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Annual Review of Environment and Resources 1.5°C Hotspots: Climate Hazards, Vulnerabilities, and Impacts

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Abstract

Differentiating the impacts of climate change between 1.5°C and 2°C requires a regional and sector-specific perspective. Whereas for some regions and sectors the difference in climate variables might be indistinguishable from natural variability, other areas especially in the tropics and subtropics will experience significant shifts. In addition to region-specific changes in climatic conditions, vulnerability and exposure also differ substantially across the world. Even small differences in climate hazards can translate into sizeable impact differences for particularly vulnerable regions or sectors. Here, we review scientific evidence of regional differences in climate hazards at 1.5°C and 2°C and provide an assessment of selected hotspots of climate change, including small islands as well as rural, urban, and coastal areas in sub-Saharan Africa and South Asia, that are particularly affected by the additional 0.5°C global mean temperature increase. We interlink these with a review of the vulnerability and exposure literature related to these hotspots to provide an integrated perspective on the differences in climate impacts between 1.5°C and 2°C.

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INTRODUCTION

The adoption of the 1.5°C long-term temperature limit in the Paris Agreement (1, 2) has led to a surge in interest on differentiating climate impacts between present day increases in global mean surface air temperature (GMT) of approximately 1°C relative to preindustrial levels, 1.5°C, and 2°C. The Intergovernmental Panel on Climate Change (IPCC) is assessing this differentiation in its special report on 1.5°C. However, the available information on impacts at 1.5°C and differences between 1.5°C and 2°C focusses strongly on biophysical systems for which process-based models are readily available. Differential impacts on human and socio-ecological systems that require more comprehensive assessments of the changing climate hazards in the context of vulnerability and exposure are more difficult to assess in the limited time that has been available for the special report. These limitations notwithstanding, differential vulnerability and exposure are at the very heart of the political dynamics that led to the establishment of the 1.5°C warming limit in the Paris Agreement, a goal championed by those at the forefront of climate change (3). As early as 2009, about 100 countries, including small island states and least developed countries, were already arguing for warming to be limited to below 1.5°C (4, 5).

These nations insisted that when the "hold warming below 2°C" was agreed upon by the United Nations Framework Convention on Climate Change (UNFCCC) in Cancun in 2010, this was tied to a periodic science-based process reviewing the adequacy of this limit with an explicit reference to 1.5°C as an alternative (6). The subsequent 2013–2015 Review adopted a science-policy format called the Structured Expert Dialogue (SED) for its deliberations on the state of the science with regard to its objectives. The SED concluded its work just before the Paris climate conference in 2015. The final report was based on the available science at the time, specifically the Fifth Assessment Report (AR5) of the IPCC (7). It found that the "concept, in which up to 2°C of warming is considered safe, is inadequate" (8, message 5, p. 18) as "many systems and people with limited adaptive capacity, notably the poor or otherwise disadvantaged, will still be at very high risk," (8, message 5, p. 18) and that "limiting global warming to below 1.5°C would come with several advantages" (8, message 10, p. 33). This science-based assessment was an essential input into the political deliberations that led to the adoption of the 1.5°C limit.

Various climate hazards scale well with global mean temperature, which makes it a useful focal point for climate action (8, 9). However, other elements of the climate system show a time-lagged response to warming, including the ocean and cryosphere (10), the terrestrial and marine carbon sink (11), large-scale circulation systems such as the El Niño Southern Oscillation (12) or the Atlantic meridional overturning circulation (13), as well as the global hydrological cycle (14). Other anthropogenic interferences related to, for example, aerosol emissions (15, 16) or land use (17, 18) may also strongly affect the (regional to local) climate response.

Changes in climate hazards between 1.5°C and 2°C need to be assessed using event- and regionspecific indicators, as changes affect multiple processes/sectors and are not geographically uniform (2). This is particularly important for tropical regions, which will experience a more pronounced change in climatic conditions as the result of half a degree global mean temperature increase (19, 20). To evaluate the outcomes of the 2013–2015 Review (8) in the light of new scientific findings, assessments of differential climate hazards should thus aim at reconnecting with appraisals of vulnerability and exposure.

We highlight regional differences in biophysical impacts at 1.5 and 2°C and the importance of the regionally specific socioeconomic setting in order to understand the potential human impacts of such changes. On the basis of their contextual vulnerability, we identify hotspot regions for which we provide a comprehensive review of projections of differential climate hazards for various indicators and sectors for 1.5 and 2°C. We continue to outline the regionally specific vulnerabilities with respect to the projected biophysical impacts in hotspot regions in order to highlight the relevance of an improved understanding of regionally differentiated impact analyses.

Half a Degree Differences in Warming Over the Historical Record

Assessments of future changes under 1.5°C and 2°C warming have to rely on model projections and are thereby prone to model uncertainties that may obscure incremental differences in the climate signal. At the same time, such assessments typically remain limited to impacts for which robust quantitative models are available in the first place. In this context, the observational record can provide a very useful additional line of evidence and inform expectations on differences in hazards between 1.5°C and 2°C, in particular, as warming over the second half of the twentieth century amounts to approximately 0.5°C warming until the recent past (21, 22). Because only few data records extend back in time beyond the 1950s in a comprehensive fashion, most of the attributed changes in observed climate impacts as examined, for example, in the AR5 relate to a warming of approximately 0.5°C or even less. Widespread attributable changes have been identified for all world regions and physical, biological, and human systems including changes in the cryosphere,

water availability, sea level, terrestrial and marine ecosystems, food production, livelihoods, health, and economic impacts (23). Such assessment may, however, still underestimate the attributable impacts in most vulnerable countries due to data gaps (24).

Observed attributable impacts on human and natural systems may in many cases present a lower bound for the effects of future 0.5°C warming increments as our climate moves more and more outside the range of natural variability (25), and risks of reaching systemic thresholds or tipping points may increase in a nonlinear fashion as a consequence. These caveats notwithstanding, observed impacts can provide useful guidance for the identification of future hotspots of change.

Projections of Global Warming of 1.5°C versus 2°C Above Preindustrial Levels

The set of Representative Concentration Pathways (RCPs), i.e., greenhouse gas concentration trajectories used for climate modeling in the fifth Coupled Model Intercomparison Project (CMIP5) underlying the IPCC AR5, do not include targeted 1.5°C or 2°C climate scenarios. As a result, assessing regional climate and climate impact differences at 0.5°C warming increments requires specific methodological approaches such as pattern scaling (26–29), time-slicing (9, 19), or dedicated scenarios experiments (30, 31). All these approaches come with specific strengths and weaknesses (32). Finally, the multimodel intercomparison project "Half a degree additional warming, prognosis and projected impacts" (HAPPI) (31) provides a set of multimodel experiments at 1.5°C and 2°C, specifically designed to examine patterns of extreme weather events. HAPPI provides multi-ensemble member projections (50–100 members per model) for decadal end-of-century 1.5°C and 2°C warming levels with prescribed sea-surface temperatures and sea-ice forcing conditions. This unique ensemble allows us to assess changes in indicators with a low signal-to-noise ratio such as extreme weather events in greater detail.

Concepts of Vulnerability

Vulnerability to climate change has been interpreted in various ways and several, sometimes contrasting, definitions exist. Among other things, differences include the components that define vulnerability as well as the character and timing of being vulnerable (see, e.g., 33). For the purposes of this review, we follow the definitions put forward by the IPCC AR5, where vulnerability is understood as "the propensity or predisposition to be adversely affected," further differentiated into contextual as well as outcome vulnerability (34).¹ Contextual vulnerability, also referred to as starting-point vulnerability, refers to the current inability of a system to cope with change and does not take into account potential adaptation strategies. Outcome, or end-point, vulnerability includes an analysis of potential adaptive options-the impacts that remain after adaptation occurs thus define levels of vulnerability. For a review at regional resolution as presented here, we therefore refer to contextual vulnerability characteristics, as an assessment of potential adaptation would be beyond the scope of this review. Contextual vulnerability is based on the view that characteristics of systems influence the ability to respond to climate change, and, as such, potential adaptation options cannot be assessed before considering how several factors lead to differential vulnerabilities and thereby adaptive capacities (36). In conjunction with regional exposure as well as climate hazards, vulnerability is an important determinant of regional climate risk, defined as "the potential for consequences where something of value is at stake..." (34).

¹In contrast to the previous definition in the AR4, where vulnerability is understood as a "function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity" (35) and thus incorporates climate change as a central component, the present definition of vulnerability is a description of the socioeconomic conditions, which may render a region more susceptible to a given climate hazard.

Vulnerability is influenced by a variety of socioeconomic, demographic, biophysical, cultural, and institutional factors, including characteristics such as levels of poverty, gender, age, ethnicity, and education (37, 38). Different characteristics may be considered, depending on the spatial and temporal resolution of the assessment. Assessing vulnerability at household or community scales, for example, often includes nuanced considerations of several factors (39, 40), whereas at the regional scale, mostly broad, quantitative, and sector-specific indicators and indices are used (41). For instance, to quantify regional vulnerability of agriculture to climate change, several indicators are used to identify biophysical, socioeconomic, and technological factors that contribute to vulnerability, including soil characteristics, groundwater availability, literacy rates, availability of alternative economic activities, gender equity, and crop management techniques (42, 43).

A diverse range of factors determining contextual vulnerability are comprised in the Multidimensional Poverty Index (44) shown in **Figure 1**. On the basis of this index we identify sub-Saharan Africa and South Asia as key vulnerability hotspots. In addition, we are also specifically focusing on small island developing states (SIDS), which are characterized by relatively small physical



Share of population living in multidimensional poverty, 2014

Figure 1

Multidimensional poverty index highlighting the hotspot regions reviewed here. In addition to the broad contextual vulnerability elements, specific key climate-related factors are highlighted per region. Figure reprinted from Reference 44.

sizes, concentration of infrastructure, economic activities, and populations in coastal zones that all contribute to high contextual vulnerability (45, 46). This vulnerability is increased by the exposure of small islands to a full array of climate change hazards. Tropical cyclones, sea level rise and coastal erosion are particularly disturbing, as encroaching seas and limited adaptive capacity threaten the very existence of many small, low elevation islands (47, 48). In the following, we review changes in climate hazards and biophysical impact projections between 1.5°C and 2°C before interlinking contextual vulnerabilities and changes in climate hazards to identify risks and impacts for the three hotspot regions.

ASSESSING DIFFERENCES IN CLIMATE HAZARDS AND SECTORIAL IMPACTS AT 1.5°C AND 2°C

A growing body of literature assesses the differences in climate hazards between 1.5°C and 2°C for various different regions and sectors. Limiting warming to 1.5°C will more than half the number of plants, insects, and invertebrates critically affected by climate change (49). Already half of the global glacier ice mass will be lost for a warming of 1.5°C compared to approximately 66% at 2°C, with losses being strongest for lower latitude and altitude glaciers (50) At the same time, evidence is increasing that warming above 1.5°C would substantially increase the risks of a seasonally ice-free Arctic (51–54). Furthermore, economic productivity is projected to be impeded by increasing warming with a substantial shift between 1.5°C and 2°C in tropical countries in particular (55).

Changes in Mean Climate

Figure 2 (56) shows changes in annual mean temperature and precipitation for four models from the HAPPI 1.5°C and 2°C experiments at the end of the century, relative to the reference period (2006–2015). Global land mass is found to warm more than the global average, and polar amplification leads to regional warming in the high northern latitudes of more than three times the global average already under in a 1.5°C warmer world. This effect is further amplified for 2°C. As in the CMIP5 simulations, changes in mean precipitation are more uncertain (57). However, a robust drying is projected in the subtropical regions, including the Mediterranean, Central America and the Caribbean, South Africa, and parts of Australia. At the same time, precipitation variability might increase with increasing warming. Pendergrass et al. (58) and Saeed et al. (59) report robust changes in rainy season characteristics in large parts of the tropics. Saeed et al. find that approximately 27% of West Africa is projected to experience robust changes in the rainy season length with a mean shortening of approximately seven days under 1.5°C and nine days under 2°C.

Extreme Weather Events

Robust changes in extreme weather indicators for 0.5°C warming increments are already evident from the observational record (21). **Figure 3** depicts changes between 1.5°C and 2°C from time-sliced fully coupled CMIP5 simulations (60) and atmosphere-only HAPPI simulations (61) resolved for 26 world regions, as in Reference 62 (see also **Table 1**). Changes in indicators are as follows (63):

- Intensity of hot extremes (TXx): annual maximum value of daily maximum temperature
- Intensity of cold extremes (*TNn*): annual minimum value of daily minimum temperature)
- Dry spell length or consecutive dry days (*CDD*): annual maximum number of consecutive days for which precipitation is below 1 mm
- Heavy precipitation intensity or maximum accumulated five-day precipitation (*RX5day*): absolute annual maximum of consecutive five-day precipitation.



Figure 2

Changes in annual mean temperature (*left*) and precipitation (*right*) at end of century warming levels of 1.5°C and 2°C above preindustrial relative to the 2006–2015 period (approximately 0.9°C warmer than preindustrial), based on an ensemble from the HAPPI (Half a degree additional warming, prognosis and projected impacts) model intercomparison project (31). Hatching indicates significant changes based on a student' two-tailed t-test.

Significant increases in hot extremes are projected globally and lead to a substantial increase in threshold exceeding extreme heat events between 1.5°C and 2°C (64–66). At the same time, the intensity of cold extremes is reduced. These findings are robust in both model ensembles displayed in **Figure 4**.

Both the intensity and the length of extreme hot events are increasing. Substantial increases in the warm spells are evident for the global land area, but in particular over tropical regions, where natural variability is lower (19). A significant increase in heat wave magnitude is expected over Africa, South America, and Southeast Asia (67, 68). Under a warming of 2°C, unusual heat waves will become the new normal in tropical Africa (69). Dosio et al. (67) found that already in a 1.5°C world, 13.8% of the world population will be exposed to severe heat waves at least once every five years and centered in tropical regions. This fraction becomes nearly three times larger (36.9%) under 2°C warming, that is, a difference of approximately 1.7 billion people. This will have far-reaching effects, for example, on human health and outside labor productivity that is already in decline worldwide (70).

For precipitation extremes, the uncertainty in projection is much larger than for heat extremes, and differences between the CMIP5 and HAPPI estimates are more apparent. Although significant changes in CMIP5 simulations are apparent predominantly in high-latitude regions,



Figure 3

Changes in regional extreme weather indices between 1.5°C and 2°C of global warming for an ensemble of fully-coupled CMIP5 models (*a*) and atmosphere only HAPPI (Half a degree additional warming, prognosis and projected impacts) simulations (*b*): Significant increases are indicated by orange plus signs, significant decreases by blue minus signs, and nonsignificant in gray. Significance is determined using a two-sided paired Wilcoxon test (60). Regional acronyms here are the same as that for **Table 1**. Figure reprinted from Reference 61.

HAPPI simulations also indicate significant shifts in tropical extreme precipitation. This could be linked to the larger ensemble of runs per model that allows for a more robust statistical estimate. However, there is a risk that the HAPPI ensemble might be overconfident compared to CMIP5 (61, 71), given it consists of only five different models (compared to 26 for CMIP5) and does not account for coupled ocean-atmosphere variability that is relevant for drought events in particular (72, 73). For extreme precipitation (*RX5day*), the difference in timing and forcing composition between HAPPI and CMIP5 simulations may also play a role. Whereas CMIP5 1.5°C and 2°C estimates are taken from time slices around and before mid-century, HAPPI simulations assess 1.5°C and 2°C worlds at end of century forcing conditions. Adjustments in the hydrological cycle (14) and reduction in atmospheric aerosol loading, as well as harmonization of aerosol-loading patterns, may therefore contribute to a more robust signal (15, 16).

Altogether, most of the global land region project an increase in *RX5day* signal at 1.5°C and a robust difference between 1.5°C and 2°C. Kharin et al. (74) find that *RX5day* increases by approximately 6% per degree of warming in the global average. The Asian monsoon regions may experience increases in extreme precipitation of well above the global average (75) of approximately 10% under a 2°C warming (19).

Changes in meteorological drying (*CDD*) are predominantly confined to subtropical regions such as the Mediterranean, the Amazon and Brazil, Central and South Africa, as well as Southern South America. Among the available drought indicators, *CDD* is a mere meteorological indicator that does not account for changes in evapotranspiration or soil moisture. A more complex drought

Acronym	World region			
ALA	Alaska, North-West Canada			
AMZ	Amazon			
CAM	Central America, Mexico, Caribbean			
CAS	Central Asia			
CEU	Central Europe			
CGI	East Canada, Greenland, Iceland			
CNA	Central North America			
EAF	East Africa			
EAS	East Australia			
ENA	East North America			
MED	Mediterranean			
NAS	North Asia			
NAU	North Australia			
NEB	North-East Brazil			
NEU	Northern Europe			
SAF	South Africa			
SAH	Sahara			
SAS	South Asia			
SAU	South Australia, New Zealand			
SEA	South-East Asia			
SSA	South-East South America			
TIB	Tibetan Plateau			
WAF	West Africa			
WAS	West Asia			
WNA	West North America			
WSA	West Coast South America			

Table 1Overview of the world regions used as well as the respective acronyms based onReference 62

indicator that also incorporates hydrological effects provided by Lehner et al. (76) finds similar patterns and also reports an increase in drought risk in Central Europe, which is evident in both HAPPI and CMIP5 simulations.

Changes in extreme weather indicators, in particular related to extreme heat and dryness, are of great importance for estimates of future agricultural impacts. In order to inform such assessments, aggregated changes over cropland and pasture are analyzed for different climatic zones shown in **Figure 4**. For each climatic zone, changes in extreme indicators at all grid cells within the climatic zone are aggregated into one distribution. Percentile changes and mean changes are computed by weighting each grid cell by its area covered by cropland or pasture. Data on fractional cropland and pasture use are taken from Reference 77. At both 1.5°C and 2°C, tropical agricultural lands show the larger increase in extreme weather, including longer and more frequent dry spells, longer and more frequent heat waves, and increases in heavy rainfall intensity (**Figure 4**). When comparing results between 1.5°C and 2°C, duration and frequency of heat waves double for all regions. Changes in dry spell lengths under 1.5°C are most pronounced over tropical agricultural land, but with little change between 1.5°C and 2°C. To the contrary, drying increases over temperate and cold agricultural regions for this 0.5°C warming increment.



Figure 4

Changes in extreme weather indicators for a set of HAPPI simulations from Reference 56, aggregated over cropland and pasture in each of the four climate zones (tropical, arid, temperate, cold) and for the whole land area (excluding Greenland and Antarctica). Climate extreme indicators are warm spell days (*upper left*), warm spell periods (*upper right*), *CDD* periods (*lower left*), and *RX5day* (*lower right*). Warm spells are derived following the warm spell duration indicator (*WSDI*): total count of days in a decade with at least six consecutive days when daily maximum temperature exceeds the 90% quantile over the reference period. The number of warm spell periods counts periods longer than or equal to 6 days under warm spell conditions. Boxes indicate the interquartile range (25th–75th percentile), the horizontal line (*star*) indicates the median (mean) value. Abbreviations: CDD, consecutive days; HAPPI, Half a degree additional warming, prognosis and projected impacts; RX5day, five-day precipitation; WSDI warm spell duration indicator.



Figure 5

Assessment of differences between 1.5° C and 2° C for annual mean run off (*top row*) and local yields for four major staple crops (*row 2–5*), based on ensembles of five climate models and multiple sectorial impact models from Reference 19. Significant increases between 1.5° C and 2° C are shown in orange, decreases are in blue, and nonsignificant changes are in gray. Significance is determined by the following criteria: The difference in the mean change exceeds 0.5%, and more than 83% of all ensemble members show robust regional changes between 1.5° C and 2° C (see Reference 19 for more information on the methodology). The sign indicates the change between the 1986-2005 reference period and 1.5° C warming. The combinations blue/plus sign (orange/minus sign) indicate a sign reversal from an increase (decrease) between the reference period and 1.5° C to a decrease (increase) between 1.5° C and 2° C. Regional acronyms are the same as that for Table 1.

Water Resources

Changes in water resources resemble to a large extent the changes in precipitation patterns. Substantial increases in annual run-off at 1.5°C are projected for the high northern latitudes and the Asian monsoon regions, whereas water availability at the same time is reduced in subtropical regions (19). The same study projected annual run-off to the Mediterranean region reducing by approximately 9% under 1.5°C in a transient time slicing ensemble, compared to 17% in a 2°C world. Other regions experiencing substantial reductions in annual run-off include Australia, South Africa, Central America, the Amazon and Northeast Brazil, as well as Central and West Asia (compare with **Figure 5**). These regions are also found to be at risk of further aridification, in particular under 2°C warming. Limiting warming to 1.5°C reduces the area experiencing aridification by approximately two-thirds in a transient time slicing setup (78). Arnell et al. (29) estimate that limiting warming to 1.5°C would reduce the global population exposed to drought or river flooding by approximately 40% compared to 2°C.

In addition to hydrological effects, changes in glaciers will affect water resources globally (79), and approximately one-third of global glacier ice mass is already unstable at present levels of warming (50). Among these, tropical glaciers are particularly sensitive to temperature increases (80). Limiting warming to 1.5°C may prevent melting of almost two-thirds of presently stored ice mass in high mountain glaciers in Asia, which decreases to approximately 50% if warming exceeds 2°C (81). More than 1.5 billion people in Nepal, Bhutan, India, and Pakistan depend on upstream water flow from the Himalayas (82). Although water demand is high, especially for irrigated agriculture, freshwater resources per capita are 3–4 times lower than the world average (2,000–3,000 m³/capita/year) (82). Similarly, the tropical Andes face growing retreat of glaciers, making the Andean community in Peru, Colombia, Ecuador, Bolivia, and Venezuela particularly vulnerable to droughts and other climate hazards (83).

Agriculture and Terrestrial Ecosystems

As most impact projection studies published to date focus on long-term and high levels of warming (e.g., 84), a review of historical yield change can provide useful insights into the projected effect of an additional half degree of warming. For example, analyses of observed temperature changes and variability with crop models showed that global maize and wheat production declined over 1980–2008 by 3.8 and 5.5%, respectively, relative to a counterfactual without climate trends (85). An analysis of observed crop-climate variability revealed that 20-40% of yield interannual variability over the past 40 years can be attributed to climate variability, depending on crop types (86, 87). Another recent study found droughts and extreme heat stress events-but less so floods and extreme low temperatures—have been responsible for 9-10% losses in national crop production over the past 40 years (88). While relative losses appear to be more substantial in developed agricultural systems (88), there is also evidence that crops grown in tropical climates are highly exposed to upper-end temperatures, and even a small rise in temperatures could be detrimental. Schleussner et al. (19) have found that reductions in median local yields in tropical regions could double between 1.5°C and 2°C for wheat and maize. Figure 5 depicts regionally resolved differences between 1.5°C and 2°C for local yields. For most regions and crops (with the notable exception of high-latitude regions), a reduction in local yields between 1.5°C and 2°C is evident (blue colored boxes), even for those where the effects of a 1.5°C warming on local yields are positive compared to the reference period (indicated by the pluses). These findings were recently confirmed in regional studies for West Africa that further highlight the vulnerability of low-input cropping systems (89). As these estimates combine climate and CO_2 forcing, these sign reversals between 1.5°C and 2°C indicate the existence of a "sweet spot" for crop yields beyond which detrimental effects of warming dominate even for temperate regions such as Central North America, Central Europe, or parts of Southeast Asia. Without considering CO₂ fertilization or adaptation, each degree of increase in global mean temperature has been found to reduce global yields of wheat by 6.0 \pm 2.9%, rice by 3.2 \pm 3.7%, maize by 7.4% \pm 4.5%, and soybean by 3.1% (90). The effects of CO₂ fertilization are still subject to considerable uncertainty and (91) have found that the consequences of geophysical uncertainties related to CO_2 concentrations at 1.5°C and 2°C are of similar order of magnitude as the effects of a 0.5°C temperature increase.

In sub-Saharan Africa, observations data based on historical maize trials indicate an upper temperature threshold is already reached for maize, and yield declines are projected for each additional degree of warming (85). As shown in **Figure 4**, tropical cropland (28% of global cropland areas) and tropical pastures (21% of global pasture areas) face the largest change in extreme weather events at both 1.5°C and 2°C, including more intense and frequent extreme rainfall, dry spell events, and heatwave. These extreme climate events threaten crops and other terrestrial ecosystems. In addition, despite the key impacts of pests and diseases on important cash crops grown in the tropics, such as coffee, cocoa, and banana (92), the role of climate change on pests and diseases is typically overlooked and the impact on crops is likely to be underestimated (93). As severe food insecurity is centered in tropical regions (94), limiting warming to 1.5°C appears to be of key importance to ensure sustained tropical agriculture potential and thereby ensure food security.

Sea Level Rise

Unlike many land-based impacts of climate change, future sea level rise is not directly constrained by atmospheric temperature and will continue to rise long after GMT has peaked (95). On millennial timescales, global sea level may rise by approximately 2.3 m/°C of GMT increase (96). Peak and decline 1.5°C scenarios could be the only chance to limit long-term sea level rise to less than 1 m (97). Since the AR5, several studies have highlighted the vulnerability of parts of the Antarctic ice sheet to irreversible and self-amplifying ice loss that could happen at warming levels much lower than previously thought (98, 99). Although the AR5 considered a potential additional contribution from Antarctic rapid dynamical change of several tenths of a meter by 2100 to be unlikely (95), recent research suggests that instability processes previously not included in ice sheet models may contribute more than 1 m by the end of the twenty-first century under unmitigated emission scenarios (100). Although the inclusion of new processes represents an important advancement, and allows for revised global mean sea level rise (GMSLR) estimates for the twenty-first century and beyond (101, 102), the exact dynamics and system thresholds are still subject to considerable uncertainty.

We have applied this updated methodology (101) to illustrative 1.5°C and 2°C pathways from Reference 103 (and used in 19), which allows for direct intercomparison of projections with and without updated Antarctic ice sheet instabilities. Projections presented in Schleussner et al. (19) are based on a scaling methodology introduced in Perrette et al. (104) that does not account for such potential instabilities. **Figure 6** shows updated GMSLR projections based on a recently



Figure 6

Projections of GMSLR for illustrative 1.5°C and 2°C emission scenarios from Schleussner et al (19). (*a*,*b*) Probabilistic GMT projections for illustrative emission scenarios with a peak warming of 1.5° C (*a*,*c*) and 2° C (*b*,*d*) above preindustrial levels during the 21st century. (*c*,*d*) probabilistic GMSLR projections relative to 1986–2005 levels based on a methodology introduced by Nauels et al. (101). Uncertainty bands indicate the likely range (66% probability) and the very likely range (90% probability), respectively. Abbreviations: GMSLR, global mean sea level rise; GMT, global mean surface air temperature.

	1.5°C		2°C	
	NAUE	SCHLEU	NAUE	SCHLEU
2081–2100 GMSLR [c]	0.41 [0.27, 0.57]	0.37 [0.27, 0.48]	0.55 [0.37, 0.84]	0.44 [0.32, 0.57]
2100 GMSLR [c]	0.44 [0.29, 0.61]	0.41 [0.29, 0.53]	0.60 [0.40, 0.96]	0.5 [0.36, 0.65]
2041–2060 GMSLR rate [mm/year]	4.7 [3.3, 6.5]	4.6 [3.2, 5.8]	6.8 [4.7, 9.6]	5.6 [4.0, 7.0]
2081–2100 GMSLR rate [mm/year]	3.1 [1.9, 4.9]	4.0 [2.7, 5.5]	5.8 [3.8, 12.5]	5.6 [3.8, 7.7]

Table 2Projections of global mean sea level rise (GMSLR) relative to 1986–2005 levels based on a methodology appliedby Schleussner et al. (19; SCHLEU) and Nauels et al. (101; NAUE)^{a,b}

^aData are from Figure 6.

^bSquare brackets give the likely (66%) range.

developed comprehensive sea level emulator (101, 105), coupled with the simple climate carboncycle model MAGICC6 (106). The illustrative 1.5°C and 2°C pathways used here limit median peak warming to 1.5°C and 2°C. As a result of uncertainty in the climate response, the probabilistic 600-member ensemble of future GMT trajectories thereby includes pathways that exceed these target warming levels by a substantial margin (compare with the upper panel of **Figure 6**). The sea level projections presented here are tied to the emission scenarios and consequently include projections for trajectories exceeding the target warming levels of 1.5°C and 2°C.

Table 2 provides a direct comparison of sea level projections based on the methodologies in Schleussner et al. (19; hereinafter SCHLEU) and Nauels et al. (101; NAUE). Projections for 1.5°C are consistent between the methods, with the noticeable difference that although the midcentury rate of rise is similar between both methods (median of 4.6 and 4.7 mm/year, respectively), the slowdown of sea level rise after a peak in global mean temperature in NAUE is much more pronounced, leading to a median 2081–2100 rate of rise in global sea level rise of approximately 3 mm/year compared to 4 mm/year in SCHLEU.

For the 2°C scenario, however, the effects of ice sheet instability could lead to substantially higher sea level rise. The NAUE 2100 median sea level rise estimate is 60 cm and thereby 10 cm or 20% higher than the 50 cm estimated in SCHLEU and approximately 36% higher than for 1.5°C. The difference is even more pronounced for the upper end of the likely range that is approximately 30 cm higher in the NAUE estimate close to 1 m in 2100.

The end-of-century rate of rise based on NAUE is almost twice as high in a median 2°C scenario than in the 1.5°C scenario (5.8 mm/year versus 3.1 mm/year, respectively). This points to a potentially much higher sea level commitment beyond 2100 in a 2°C scenario. In summary, the inclusion of new processes leads to more pronounced differences in sea level projections between 1.5°C and 2°C already in 2100. These differences are expected to increase even more in the longer term.

Sea level rise, however, is not globally uniform and is affected both by dynamical as well as gravitational effects (104, 107). Furthermore, local sea level rise depends also on other dynamics such as land subsidence, groundwater pumping, or geological processes (108). Metropolitan areas in particularly vulnerable coastal regions, such as New York City, will face considerable adaptation challenges in the future (109). The tropics are among the regions with highest projected regional sea level rise including low-lying coastal deltas in South Asia and small islands (108). These regions may also experience the fastest increase in extreme sea levels. Already under a sea level rise of 25 cm, a current 1-in-50-year extreme water level may occur annually (110). Rising seas in tropical regions will exaggerate the destructive potential of tropical cyclones (111). Furthermore, extreme sea levels in the Pacific are strongly modulated by the El Niño Southern Oscillation (ENSO) (112) and are projected to become more frequent as the result of increasing frequency of extreme El Niño events (113).

Fisheries and Marine Ecosystems

Ocean warming accounts for approximately 90% of the additional energy added to the Earth system as a result of anthropogenic warming between 1971 and 2010 (114), and they absorbed approximately 20% of emitted CO₂ over the past decade (115). As a result, ocean systems and marine ecosystems are already undergoing drastic changes today and some marine extreme events observed today, such as the 2016 heat wave in the coral sea, are attributable in full to climate change (66). Time intervals between bleaching events have steadily been decreasing (116) and impacts on coastal and marine organisms as well as ecosystem services are already widespread at current levels of warming and atmospheric CO₂ concentrations. They will become severe for warming around 1.5°C in particular for tropical ecosystems and fisheries (117). Warm water corals are already heavily impacted by the combined effects of pollution, fisheries, ocean acidification, and marine heat waves (118), and warming beyond 1.5°C will condemn virtually all of these unique and precious systems to long-term degradation (119, 120).

The spatial distribution of species is expected to undergo large irreversible shifts in the distribution in response to further warming by 1°C (121). This has consequences for the availability of potential catch at any given location. An observed and projected poleward migration of tropical species implies reduction in maximum catch potential in most parts of the tropics and subtropics, with the exception of the Indian Ocean (121). At the same time, marine deoxygenation will represent a major stressor to marine ecosystems already for warming levels around 1.5°C and even more so for higher levels of warming (122).

HOTSPOTS

In the following, we link the changes in climate hazards to a review of contextual vulnerabilities for the hotspot regions identified in **Figure 1**. This allows for a regional-specific assessment of changes in climate risks between 1.5°C and 2°C. We discuss the effects on tropical coastal regions and low-lying land separately from the land-based effects for these regions.

Sub-Saharan Africa

Africa has been identified as one of the most vulnerable continents to climate change due to its high exposure to climate stress and low adaptive capacity (e.g., poor infrastructure, limited access to markets, high illiteracy rates) (123). Climate change superimposed on the region's typical high interannual and spatial rainfall variability will pose severe challenges to the development of most countries in the region. West Africa is already experiencing a warming of 1°C since 1950 (124). In the case of the Sahel, the average warming since 1950 is even higher, especially during the spring (more than 2°C) (125). The recent decades have been characterized by the emergence of a warming trend independent of precipitation behavior (126), by a partial recovery of the rains since persistent late twentieth century drought (127) and by increased variability on all timescales, with alternation of years of drought and abundant rains, as well as recurrence of dry spells and heavy precipitation events within a year (128–130). For the future, under the RCP 4.5 scenario, warming temperatures for West Africa are estimated at 3°C and at 6°C under the RCP 8.5 scenario, which represents a warming of 60% higher than the global average warming of the planet (131). Regarding precipitation, many uncertainties remain for the region; however, the western Sahel might expect a decrease in total annual precipitations, whereas the eastern Sahel might observe an increase (131).

Limiting end-of-century warming to 1.5°C will robustly reduce the frequency of heat extremes compared to 2°C in Africa (132). In Southern Africa for instance, risk of devastating extreme climatic events such as the 1991–1992 heat wave could be reduced by 25%.

Rising temperatures, changing precipitation patterns and rising sea levels will impact natural resources and exacerbate already existing environmental stresses such as soil and land degradation and coastal erosion. Agriculture is predominantly rainfed (more than 90%) and consequently highly sensitive to climatic variation (133). The agriculture sector employs 60% of the active population but contributes only 35% of the Gross Domestic Product (GDP) (134). Increasing climate hazards may thereby directly compromise ecosystem services, local food and water supplies, local economies, and livelihoods. Increasingly extreme climatic conditions (69) translate into recurrent flooding, emerging infectious diseases, urban and rural food shortages, and economic damage, which are likely to continue in the near future (123, 135).

South Asia

South Asia (comprising the seven countries India, Bangladesh, Pakistan, Sri Lanka, Nepal, Bhutan, and Maldives) has a total population of approximately 1.75 billion people, which is projected to rise to more than 2.2 billion by 2050 (136, 137). Three of the most populated countries of the region (India, Pakistan, and Bangladesh) have been featured among the worst affected countries in the world by climate change in the Germanwatch long-term vulnerability index (138). Although the economic transformation in the region is happening rather quickly, albeit at uneven speed, toward industrial and services sectors, agriculture has remained the mainstay of the South Asian economy for centuries. At the same time, the region has a high incidence of poverty with 256 million people living under \$1.90 a day, hence making them the most vulnerable in the face of climate change, as their ability to bear risk is extremely low (136). According to some estimates, 67% of the South Asian population lives in rural areas, most of whom make their living by depending on the natural resources that surround them, i.e., land, water, and coastal fisheries (136). The agriculture sector has remained the largest employer in South Asia, providing 44% of the total employment (136), and it is heavily dependent on water resources and strongly connected to the South Asian Summer Monsoon rainfall as well as snow and glacier melt from the Hindukush-Karakoram-Himalayan region. Climate change is exacerbating the vulnerability of both of these resources. As well, a recent analysis of extreme flows of the Brahmaputra River, which crosses large parts of China, India, and Bangladesh, shows that flood risk in the Brahmaputra River basin could be reduced by half at 1.5°C warming relative to 2°C (139). Another recent study shows similar avoided risk estimates at 1.5°C for the Ganges basin (140). They further identify several countries in sub-Saharan Africa and South and East Asia to be particularly vulnerable to food insecurity as a result of changes in climate extremes and freshwater availability at both 1.5 and 2°C (140). At the same time, extreme heat stress and related drought are compromising local food production, and crop production failure may have contributed to the suicides of nearly 60,000 Indian farmers and farm workers over the recent years (141).

Figure 3 indicates an increase in heavy precipitation events over South Asia for 1.5 and 2°C warming, which is in line with the trends in recent years during which the region has witnessed devastating floods. Pakistan experienced its worst flooding in July–August 2010, which resulted in 1,700 fatalities and disruptive impacts on 20 million people (142). In 2013, northern parts of India and Pakistan experienced another flooding once again, resulting in more than 5,800 deaths and impacting hundreds of thousands of people (143). Heavy floods following unusually heavy monsoon rains killed more than 1,200 people and affected 43 million people in Bangladesh, Nepal, and India in July 2017 (144).

The region is also specifically vulnerable to heat stress, which is also projected to increase significantly between 1.5 and 2°C warming, as shown in **Figure 3**. Heat waves have intensified globally in the recent years and are projected to increase strongly over South Asia under all warming

scenarios (145, 146). Future heat waves are expected to exceed by the end of the century the human survivability threshold in the densely populated Indus and Ganges river basin areas in South Asia under business-as-usual scenarios (RCP 8.5) (147). However, limiting global temperatures to 1.5 °C instead of following the business-as-usual scenario (RCP 8.5) would reduce the exposure by half by the mid-twenty-first century for India (148).

Extreme heat has substantial negative impacts on health, but also labor productivity in the region (70). Over Pakistan, heat stress has been found to affect the farm and nonfarm income, which consistently increases the long-term migration of laborers (149). Therefore, the increase in heat stress may increase rural to urban migration, expanding the cities, and hence making the urban population more vulnerable to heat extremes in the future (150).

Tropical Coastal Areas and Low-Lying Land

Coastal areas and low-lying land are both increasingly exposed and vulnerable to hazards from sea level rise, extreme weather events such as cyclones, and ocean temperature and acidity changes, resulting in significant impacts across all timescales (151). Exposure to coastal hazards impacting human systems is generally assessed by quantifying the number of people, area of land, or value of economic activities that are located within different elevations above sea level. Countries in South, Southeast, and East Asia have particularly high population densities in deltas, exposing significant percentages of national populations and financial assets to coastal hazards (152–154). In Africa, rapid population growth in coastal cities along with existing concentrations of population and economic activity in coastal areas have led to assessments of high exposure (153, 155, 156). Scenarios of future demographic changes and socioeconomic growth project that developing countries in Asia and Africa are expected to experience the highest rates of population growth and urbanization in coastal areas, resulting in increased exposure to coastal hazards (157). Although the small size of SIDS often results in their exclusion from large-scale studies (158, 159), these nations are recognized as being among the most exposed groups to coastal hazards due to their limited adaptive capacity and prospects of complete submersion of islands (160, 161).

Globally, an estimated 189 million people have been living in low-lying coastal zones exposed to 1-in-100-year flood events in 2000. This number is estimated to increase to between 315 and 411 million people in 2060, assuming a low population growth scenario (157). On the basis of current population estimates, recent research accounting for suggested additional Antarctic dynamics projects close to 100 million people at risk of permanent inundation in 2100 under a scenario with a likely chance to stay below 2.0°C of warming, as opposed to approximately 150 million people under a business-as-usual pathway (102).

Regional sea level rise can be enhanced by non-climate-related anthropogenic interferences such as ground subsidence due to extraction of groundwater or reduced river sediment supply to coastal areas due to construction of dams (153). These human activities increase the exposure of coastal systems and will be exacerbated by population growth in coastal zones throughout the twenty-first century, particularly in developing regions (158).

Level of income and development play a significant role in vulnerability of coastal areas and low-lying land to climate hazards. Whereas industrialized countries often have long histories of assessing, planning for, and responding to coastal change (162, 163), many developing countries face capacity constraints that impede similar efforts (164, 165). The significant impacts that may result from coastal hazards have led to cost-benefit analyses that advocate for widespread protection of developed coastal areas (166, 167). However, such adaptation strategies are not applicable to countries with extensive coastal zones or with low levels of socioeconomic development due to exorbitant costs. The lack of institutions, experience, and financial resources for coastal management thus contributes to limited adaptive capacity and increased vulnerability of developing countries with coastal areas and low-lying land.

Consequently, impacts of coastal hazards are most significant for low-income, low-lying coastal regions (168). Impacts include submergence of coastal areas, increased storm surges, flooding of land, saltwater intrusion, coastal erosion, and loss of coastal wetlands and their related ecosystem services (151). These biophysical changes also result in significant socioeconomic and cultural effects. For vulnerable regions, coastal hazards may precipitate the decline of entire industries such as coastal tourism and the loss of livelihoods including fisheries (156). Essential infrastructure in coastal regions such as wastewater systems could be compromised, leading to significant damage and loss of essential services (169). Ultimately, coastal hazards, particularly sea level rise, can result in the displacement of coastal populations (170).

Small Islands

For SIDS, intrinsic characteristics including relatively small physical sizes and concentration of infrastructure, economic activities, and population in coastal zones contribute to high contextual vulnerability (45, 46). At the same time, small island nations are particularly exposed to climate hazards, including tropical cyclones and sea level rise, at times threatening their very existence. Storlazzi et al. (171) project that most Atoll islands will be uninhabitable by mid-century, underscoring the need for robust mechanisms related to loss and damage to support small island states (172, 173).

In addition, observed and projected impacts on coastal ecosystems, especially on coral reefs, severely threaten livelihoods in island regions and are projected to cause extensive economic damages (174). These adverse impacts are amplified as coastal and marine ecosystems provide many critical services without which small island communities would be far more vulnerable to climate change impacts, including coastal protection and access to a local source of protein. Approximately 70% of protein in the diet of Pacific islanders is derived from near-shore pelagic and inshore reef and lagoon fisheries (175). A vulnerability assessment of reef-dependent communities to ocean acidification impacts in the Pacific (176) found that high ratios of reef to land area, dependence of household incomes on coastal fisheries, and limited education were key components of low adaptive capacity and were all significant drivers of vulnerability.

Small islands also have especially sensitive freshwater supply systems, and water stress is likely to pose a serious threat (177, 178). Freshwater availability will be reduced at 1.5°C for Caribbean and South Pacific islands and further reduced at 2°C (179). In conjunction with population growth, this might lead to a substantial increase in freshwater stress. Increased intensity of extreme events and changes in temperature and precipitation patterns also have dire implications for economic, social, and cultural structures in SIDS (180, 181). Extreme events such as tropical cyclones impede adaptation efforts and therefore further reinforce vulnerability.

DISCUSSION AND OUTLOOK

Integrating changing climate hazards with future trajectories of exposure and vulnerability is at the heart of the scenario approach under the upcoming Coupled Model Intercomparison Project 6 (CMIP6) linking the RCPs with the shared socioeconomic pathways (SSPs) (182). Given the differences between the different SSPs in relation to vulnerability and adaptation challenges, future impact differences may depend at least as much on scenarios of socioeconomic development as on differential climate hazards. At the same time, sustainable development trajectories are

enabling very stringent mitigation pathways (183), illustrating the substantial potential for cobenefits between climate mitigation and sustainable development (184).

However, such integrated scenarios are not yet available for assessing differential climate impacts at 1.5°C. In this review, we have aimed to fill this gap by assessing differential climate hazards and interlinking those with contextual vulnerability in hotspot regions of interest. Figure 7 provides an overview of some of the key climate hazard differences identified between 1.5°C and 2°C. There are clear limitations to our approach. We do not provide a systematic assessment of differential vulnerabilities across regions. Other regions that are missing from our analysis, but will experience substantial changes in climate hazards between 1.5°C and 2°C, include, for example, high mountainous regions and the Arctic. Similarly, the Mediterranean region emerges as a hotspot region for drying between 1.5°C and 2°C. Reductions in Mediterranean annual water



Figure 7

Projected impacts at 1.5°C and 2°C GMT increase above preindustrial levels for a selection of indicators and regions. (*a*) Global hot extremes. Increase in global occurrence probability of preindustrial 1-in-1,000-day extreme temperature events (188). (*b*) Extreme precipitation. Increase in extreme precipitation intensity (RX5Day) for the global land area below 66°N/S and South Asia (19). (*c*) Mediterranean water availability. Reduction in annual water availability in the Mediterranean (19). (*d*) Coral reef degradation. Share of global tropical coral reefs at risk of long-term degradation (189). (*e*) Multimillennial sea level rise. Global sea level rise commitment for persistent warming of 1.5°C and 2°C over 2,000 years (190). (*f*) Local yields of tropical agricultural area. Changes in local crop yields for present-day tropical agricultural areas (19) [below 30°N/S; model dependent on implementation of present day management (84)]. (*Dashed baxes*) No increase in CO₂ fertilization. Panels *b*, *c*, and *f* display median changes that exceed more than 50% of the respective land areas. Figure reprinted from Reference 2.

availability might double between 1.5°C and 2°C to up to 20% compared to the recent past (19), with far-reaching effects in this already water-scarce region for agricultural production, tourism, and ecosystems. Guiot & Cramer (185) have estimated that a warming of 2°C would cross a tipping point for Mediterranean ecosystems into a new climate regime unprecedented over the Holocene. At the same time, increasing drought conditions may contribute to security challenges in the region (186) that, being a major food importing region, is also highly vulnerable to teleconnected climate impacts on food production (187).

Furthermore, our review of vulnerability factors is limited to regional and national scales. However, vulnerability factors such as gender or belonging to an ethnic minority are also effective at smaller scales (37) and need to be considered. Nonetheless, providing regionally specific information on exposure together with a first assessment of vulnerability factors in strongly exposed regions provides useful details beyond global averages.

For most of the regions and indicators investigated here, we find that increasing climate hazards under 1.5°C, which could materialize as early as the 2030s, are met by high present-day vulnerability, indicating substantial adaptation challenges. Illustrated by the risks posed by sea level rise, but also impacts on marine ecosystems such as tropical coral reefs, or extreme heat and agriculture potentials, substantial climate-related loss and damage (173) will be inflicted also under warming levels of 1.5°C, but will rise steeply with any further warming. Several countries in sub-Saharan Africa and South and East Asia have been found to be at risk of food insecurity as a result of changes in climate extremes and freshwater availability at both 1.5 and 2°C (165). Even the most stringent warming targets, although avoiding the worst impacts of climate change, will not spare the most vulnerable.

SUMMARY POINTS

- 1. Climate impacts are projected to increase in a world 1.5°C above pre-industrial levels and even more so in a 2°C world.
- 2. These projected changes are not distributed evenly, and it would be vulnerable countries and regions that bear the brunt of the additional impacts between 1.5°C and 2°C.
- Assessing changes in climate hazards at different levels of warming in conjunction with regional specific vulnerabilities allows for an integrated perspective on the differences in climate impacts between 1.5°C and 2°C.

FUTURE ISSUES

- 1. Since changes in climate impacts at different warming levels depend on a variety of geophysical and socioeconomic factors, an integrated scenario perspective will help to provide consistent assessments of future impacts at 1.5°C.
- To fully assess the relevance of projected differences in climate impacts between 1.5°C and 2°C, an adaptation perspective is required.
- Linking estimates of future adaptation potential, capacity, as well as limits to adaptation to projected changes in climate would allow for a more realistic view on future impacts and loss and damage.

DISCLOSURE STATEMENT

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