissions remain high. Limiting global warming to 1.5°C would result in 420 million fewer people being frequently exposed to 'extreme heatwaves' (defined by duration and intensity (*54*)) and about 65 million fewer people being exposed to 'exceptional' heatwaves as compared to conditions at 2.0°C GMST warming (*55*). Human health will also be affected by changes in the distribution and abundance of vector-borne diseases such as dengue fever and malaria, which are projected to increase with warming of 1.5°C and further at 2.0°C in most regions (*5*). Risks vary by human vulnerability, development pathways, and adaptation effectiveness (*43*, *44*, *56*). In some cases, human activities can lead to local amplification of heat risks from urban heat island effects in large cities (*57*, *58*). More specific impacts of, and solutions to, climate change on cities are provided elsewhere (*43*, *56*)

Global warming of 1.5°C will also affect human well-being through impacts on agriculture, industry and employment opportunities. For example, increased risks are projected for tourism in many countries, whereby changes in climate have the potential to affect the attractiveness and/or safety of destinations, particularly those dependent on seasonal tourism including sun, beach and snow sport destinations (*5*, *15*). Businesses that have multiple locations or markets may reduce overall risk and vulnerability, although these options are likely to be reduced as stress and impacts increase in frequency and areal extent. Risks and adaptation options may lie in developing alternative business activities that are less dependent on environmental conditions. These risks become greater as warming increases to 2.0ºC and pose serious challenges for a large number of countries dependent on tourism and related activities for national income (*5*).

Multiple lines of evidence also reveal that poverty and disadvantage are also correlated with warming to 1.0°C above pre-industrial period, with the projection of increasing risks as GMST increases from 1.0°C (today) to 1.5°C and higher (*43*, *44*). In this regard, out-migration from agriculturally-dependent communities is positively correlated with global temperature although our understanding of the links between human migration and further warming of 1.5°C and 2.0°C is at an early stage (*5*). Similarly, risks to global aggregate economic growth due to climate change impacts are projected to be lower at 1.5°C than 2.0°C by the end of the century (*5*). The largest reduction in economic growth at 2.0°C compared to 1.5°C are projected for low- and middle-income countries and regions (the African continent, Southeast Asia, India, Brazil and Mexico). Countries in the tropics and Southern Hemisphere subtropics, are projected to experience the largest negative impacts on economic growth if global warming increases from 1.5°C to 2.0°C above the pre-industrial period (*5*, *43*, *44*). The most perceptible impacts of climate change are likely to occur in tropical regions as GMST increases to 1.5 ºC and eventually to 2ºC above the pre-industrial period (*59*).

Table 1 summarizes the emergence of potential climate change 'hotspots' (i.e. areas where risks are large and growing rapidly) for a range of geographies and sectors (*5*). In all cases, these vulnerable regions show increasing risks as warming approaches 1.5ºC and higher. Not all regions, however, face the same challenges. In the Arctic, for example, habitat loss is paramount, while changing temperature and precipitation regimes represent primary risks in the Mediterranean, Southern Africa, West Africa and the Sahel. These rapidly changing locations represent interactions across climate systems, ecosystems and socio-economic human systems, and are presented here to illustrate the extent to which risks can be avoided or reduced by achieving the 1.5°C global warming goal (as opposed to 2.0°C).

[Insert Table 1 here]

Trajectories toward hotspots can also involve significant non-linearities or tipping points. Tipping points refer to critical thresholds in a system that result in rapid systemic change when exceeded (*5*). The risks associated with 1.5ºC or higher levels of global warming reveal relatively low risks for tipping points at 2.0°C but a substantial and growing set of risks as global temperature increases to 3ºC or more above the pre-industrial (Table 2) (*5*). For example, increasing GMST to 3°C above the pre-industrial period substantially increases the risk of tipping points such as permafrost collapse, Arctic sea ice habitat loss, major reductions in crop production in Africa as well as globally, and persistent heat stress that is driving sharp increases in human morbidity and mortality (Table 2) (*5*).

[Insert Table 2 here]

Solutions: scalability, feasibility and ethics

GMST will increase by 0.5°C between 2030 and 2052 and will multiply and intensify risks for natural and human systems across different geographies, vulnerabilities, development pathways, as well as adaptation and mitigation options (*1*, *43*, *44*, *56*). To keep GMST to no more than 1.5°C above the pre-industrial period, the international community will need to bring GHG emissions to net zero by 2050 while adapting to the risks associated with an additional 0.5°C being added to GMST (*3*, *5*) The impacts associated with limiting warming to 1.5°C, however, will be far less than those at 2.0°C or higher (Table 1, 2). Aiming to limit warming to 1.5°C is now a human imperative if escalating risks of dangerous if not catastrophic tipping points and climate change hotspots are to be avoided (*2*, *5*).

An important conclusion of the IPCC special report on 1.5°C is that limiting GMST to 1.5°C or less is still possible (*3*, *60*). This will require limiting GHG emissions to a budget of 420 Gt CO_2 for a 66% or higher probability of not exceeding 1.5°C (*44*). As global emissions are currently around 42 Gt CO_2 per year, pathways should bring CO_2 emissions to net zero over the next few decades (i.e. phase out fossil fuel use) alongside a substantial reduction (~35% relative to 2010) in emissions of methane and black carbon over the same time scale (*44*). The current set of national voluntary emission reduction pledges (Nationally Determined Contributions or NDCs), however, will not achieve the goals of the Paris Agreement (*2*, *61*), particularly when considering the land-use sector (*62*). Instead, GMST is projected to increase by 3-4°C above the pre-industrial period (*1*, *44*), posing serious levels of risk for natural and human systems (*3*, *5*, *20*).

The majority of pathways for achieving 1.5°C also require the carbon dioxide removal (CDR) from the atmosphere. Delays in bringing CO_2 emissions to net zero over the next 20-30 years will also increase the likelihood of pathways that exceed 1.5°C (so-called 'overshoot' scenarios) and hence a greater reliance on net negative emissions after mid-century if GMST to return to 1.5°C (Fig 2A). Technologies designed to remove CO_2 from the atmosphere are at an early stage of development, with many questions as to their feasibility and scalability (*5*). For example, bioenergy with carbon capture and storage (BECCS), afforestation and reforestation, blue carbon (i.e. carbon sequestration by marine ecosystems and processes), soil carbon sequestration, direct capture, biochar (i.e. charcoal for burial in soils), and enhanced weathering, variously struggle from issues such as feasibility, scalability, and acceptability. These strategies are potentially in competition with each other. For example, BECCS would require approximately 18% of global land to sequester 12 Gt CO_2/yr (*5*). This requirement is likely, however, to drive an accelerating the loss of primary forest and natural grassland which would increase GHG emissions (*5*). Early emission reductions plus measures to conserve land carbon stocks may reduce these effects. Policy options might limit the expansion of agriculture at the expense of natural ecosystems, and/or safeguard agricultural productivity from reductions due to BECCS and/or biofuel production (*5*).

There are CDR options, however, that do not rely as extensively on BECCS, but rather focus on afforestation and/or the restoration of natural ecosystems. It is feasible, for example, to limit warming to 1.5°C using strategies such as changing diets and promoting afforestation to remove CO_2 (*3*, *5*, *43*, *44*). Negative consequences of afforestation such as monoculture plantations on local biodiversity might be countered by preferentially restoring natural ecosystems, re-establishing the ability of native grasslands, peatlands, forests, mangroves, kelp forests, and saltmarshes to sequester carbon. This creates a 'win-win' scenario in which both climate and biodiversity benefit, contributing to SDG 15 'Life on Land': and hence, simultaneously making an enormous contribution to the goals of both CBD and UNFCCC. Compatible with this idea is the recent UN establishment of the 2020s as the 'Decade of Restoration', with the intention to build a global resolve to conserve biodiversity, increase its resilience to climate change, and use it to sequester up to a total of 26 GtC (*63*).

Extensive adaptation to 1.5°C of global warming or higher will be very important, especially if we have underestimated climate sensitivity. Developing socially-just and sustainable adaptation responses will be increasingly necessary to help natural and human systems to prepare and respond to rapid and complex changes in risk (*43*). The global adaptation stocktake instigated by the Paris Agreement will help accountability through documentation and mechanisms that inform enhancement at national levels (*64*, *65*). It must also be acknowledged that there are limits to adaptation for natural and human systems (*66*) and hence subsequent loss and damage

(*5*, *67–69*). For example, actions to restore ecosystems may not always be possible given available resources and it may not be feasible to protect all coastal regions from erosion and loss of land. These challenges mean that identifying, assessing, prioritizing and implementing adaptation options are very important for reducing the overall vulnerability to increasing climate-related risks as GMST increases. It has become increasingly clear that long-term solutions to climate change must also reduce disadvantage and poverty. Consequently, the recent IPCC Special Report pursued its findings in the context of 'strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty' (*3*). While previous reports recognized the importance of not aggravating disadvantage, few have specifically focused on solutions that involve multiple elements of climate change, sustainable development and poverty alleviation. For example, greater insights and knowledge are required to understand how multiple Sustainable Development Goals (SDGs) interact with each other, although many of these interactions are beneficially synergistic (*70*). Importantly, SDGs are far more easily reached at 1.5°C versus 2.0°C or more of global warming (*43*).

The important issue of 'loss and damage' also highlights the inequity between nations that have largely caused climate change (and have received the greatest benefits) and those who have not. This inequity is particularly important for least developed countries (LDCs) and small island developing States (SIDSs) that have contributed relatively little to global GHG emissions but now face disproportionate risks and harm from climate change, even at 1.5°C (*67–69*, *71*). UNESCO has also emphasized the importance of ethics within a non-binding Declaration of Ethical Principles in Relation to Climate Change in 2017 (*72*). Specifically, this declaration states that "decision-making based on science is critically important for meeting the mitigation and adaptation challenges of a rapidly changing climate. Decisions should be based on, and guided by, the best available knowledge from natural and social sciences including interdisciplinary and transitionary science and by considering (as appropriate) local, traditional and indigenous knowledge". These types of initiatives are especially important in the development of policies and actions that avoid inequalities that arise through exclusion and misinformation (*61*). A transformation toward climate-resilient and low-carbon societies needs to be done in a way that addresses the issue of justice and equity, through ensuring that trade-offs and synergies are identified and actioned (*43*).

Conclusion

Warming of 1.0°C since the mid-20th century has fundamentally transformed our planet and its natural systems. Multiple lines of evidence reveal that a 1.5°C world will entail larger risks to both human and natural systems. The risks of a 2ºC world are much greater. This places us at a critical time in human history where proportionate action taken today will almost certainly minimize the dangerous impacts of a changing climate for hundreds of millions of people. Our preliminary estimates suggest that the benefits of avoided damage by the year 2200 may exceed the costs of mitigation by a factor of four or five. Current NDCs for 2030 are insufficient to drive this even if followed by 'very challenging increases in the scale and ambition of mitigation after 2030' (*44*)(p 95), because models based on the current understanding of economic and technical dynamics cannot identify how to reduce GHG emissions to net zero by 2050 from the current NDC starting point in 2030. Rather, these ambitions are consistent with a global warming level of 3-4ºC which means that immediate and transformative action is required between now and 2030 in order to greatly scale up current nationally stated plans for GHG reductions. Strategies for responding to climate change must be scalable to the challenges of climate change being faced today and into the future, while at the same time being feasible and fair. Given the scope and threats associated with climate change, there is an increasing need for large scale strategies such as the UN Climate Resilient Development Pathways (CRDP) or 'Green New Deal' (UNEP) if society is to avoid potentially catastrophic circumstances over the next few decades.

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Supplementary Materials online:

Material and Methods

SM1: Calculation of benefits versus costs for stabilizing at 1.5°C versus 3.7°C.

Damages avoided can be estimated as those that accumulate under no mitigation scenarios (e.g. 3.7°C by 2100), as compared to high mitigation scenarios in which GMST stabilizes at 1.5°C. Using PAGE09 model outputs, these are mean total damages of $550 Trillion (US$2008) versus $54 Trillion (US$2008)(*3*, *4*) The investments in the energy system required for stabilizing at 1.5°C are the sum of the required annual investments on the energy supply and demand side provided by IPCC (2018) over a 34-year period 2016-2050, amounting to a total of $2.1-4.42 Trillion (US$2010) annually, or $71-150 Trillion (US$2010). Most of the mitigation costs accrue during the period ending in 2050 since this is the target date for net zero greenhouse gas emissions in IPCC scenarios limiting warming to 1.5°C.

The ratio is consequently approximately $496 Trillion (US$2008; mean damage avoided but no mitigation costs) versus $71-150 Trillion (US$2010; mitigation costs only) which means that the avoided damage is three and seven-fold higher than the cost of restraining GMST to 1.5°C. Total mitigation cost estimates (*3*) are used in this comparison, as they include the costs of mitigation required to reach the NDCs and also the further measures required to limit warming to 1.5^{o}C, including measures which are required after 2030. If all the mitigation costs were incurred at the mid-point of 2016 to 2050, their NPV in 2008 would be about half of the $71-150 trillion USD2010 (i.e. an even higher benefit to cost ratio). Furthermore, damages could be higher than estimated, for reasons already outlined in the main text.

We also provide a further explanation of why other cost estimates provided in (*3*) were not the appropriate for use in the comparison. (*3*) also states that "Global model pathways limiting global warming to 1.5°C are projected to involve the annual average investment needs in the energy system of around 2.4 trillion US$2010 between 2016 and 2035" but as further costs could arise after 2030, and the damage estimate calculation refers to the year 2200, this is not appropriate to use for this comparison. (*3*) also provides an estimate of the costs of measures which are *additional* to the countries' Nationally Determined Contributions (NDCs). Since these NDCs correspond to a global warming level of approximately 3-4°C, this figure is not suitable for comparison with avoided damage costs that refer to a baseline level of warming of 3.66C. The estimate of the additional costs is 150 billion to 1700 billion US$2010 over the same time period.

Table 1: Emergence and intensity of climate change 'hotspots' under different degrees of global warming (summary, updated, Table 3.6 from Hoegh-Guldberg et al., 2018, see text in 3.5.4 (*5*) for supporting literature and discussion; not intended to be all inclusive). Calibrated uncertainty language is as defined by the Intergovernmental Panel on Climate Change (*3*).

Region and/or Phenomenon	**Warming of 1.5°C or less**	**Warming of 1.5°C–2°C**	**Warming of up to 3°C**
Arctic sea ice	Arctic summer sea ice is *likely* to be maintained Habitat losses for organisms such as polar bears, whales, seals and sea birds Benefits for Arctic fisheries	The risk of an ice-free Arctic in summer is about 50% or higher Habitat losses for organisms such as polar bears, whales, seals and sea birds may be critical if summers are ice free. Benefits for Arctic fisheries	The Arctic is *very likely* to be ice free in summer Critical habitat losses for organisms such as polar bears, whales, seals and sea birds Benefits for Arctic fisheries
Arctic land regions	Cold extremes warm by a factor of 2–3, reaching up to 4.5°C (*high confidence*) Biome shifts in the tundra and permafrost deterioration are *likely*	Cold extremes warm by as much as 8°C (*high confidence*) Larger intrusions of trees and shrubs in the tundra than under 1.5°C of warming are likely; larger but constrained losses in permafrost *are likely*	Drastic regional warming is *very likely* A collapse in permafrost may occur (*low confidence*); a drastic biome shift from tundra to boreal forest is possible (*low confidence*)
Alpine regions	Severe shifts in biomes are *likely*	Even more severe shifts are *likely*	Critical losses in alpine habitats are *likely*
Southeast Asia	Risks for increased flooding related to sea level rise Increases, heavy precipitation events Significant risks of crop yield reductions are avoided	Higher risks of increased flooding related to sea level rise (*medium confidence*) Stronger increases, heavy precipitation events (*medium confidence*) One-third decline in per capita crop production (*medium confidence*)	Substantial increases in risks related to flooding from sea level rise Substantial increase in heavy precipitation and high-flow events Substantial reductions in crop yield

Mediterranean	Increase in probability of extreme drought (*medium confidence*) *Medium confidence* in reduction in runoff of about 9% (likely range 4.5–15.5%) Risk of water deficit (*medium confidence*)	Robust increase in probability of extreme drought (*medium confidence*) *Medium confidence* in further reductions (about 17%) in runoff (likely range 8–28%) Higher risks of water deficit (*medium confidence*)	Robust and large increases in extreme drought. Substantial reductions in precipitation and in runoff (*medium confidence*) Very high risks of water deficit (*medium confidence*)
West Africa & the Sahel	Increases in the number of hot nights and longer and more frequent heatwaves are *likely* Reduced maize and sorghum production is *likely*, with area suitable for maize production reduced by as much as 40% Increased risks of undernutrition	Further increases in number of hot nights and longer and more frequent heatwaves are likely Negative impacts on maize and sorghum production likely larger than at 1.5°C; *medium confidence* that vulnerabilities to food security in the African Sahel will be higher at 2.0°C compared to 1.5°C Higher risks of undernutrition	Substantial increases in the number of hot nights and heatwave duration and frequency (*very likely*) Negative impacts on crop yield may result in major regional food insecurities (*medium confidence*) High risks of undernutrition
Southern Africa	Reductions in water availability (*medium confidence*) Increases in number of hot nights and longer and more frequent heatwaves (*high confidence*), High risks of increased mortality from heatwaves High risk of undernutrition in communities dependent on dryland agriculture and livestock	Larger reductions in rainfall and water availability (*medium confidence*) Further increases in number of hot nights and longer and more frequent heatwaves (*high confidence*), associated increases in risks of increased mortality from heatwaves compared to 1.5°C warming (*high confidence*) Higher risks of undernutrition in communities dependent on dryland agriculture and livestock	Large reductions in rainfall and water availability (medium confidence) Drastic increases in the number of hot nights, hot days and heatwave duration and frequency to impact substantially on agriculture, livestock and human health and mortality (*high confidence*) Very high risks of undernutrition in communities dependent on dryland agriculture and livestock

Tropics	Increases in the number of hot days and hot nights as well as longer and more frequent heatwaves (*high confidence*) Risks to tropical crop yields in West Africa, Southeast Asia and Central and South America are significantly less than under 2.0°C of warming	The largest increase in hot days under 2.0°C compared to 1.5°C is projected for the tropics. Risks to tropical crop yields in West Africa, Southeast Asia and Central and South America could be extensive	Oppressive temperatures and accumulated heatwave duration *very likely* to directly impact human health, mortality and productivity Substantial reductions in crop yield *very likely*
Small islands	Land of 60,000 less people exposed by 2150 on SIDS compared to impacts under 2.0°C of global warming Risks for coastal flooding reduced by 20–80% for SIDS compared to 2.0°C of global warming Freshwater stress reduced by 25% as compared to 2.0°C Increase in the number of warm days for SIDS in the tropics Persistent heat stress in cattle avoided Loss of 70–90% of coral reefs	Tens of thousands of people displaced owing to inundation of SIDS High risks for coastal flooding and increased frequency of extreme water-level events Freshwater stress from projected aridity Further increase of ca. 70 warm days/year Persistent heat stress in cattle in SIDS Loss of most coral reefs and weaker remaining structures owing to ocean acidification (i.e. less coastal protection)	Substantial and widespread impacts through inundation of SIDS, coastal flooding, freshwater stress, persistent heat stress and loss of most coral reefs (*very likely*) Risk of multi-meter sea level rise due to ice sheet instability
Fynbos biome	About 30% of suitable climate area lost (*medium confidence*)	Increased losses (about 45%) of suitable climate area (*medium confidence*)	Up to 80% of suitable climate area lost (*medium confidence*)

Table 2: Summary of enhanced risks in the exceedance of regional tipping points under different global temperature goals. (summary, Table 3.7 from see text in 3.5.5(*5*), for supporting literature and discussion; updated, not intended to be exhaustive).

Tipping point	**Warming of 1.5°C or less**	**Warming of 1.5°C–2°C**	**Warming of up to 3°C**
Arctic sea ice	Arctic summer sea ice is *likely* to be maintained Sea ice changes reversible under suitable climate restoration	The risk of an ice-free Arctic in summer is about 50% or higher Sea ice changes reversible under suitable climate restoration	Arctic is *very likely* to be ice free in summer Sea ice changes reversible under suitable climate restoration
Tundra	Decrease in number of growing degree days below 0°C Abrupt increases in tree cover are *unlikely*	Further decreases in number of growing degree days below 0°C Abrupt increases in tree cover are *unlikely*	Potential for an abrupt increase in tree fraction (*low confidence*)
Permafrost	17–44% reduction in permafrost Approximately 2 million km^2 more permafrost maintained than under 2.0°C of global warming (*medium confidence*) Irreversible loss of stored carbon	28–53% reduction in permafrost with Irreversible loss of stored carbon	Potential for permafrost collapse (*low confidence*)
Asian monsoon	*Low confidence* in projected changes	*Low confidence* in projected changes	Increases in the intensity of monsoon precipitation *likely*
West African monsoon & Sahel	Uncertain changes; *unlikely* that a tipping point is reached	Uncertain changes; *unlikely* that tipping point is reached	Strengthening of monsoon with wettening and greening of the Sahel and Sahara (*low confidence*) Negative associated impacts through increases in extreme temperature events
Rainforests	Reduced biomass, deforestation and fire increases pose uncertain risks to forest dieback	Larger biomass reductions than under 1.5°C of warming; deforestation and fire increases pose uncertain risks to forest dieback	Reduced extent of tropical rainforest in Central America and large replacement of rainforest and savanna grassland Potential tipping point leading to pronounced forest dieback (*medium confidence*)

Coral reefs	Increased mass coral bleaching and mortality – decline in abundance to 10-30% of values of present day by 1.0ºC (*high confidence*)	High mortality - corals decrease to very low levels (<1%), impacts on organisms that dependent on coral reefs for habitat (fish, biodiversity, *high confidence*).	Irreversible changes occur with tipping point around 2°C–2.5°C – reefs are no longer resemble coral reef ecosystems – recovery potential very low (*medium confidence*).
Boreal forests	Increased tree mortality at southern boundary of boreal forest (*medium confidence*)	Further increases in tree mortality at southern boundary of boreal forest (*medium confidence*)	Potential tipping point at 3°C–4°C for significant dieback of boreal forest (*low confidence*)
Heatwaves, unprecedented heat and human health	Continued increase in occurrence of potentially deadly heatwaves (*likely*)	Substantial increase in potentially deadly heatwaves (*likely*) More than 350 million more people exposed to deadly heat by 2050 under a midrange population growth scenario (*likely*) Annual occurrence of heatwaves similar to the deadly 2015 heatwaves in India and Pakistan (*medium confidence*)	Further increases in potentially deadly heatwaves (*very likely*)
Agricultural systems: key staple crops	Global maize crop reductions of about 10%	Larger reductions in maize crop production than under 1.5°C of about 15%	Drastic reductions in maize crop globally and in Africa (*high confidence*) potential tipping point for collapse of maize crop in some regions (*low confidence*)
Livestock in the tropics and subtropics	Increased heat stress	Onset of persistent heat stress (*medium confidence*)	Persistent heat stress *likely*

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Figure captions:

Figure 1. Changes at 1.0ºC of global warming. Increases in Global Mean Surface Temperature (GMST) of 1.0ºC have already had major impacts on natural and human systems. Examples include: A. Increased temperatures and dryness in the Mediterranean region is driving longer and more intense fire seasons with serious impacts on people, infrastructure and natural ecosystems. Image shows tragic devastation of fire in the Greek village of Mati Greece in July 25, 2018. B. Evidence of ice sheet disintegration is increasing (here showing a 30 km fracture across the Pine Island Glacier which is associated with the Western Antarctic Ice sheet, WAIS). The fracture (see arrow) appeared in mid-October 2011 and has increased concern that we may be approaching a tipping point with respect to disintegration of the WAIS. C. Many low-lying countries such as the Maldives experience flooding and will be at an increased threat from sea level rise and strengthening storms over time. D. Many insects and birds have shifted reproductive events or migration to early times in the season as conditions have warmed. Image credits: A. 'Lotus R', https://www.flickr.com/photos/66012345@N00/964251167; B. Image credits: NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science TeamLast Updated: Aug. 7, 2017, C. Male, Maldives (O. Hoegh-Guldberg) and D. Semipalmated Sand Piper (*Calidris pusilla*, Creative Commons (CC BY-SA 3.0, GNU Free Documentation License)

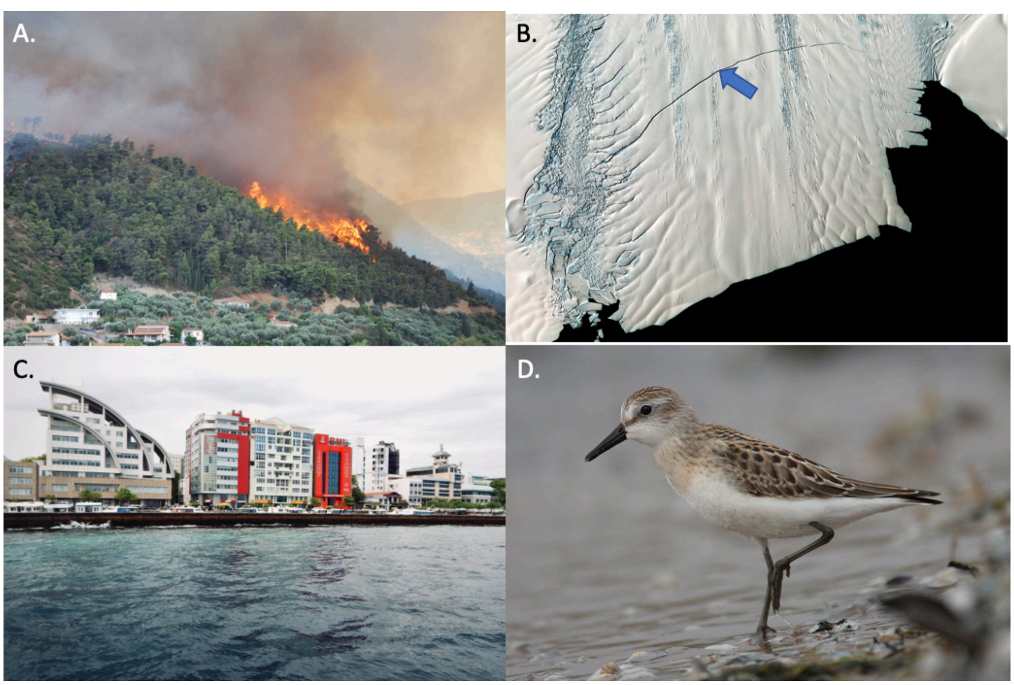

Figure 2A. Action on climate change can still result in stable or even decreasing global temperatures, although variability around projections is substantial. Strategies that include 'overshoot' (red dashed line, illustrative of a very high level of overshoot) require as yet early stage technologies to ensure that overshoot is kept as short as possible. Also, the larger overshoot, the higher the risk of irreversible change in affected systems. B. Responses to changing conditions (shown here as a thermal performance curve) are typically tilted to the right with a steep decline in performance such as growth, towards high temperature extremes. Beyond a thermal optimum, *Topt*, performance begins to decline beyond the *Pejus* temperature, *Tp*. A critical temperature, *Tc*, characterizes a low level of performance and time limited passive endurance when, as in ectothermic animals, oxygen supply capacity becomes insufficient to cover oxygen supply, or, as in corals, a symbiosis between corals and their dinoflagellate symbionts suddenly breaks down (coral bleaching) and corals go from appearing healthy to experiencing large scale mortality over days-to-weeks. Accordingly, the high *Tc* characterizes a temperature of high responsiveness to small increases in temperature extremes, such as by 0.5°C, especially, if some life stages have a narrow thermal range indicating high vulnerability(*26*).

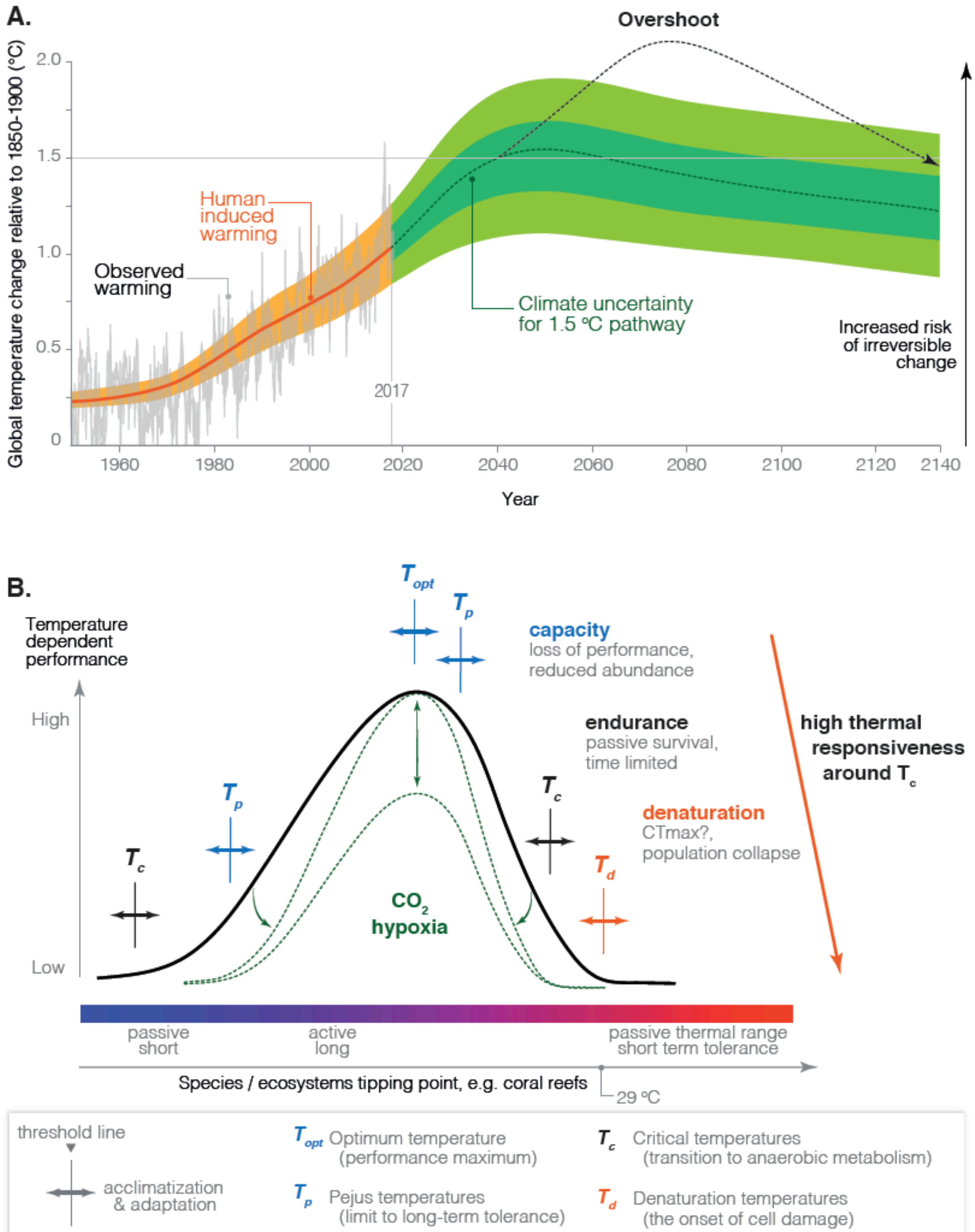
A.
Overshoot
Global temperature change relative to 1850-1900 (°C)
2.0
1.5
1.0
0.5
0
Human induced warming
Observed warming
2017
Climate uncertainty for 1.5 °C pathway
Increased risk of irreversible change
1960
1980
2000
2020
2040
2060
2080
2100
2120
2140
Year
B.
Temperature dependent performance
High
Low
T_{opt}
T_p
capacity
loss of performance, reduced abundance
endurance
passive survival, time limited
high thermal responsiveness around T_c
T_c
denaturation
CTmax?, population collapse
T_d
CO_2 hypoxia
passive short
active long
passive thermal range short term tolerance
Species / ecosystems tipping point, e.g. coral reefs
29 °C
threshold line
acclimatization & adaptation
T_{opt} Optimum temperature (performance maximum)
T_p Pejus temperatures (limit to long-term tolerance)
T_c Critical temperatures (transition to anaerobic metabolism)
T_d Denaturation temperatures (the onset of cell damage)

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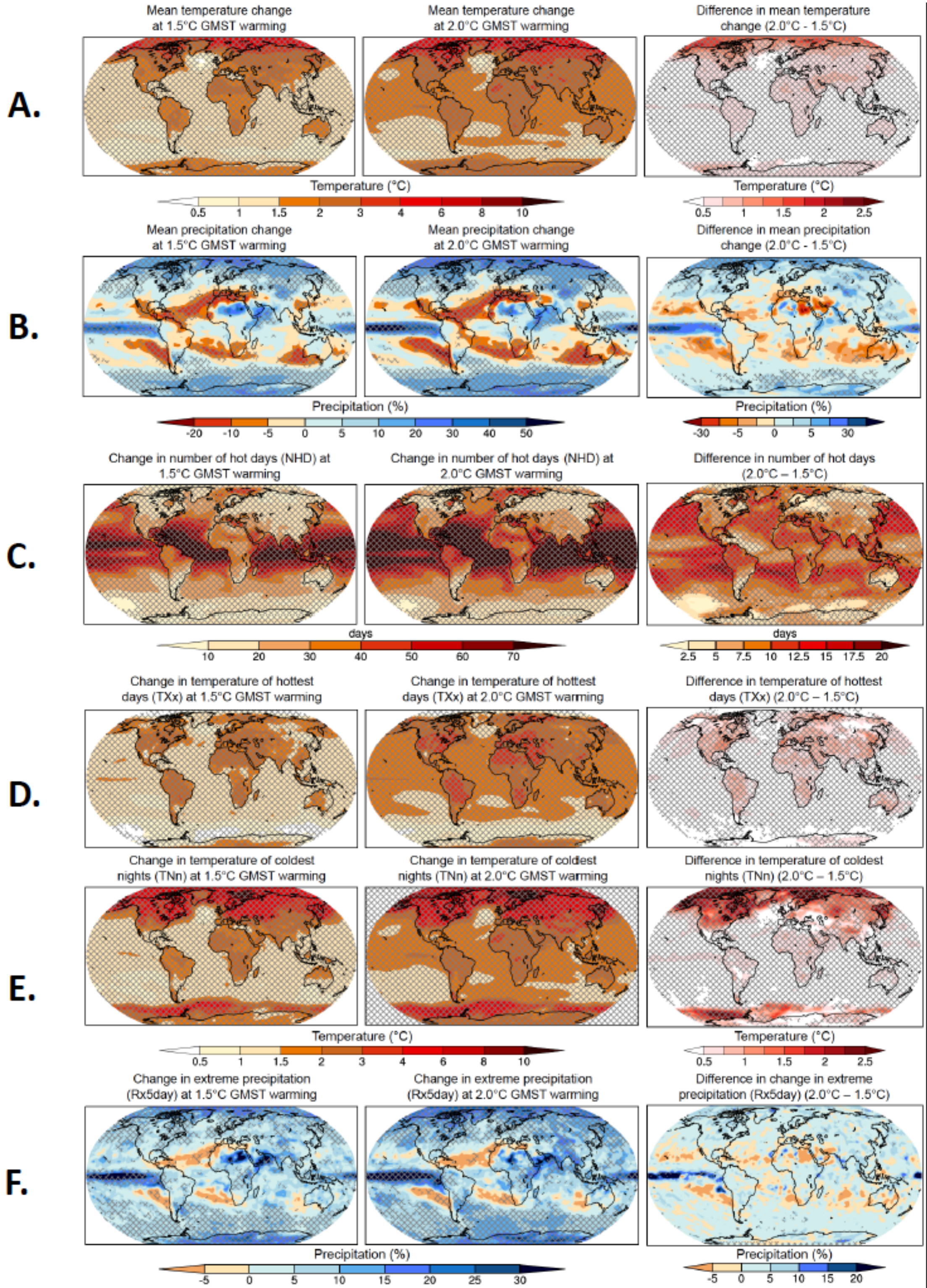
Figure 3 Projected changes in A. Mean temperature, B. Mean precipitation, C. Number of hot days (NHD; 10% warmest days), D. Temperature of hottest day (TXx), E. Temperature of coldest night (TNn), and F. Change in extreme precipitation (Rx5day). Conditions are projected for 1.5°C (left-hand column) and 2.0°C (middle-hand column) of global warming compared to the pre-industrial period (1861–1880), with the difference between 1.5°C and 2.0°C of global warming being shown in the third column. Cross-hatching highlights areas where at least two-thirds of the models agree on the sign of change as a measure of robustness (18 or more out of 26). Values were assessed from the transient response over a 10-year period at a given warming level, based on Representative Concentration Pathway (RCP) 8.5 Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulations (*5*)(*3*); adapted from (*29*, *73*); see Supplementary Material 3.SM.2 (*5*).

Figure 3


A.
Mean temperature change at 1.5°C GMST warming
Mean temperature change at 2.0°C GMST warming
Difference in mean temperature change (2.0°C - 1.5°C)
Temperature (°C)
0.5 1 1.5 2 3 4 6 8 10
Temperature (°C)
0.5 1 1.5 2 2.5
B.
Mean precipitation change at 1.5°C GMST warming
Mean precipitation change at 2.0°C GMST warming
Difference in mean precipitation change (2.0°C - 1.5°C)
Precipitation (%)
-20 -10 -5 0 5 10 20 30 40 50
Precipitation (%)
-30 -5 0 5 30
C.
Change in number of hot days (NHD) at 1.5°C GMST warming
Change in number of hot days (NHD) at 2.0°C GMST warming
Difference in number of hot days (2.0°C – 1.5°C)
days
10 20 30 40 50 60 70
days
2.5 5 7.5 10 12.5 15 17.5 20
D.
Change in temperature of hottest days (TXx) at 1.5°C GMST warming
Change in temperature of hottest days (TXx) at 2.0°C GMST warming
Difference in temperature of hottest days (TXx) (2.0°C – 1.5°C)
E.
Change in temperature of coldest nights (TNn) at 1.5°C GMST warming
Change in temperature of coldest nights (TNn) at 2.0°C GMST warming
Difference in temperature of coldest nights (TNn) (2.0°C – 1.5°C)
Temperature (°C)
0.5 1 1.5 2 3 4 6 8 10
Temperature (°C)
0.5 1 1.5 2 2.5
F.
Change in extreme precipitation (Rx5day) at 1.5°C GMST warming
Change in extreme precipitation (Rx5day) at 2.0°C GMST warming
Difference in change in extreme precipitation (Rx5day) (2.0°C – 1.5°C)
Precipitation (%)
-5 0 5 10 15 20 25 30
Precipitation (%)
-5 0 5 10 15 20

Summary of Review

Here today, gone tomorrow: the non-linearity of climate change.

Background:

United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992 with the central purpose to pursue the "stabilization of greenhouse gas (GHG) emissions at a level that would prevent dangerous anthropogenic interferences with the climate system". Since 1992, five major climate assessment reports have been completed by the UN Intergovernmental Panel on Climate Change (IPCC). These reports identified rapidly growing climate related impacts and risks, including more intense storms, collapsing ecosystems, and record heatwaves, among many others. Once thought to be tolerable, increases in global mean surface temperature (GMST) of 2.0°C or higher than the pre-industrial period look increasingly unmanageable and hence dangerous to natural and human systems.

The Paris Climate Agreement is the most recent attempt to establish international cooperation over climate change (*2*). This agreement was designed to bring nations together voluntarily in order for them to take ambitious action on mitigating climate change while also developing adaptation options and strategies, and guaranteeing the means of implementation (e.g. climate finance). Since that time, 185 countries have ratified the Agreement, including countries such as diverse as USA, Saudi Arabia and China (*74*). The Agreement is aimed at "*holding the increase in the global average temperature to well below 2.0°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.*" Many unanswered questions regarding a 1.5°C target surround the feasibility, costs, and inherent risks to natural and human systems. Consequently, the UNFCCC invited the IPCC to prepare a special report on the "*the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.*" The Special Report was completed and approved by the 48^{th} Session of the IPCC in October 2018.

Advances:

We review multiple lines of evidence that indicate that the next 0.5°C above today (which will take GMST from 1.0ºC to 1.5ºC above the pre-industrial period) will involve greater risks per unit temperature than those seen in the last 0.5ºC increase. This principle of 'accelerating risk' is also likely to drive proportionally higher risk levels in the transition from 1.5ºC to 2.0ºC above the pre-industrial period. We argue that this is a consequence of impacts accelerating as a function of distance from the optimal temperature (*Top*, Fig 2b) for an organism or process. Ecosystems like coral reefs (Fig 1), for example, often appear healthy right up until the onset of mass coral bleaching and mortality (Fig 2A,B), which can then rapidly destroy a coral reef within a few months. This also explains the observation of 'tipping points' where the condition of a group of organisms or an ecosystem can appear 'healthy' right up until they collapse, suggesting caution in extrapolating from measures of ecosystem condition (i.e. changes in the amount of coral cover). Information of this nature needs to be combined with an appreciation of where organisms are with respect to the optimal temperature (*Top*, see Fig 2, Hoegh-Guldberg et al. 2019, this issue).

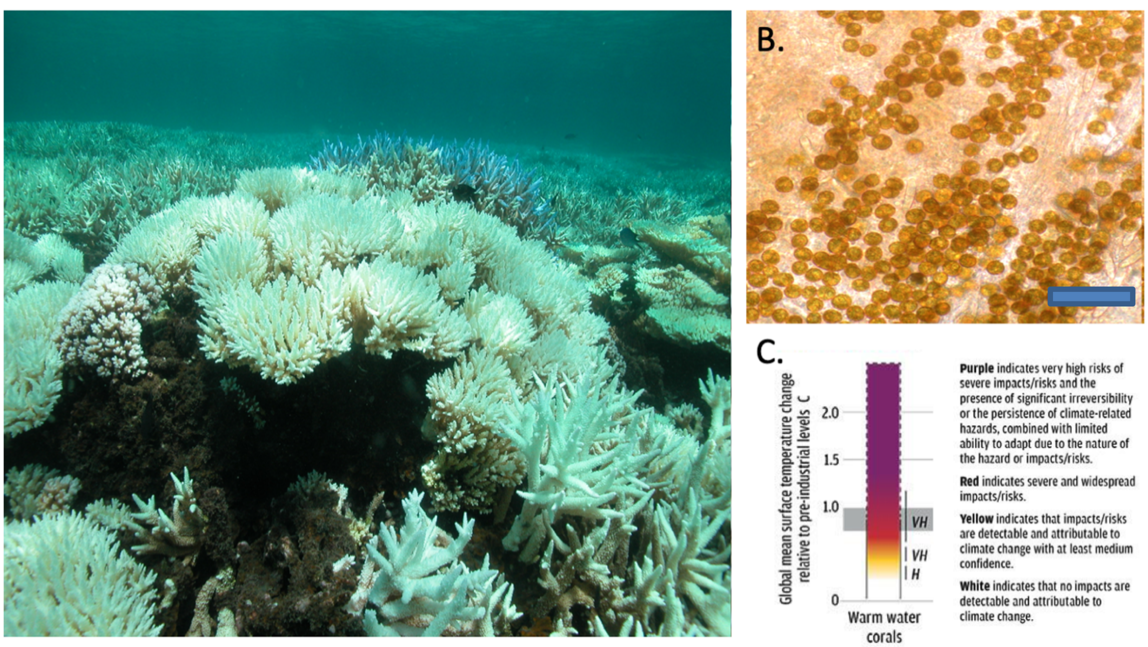


Fig 1 (legend). Responses to climate change can be non-linear in nature, such exemplified by coral reefs. (A) Reef-building corals can suddenly lose their (B) dinoflagellate symbionts (bar=50μm) and die in response to increasing temperatures, exhibiting (C) non-linear changes in the amount of impact/risk from climate change. *Attribution: A. Author, Hoegh-Guldberg ; B.*

Author, Hoegh-Guldberg; C is adapted from (*5*)*, H (high) and VH (very high) are the levels of confidence in the transition from one impact/risk level to another (i.e. colors).*

In a similar way, human systems tend to experience greater costs and risks as we move away from optimal conditions, with an increasing risk of non-linear changes. Finally, we explore the relative costs and benefits associated with acting when it comes to climate change, and come to the preliminary conclusion that restraining average global temperature to 1.5°C above the pre-industrial period may be 4-5 less costly than the damage due to inaction on global climate change.

Outlook:

As an IPCC expert group, we were asked to assess the impact of recent climate change (1.0°C, 2017) and that likely over the next 0.5 - 1.0°C of global warming. At the beginning of this exercise, many of us were concerned that the task would be hindered by a lack of expert literature available for 1.5°C and 2.0°C warmer worlds. While this was the case at the time of the Paris Agreement in 2015, it has not our experience four years later. With an accelerating amount of peer-reviewed literature since the IPCC Special Report on 1.5ºC, it is very clear that there is an even more compelling case for deepening commitment and actions for stabilizing global mean surface temperature at 1.5ºC above the pre-industrial period.