Paris Agreement's aim of 1.5°C warming may result in many possible climates

Sonia I. Seneviratne[1], Joeri Rogelj[1,2,4], Roland Séférian[3], Richard Wartenburger[1], Myles R. Allen[4], Michelle Cain[4], Richard J. Millar[4], Kristie L. Ebi[5], Neville Ellis[6], Ove Hoegh-Guldberg[7], Antony J. Payne[8], Carl-Friedrich Schleussner[9,10,11], Petra Tschakert[6], and Rachel F. Warren[12]

1. Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland
2. International Institute for Applied Systems Analysis (IIASA), Laxenburg A-2361, Austria
3. Centre National de Recherches Météorologiques, Météo-France/CNRS, Toulouse, France
4. Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, UK
5. University of Washington, Department of Global Health, Seattle, USA
6. University of Western Australia, UWA School of Agriculture and Environment, Perth, Australia
7. Global Change Institute, University of Queensland, Brisbane, Australia
8. University of Bristol, Bristol, UK
9. Climate Analytics, Berlin, Germany
10. IRITHESys, Humboldt University, Berlin, Germany
11. Potsdam Institute for Climate Impact Research, Potsdam, Germany
12. Tyndall Centre for Climate Change, School of Environmental Sciences, University of East Anglia, Norwich, UK

March 27, 2018, revised

The UN Paris Agreement[1] includes an aim of pursuing efforts to limit global warming to only 1.5°C above pre-industrial levels. Would such efforts limit climate risks evenly? Here we show that trajectories to "1.5°C warmer worlds" may result in vastly different outcomes at regional scales, due to variations in the pace and location of climate change and their interactions with society's mitigation, adaptation, and vulnerabilities to climate change. Pursuing policies considered consistent with 1.5°C will not completely remove the risk of global temperatures being much higher or regional extremes reaching dangerous levels for ecosystems and society over the coming decades.

Since 2010, international climate policy under the United Nations moved the public discourse from a focus on atmospheric concentrations of greenhouse gases to a focus on distinct global temperature targets above the pre-industrial period[1,2]. In 2015, this led to the inclusion of a long-term temperature goal in the Paris Agreement that makes reference to two levels of global mean temperature increase: 1.5°C and 2°C. The former is set as an ideal aim ("pursuing efforts to limit the temperature increase to 1.5°C") and the latter is set as an upper bound ("well below 2°C")[1]. This change in emphasis allows a better link between mitigation targets and the required level of adaptation ambition[3,4].

Assessing the effects of the reduction of anthropogenic forcing through a single qualifier, namely global mean temperature change compared with the pre-industrial climate, however, also entails risks. This deceivingly simple characterization may lead to an oversimplified perception of human-induced climate change and of the potential pathways to limit impacts of greenhouse gas forcing. We highlight here the multiple ways in which a 1.5°C global warming may be realized. These alternative "1.5°C warmer worlds" are related to a) the temporal and regional dimension of 1.5°C pathways, b) model-based spread in regional climate responses, c) climate noise, d) and ranges of possible options for mitigation and adaptation. We also highlight potential high-risk temperature outcomes of mitigation pathways currently considered consistent with 1.5°C due to uncertainties in relating greenhouse gas emissions to subsequent global warming, and to uncertainties in relating global warming to associated regional climate changes.

Definition of a "1.5°C warming"

Global mean temperature is a construct: It is the globally averaged temperature of the Earth that can be derived from point-scale ground observations or computed in climate models. Global mean temperature is defined over a given time frame (e.g. averaged over a month, a year, or multiple decades). As a result of climate variability, which is due to internal variations of the climate system and temporary naturally-induced forcings (e.g. from volcanic eruptions), a climate-based global mean temperature typically needs to be defined over several decades (at least 30 years under the definition of the World Meteorological Organization)[5]. Hence, to determine a 1.5°C global temperature warming, one needs to agree on a reference period (assumed here to be 1850-1900 inclusive, unless otherwise indicated), and on a time frame over which a 1.5°C mean global warming is observed (assumed here to be of the order of one to several decades). Comparisons of global mean temperatures from models and observations are also not straightforward: Not all points over the Earth's surface are continuously observed, leading to methodological choices about how to deal with data gaps[6] and the mixture of air temperature over land and water temperatures over oceans[7] when comparing full-field climate models with observational products.

Temporal and spatial dimensions

There are two important temporal dimensions of 1.5°C warmer worlds: a) the time period over which the 1.5°C warmer climate is assessed; and b) the pathway followed prior to reaching this temperature level, in particular whether global mean temperature returns to the 1.5°C level after previously exceeding it for some time (also referred to as "overshooting", Figure 1a). As highlighted hereafter, for some components of the coupled Human-Earth system, there are substantial differences in risks between 1.5°C of warming in the year 2040, 1.5°C of warming in 2100 either with or without earlier overshooting, and 1.5°C warming after several millennia at this warming level.

The time period over which 1.5°C warming is reached is relevant because some slow-varying elements of the climate system respond with a delay to radiative forcing, and the resulting temperature anomalies. Hence their status will change over time, even if the warming is stabilized at 1.5°C over several decades, centuries, or millennia. This is the case with the melting of glaciers, ice caps and ice sheets and their contribution to future sea level rise, as well as the warming and expansion of the oceans, so that a substantial component of contemporary sea-level rise is a response to past warming. In addition, the rate of warming is also an important element of imposed stress for resulting risks, because it may affect adaptation or lack thereof[8,9,10]. For example, the faster the rate of change the fewer taxa (and hence ecosystems) can disperse naturally to track their climate envelope across the Earth's surface[8,11]. Similarly, in human systems, faster rates of change in climate variables such as sea level rise present increasing challenges to adaptation to the point where attempts may be increasingly overwhelmed.

Whether mean global temperature temporarily overshoots the 1.5°C limit is another important consideration. All currently available mitigation pathways projecting less than 1.5°C global warming by 2100 include some probability of overshooting this temperature, with some time period during the 21st century in which warming higher than 1.5°C is projected with greater than 50% probability[12,13,14,15]. This is inherent to the difficulty of limiting warming to 1.5°C given that the Earth at present is already very close to this warming level (ca. 1°C warming for the current time frame relative to 1851-1900[16]). The implications of overshooting are very important for projecting future risks and for considering potentially long-lasting and irreversible impacts in the time frame of the current century and beyond, for instance associated with ice melting[17] and resulting sea level rise, loss of ecosystem functionality and increased risks of species extinction[11], or loss of livelihoods, identity, and sense of place and belonging[18]. Overshooting might cause the temporary exceedance of some thresholds for example in ecosystems, which might be sufficient to cause permanent loss of these systems; or, those systems and species able to adapt rapidly enough to cope with a particular rate of change would be faced with the challenge of adapting again to a lower level of warming post-overshoot. The chronology of emission pathways and their implied warming is also important for the more slowly evolving parts of the Earth system, such as those associated with sea level rise (see above).

On the other hand, to minimize the duration and magnitude of the exceedance above a 1.5°C level of warming (overshooting), the remaining carbon budget available for emissions is very small, implying that deeper global mitigation efforts are required immediately (next section; see also Table 1 and Box 1).

The spatial dimension of 1.5°C warmer worlds is also important. Two worlds with similar global mean temperature anomalies may be associated with very different risks depending on how the associated regional temperature anomalies are distributed (Fig. 1b). Differential geographical responses in temperature are induced by: a) spatially varying radiative forcing (e.g. associated with land use[19,20,21] or aerosols[22]; b) differential regional feedbacks to the applied radiative forcing (e.g. associated with soil moisture-, snow, or ice feedbacks[4,23]); and/or c) regional climate noise[24] (e.g.

associated with modes of variability or atmospheric weather variability). Similar considerations apply to regional changes in precipitation means and extremes, which are not globally homogeneous[3,4]. These regional temperature and precipitation anomalies and their rates of change determine the regional risks to human and natural systems and the challenges to adaptation which they face.

We note that mitigation, adaptation, and development pathways may result in spatially varying radiative forcing. While greenhouse gases are well mixed, changes in land use or air pollution may strongly affect regional climate. Land-use changes can be associated, for example, with the implementation of increased bioenergy plantations[25], afforestation, reforestation, or deforestation, and their resulting impacts on local albedo or evapotranspiration; levels of aerosol concentrations may vary as a result of decreased air pollution[22]. Considering these regional forcings is essential when evaluating regional impacts, although there is still little available literature for 1.5°C warmer worlds, or low-emissions scenarios in general[22,26,27,28]. The spatial dimension of regional climates associated with a global warming of 1.5°C is also crucial when assessing risks associated with proposed climate engineering schemes based on solar radiation management (see hereafter). Beside the geographical distribution of changes in climate, non-temperature related changes are important, particularly where atmospheric CO_2 has additional and serious impacts through phenomena such as ocean acidification.

Uncertainties of emissions pathways

Emissions pathways that are currently considered to be compatible with limiting global warming to 1.5°C[12,13,14,15] are selected based on their probability of limiting warming to below 1.5°C by 2100 given current knowledge of how the climate system is likely to respond. Typically, this probability is set at 50% or 66% (i.e. 1/2 or 2/3 chances, respectively, of limiting warming in 2100 to 1.5°C or lower). The adequacy of these levels of probability is rather a political than a scientific question. This implies that even when diligently following such 1.5°C pathways from today onwards, there is considerable probability that the 1.5°C limit will be exceeded. This also includes some possibilities of warming being substantially higher than 1.5°C (see hereafter for the 10% worst-case scenarios). These risks of alternative climate outcomes are not negligible and need to be factored into the decision-making process.

Table 1 provides an overview of the outcomes of emissions pathways that are currently considered 1.5°C- and 2°C-compatible with a specific probability[15] (and broadly consistent with the literature assessed in the IPCC AR5[12,14], see Box 1 and Supplementary Information). Both "probable" (66th percentile, which remains below the respective temperature targets) and "worst-case" (10% worst, i.e. high-end) outcomes of these pathways are presented, including resulting global temperatures and regional climate changes (see next section and Box 1 for details, and Supplementary Information for median outcomes). The reported net cumulative CO_2 emissions characteristics for these scenario categories include effects of carbon dioxide removal options (CDR, also termed "negative emissions"[29]), which explains the decrease in cumulative CO_2 budgets after peak warming. Possible proposed CDR approaches include bioenergy use with carbon capture and storage (BECCS) or afforestation and changes in agricultural practice increasing carbon sequestration on land[29]. We note that the use of these approaches is controversial and could entail own sets of risks, for instance related to competition for land use[30,31]. Their implementation is at present also still very limited, and the feasibility of their deployment as simulated in low-emissions scenarios has been questioned[32]. Current publications[12,14,15] indicate that scenarios in line with limiting year-2100 warming to below 1.5°C require strong and immediate mitigation measures and would require some degree and some kind of CDR. Alternative scenario configurations can be considered to limit the amount of CDR[32,33]. The current scenarios[15] as well as recent publications[34,35,36] provide updated cumulative CO_2 budgets estimates, which have larger remaining budgets compared to earlier estimates[12,14]. These, however, do not fundamentally change the need for strong near-term mitigation measures and technologies capable of enabling net-zero global CO_2 emissions near to mid-century if the considered emissions pathways are to be followed.

Global and regional climate responses

Considering a subset of regions and extremes shown to retain particularly strong changes under a global warming of 1.5°C or 2°C[4,37], Table 1 provides corresponding regional responses for the evaluated 1.5°C- and 2°C-compatible emissions pathways. The Figures 2 and 3 display associated regional changes for a subset of considered extremes: temperature extremes (coldest nights in the Arctic, warmest days in the contiguous United States) and in heavy precipitation (consecutive 5-day maximum precipitation in Southern Asia). Changes in hot extremes in Central Brazil and in drought occurrence in the Mediterranean region are additionally provided in Table 1. We note that the spread displayed for single scenario subsets in Figures 2 and 3 correspond to the spread of the global climate simulations of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) underlying the derivation of the regional extremes for given global temperature levels[4,37] (see Box 1 for details).

In terms of the resulting global mean temperature increase, Figure 2 shows that the difference between the 10% "worst-case" and the "probable" (66%) outcome of the scenarios is substantial, both for the 1.5°C and 2°C scenarios. Interestingly, the "worst-case" outcomes from the 1.5°C scenarios are similar to the probable outcome of the 2°C scenarios. Indeed, both of these show less than 2°C warming by 2100, and approximately 2°C in the overshoot phase, while the warming in the overshoot phase can be slightly higher for the "worst-case" 1.5°C than for the probable 2°C scenarios assessed here. Hence, the scenarios aiming at limiting global warming to 1.5°C also have a clear relevance for limiting global warming to 2°C[13], in that they ensure that the 2°C threshold is not exceeded at the end of the 21st century. This contrasts with pathways designed to keep warming to 2°C, but have a 10% high-end ("worst-case") warming of more than 2.4°C. This result is important when considering a 2°C warming as a "defence line" that should not be exceeded[2].

Assessing changes in regional extremes illustrate the importance of considering the geographical distribution of climate change in addition to the global mean warming. Indeed, the average global warming does not convey the level of regional variability in climate responses[4]. By definition, because the global mean temperature is an average in time and space, there will be locations and time periods in which 1.5°C warming is exceeded even if the global mean temperature rise is restrained to 1.5°C. This is even already the case today, at about 1°C of global warming compared to the preindustrial period[16]. Similarly, some locations and time frames will display less warming than the global mean.

Extremes at regional scales can warm much more strongly than the global mean. For example, in scenarios compatible with 1.5°C global warming, minimum night-time temperatures (TNn) in the Arctic can increase by more than 7°C at peak warming if the "probable" (66th percentile) outcome of scenarios materializes, and more than 8°C if the "worst-case" (highest 10%, i.e. 90th percentile) outcome of the scenarios materializes (Fig. 2). For the "worst-case" outcome of scenarios considered 2°C compatible, the changes in these cold extremes is even larger, and can reach more than 9°C at peak warming (Fig. 2). While the change is more limited for hot extremes (annual maximum mid-day temperature, TXx) in the contiguous United States, it is also substantial there. At peak warming, these hot extremes can increase by more than 4°C for the probable 1.5°C scenarios (maximum in 66% of the cases), and can reach up to 5°C warming for the "worst-case" 1.5°C scenarios and slightly less for the highest "probable" 2°C scenarios. If the 10% "worst-case" temperature outcome materializes after following a pathway considered 2°C-compatible today, the temperature increase of the hottest days (TXx) can exceed 5°C at peak global warming in that region (Fig. 2).

These analyses also reveal the level of inter-model range in regional responses, when comparing the full spread of the CMIP5 distributions (Fig. 2). This interquartile range reaches about 2°C for TNn in the Arctic and 1°C for TXx in the contiguous US at peak warming, i.e. it is 2-4 times larger than the difference in global warming at 1.5°C vs 2°C. The intermodel range is also very large for changes in heavy precipitation in Southern Asia (Fig. 2), with an approximate doubling of the response at peak warming for the 75th quantile in the most sensitive models compared to the 25th quantile in the least sensitive models. This highlights that uncertainty in regional climate sensitivity to given global warming levels is an important component of uncertainty in impact projections in low-emissions scenarios (similarly as uncertainty in mitigation pathways or the global transient climate response). Indeed, in cases showing a high regional climate sensitivity (either due to model specificities or internal climate variability), the tail values of the climate model distributions for "probable" 1.5°C-scenario outcomes overlap or even exceed likely values for the worst-case 2°C-scenario outcome (Fig. 2). This thus shows that even under most stringent mitigation (1.5°C) pathways, some risk of dangerous changes in regional extremes (i.e. equivalent or stronger than expected responses at 2°C global warming) cannot be excluded.

Whilst most climate change risk assessments factor in the inter-model range of regional climate responses, relatively few consider the effects of extreme weather, for example the temperature increase of hottest days (TXx). Emerging literature highlights how these extreme events strongly influence levels of risk to human and natural systems, including crop yields[38] and biodiversity[39], suggesting that the majority of risk assessments based on mean regional climate changes alone are conservative in that they do not incorporate the effects of extreme weather events. In addition, the co-occurrence of extreme events is also of high relevance for accurately assessing changes in risk, although analyses in this area are still lacking[40,41].

Hence, the regional analyses of changes in extremes for scenarios aiming at limiting warming to 1.5°C and 2°C highlight the following main findings:

- Some regional responses of temperature extremes will be much larger than the changes in global mean temperature, with a factor of up to 3 (TNn in the Arctic).
- The regional responses at peak warming for scenarios that are considered today as compatible with limiting warming to 1.5°C (i.e. having 66% chance of stabilizing at 1.5°C by 2100) can still involve an extremely large increase in temperature in some locations and time frames, in the worst case more than 8°C for extreme cold night time temperatures or up to 5°C for daytime hot extremes (Fig. 2). We note that these numbers are substantially larger than for present-day variability (see Suppl. Information).
- The 10% highest response ("worst-case") temperature outcome of pathways currently considered compatible with 1.5°C warming is comparable with the 66th percentile outcomes ("probable") of scenarios that are considered for limiting warming below 2°C, at global and regional scales. This indicates that pursuing a 1.5°C compatible pathway can be considered a high-probability 2°C pathway[13] that strongly increases the probability of avoiding the risks of a 2°C warmer world.

Realization at single locations and times

The analyses of Figs. 2 and 3 represent the statistical response over longer time frames. Several dominant patterns of response are documented in the literature[4], for instance that land temperatures tend to warm more than global mean temperature on average, in particular with respect to hot extremes in transitional regions between dry and wet climates, and coldest days in high-latitudes (see also Figs. 2 and 3). Nonetheless, due to internal climate variability (and in part model-based uncertainty), there may be large local departures from this typical response at single points in time (any given year within a 10-year time frame) as displayed in Fig. 4. Many locations show a fairly large probability (25% chance) of temperature anomalies below 1.5°C, and in some cases even smaller anomalies (mostly for the extreme indices). On the other hand, there is a similar probability (25%, for 75th percentile) that some locations can display temperature increases of more than 3°C, and in some cases up to 7-9°C for cold extremes. This illustrates that highly unusual and even unprecedented temperatures may occur even in a 1.5°C climate. While some of the patterns reflect what is expected from the median response[4], the spread of responses is large in most regions.

Aspects insufficiently considered so far

The integrated assessment models used to derive the mitigation scenarios discussed here did not include several feedbacks that are present in the coupled Human-Earth system. This includes, for example, biogeophysical impacts of land use[26,26,27], potential competition for land between negative emission technologies and agriculture[29,31], water availability constraints on energy infrastructure and bioenergy cropping[30,31], regional implications of choices of specific scenarios for tropospheric aerosol concentrations, or behavioural and societal changes in anticipation of or response to climate impacts[33,42]. For comprehensive assessments of the regional implications of mitigation and adaptation measures, such aspects of development pathways would need to be factored in.

We note also that non-CO_2 greenhouse gas emissions have to be reduced jointly with CO_2. The numbers in Table 1 consider budgets for cumulative CO_2 emissions taking into account consistent evolutions for non-CO_2 greenhouse gas emissions. To compare the temperature outcome of pathways from many different forcings (e.g. methane, nitrous oxide), a CO_2-only emission pathway that has the same radiative forcing can be found, which is termed CO_2-forcing equivalent emissions (CO_2-fe)[43,44]. Hence stronger modulation in non-CO_2 greenhouse gas emissions could be considered in upcoming scenarios.

Furthermore, a continuous adjustment of mitigation responses based on the observed climate response (that can e.g. reduce present uncertainties regarding the global transient climate response) might be necessary to avoid undesired outcomes. Pursuing such “adaptive” mitigation scenarios[34] would be facilitated by the Global Stocktake mechanism established in the Paris Agreement. Nonetheless, there are limits to possibilities for the adaptation of mitigation pathways, notably because some investments (e.g. in infrastructure) are long-term, and also because the actual departure from a desirable pathway will need to be detected against the backdrop of internal climate variability. The latter can be large on decadal time scales as highlighted with the recent so-called “hiatus” period[45], but its impact can be minimized by using robust estimates of human-induced warming[16]. Hence, while adaptive mitigation pathways could provide some flexibility to avoid the highlighted "worst-case" scenarios (Table 1), it is not yet clear to which the extent they could be implemented in practice.

For a range of indicators, global mean temperature alone is not a sufficient indicator to describe climate impacts. CO_2 – sensitive systems, such as the terrestrial biosphere and agriculture systems, respond not only the impact of warming but also of increased CO_2 concentrations. Although the potential positive effects of CO_2 fertilisation are not well constrained[46], it appears that the impacts of anthropogenic emissions on those systems will depend not only on the warming inferred, but also on the CO_2 concentrations at which these warming levels are reached. Similarly, impacts on marine ecosystems depend on warming as well as on changes being driven by ocean acidification[47].

Impacts on ocean and cryosphere will respond to warming with a substantial time lag. Consequently, ice sheet and glacier melting, ocean warming and as a result sea level rise will continue long after temperatures have peaked[48]. For some of these impacts, this may imply limited detectable effects of mitigation pathways in the short-term, but major ones in the long-term[49]. Large-scale oceanic systems will also continue to adjust over the coming centuries. One study identified as a result a continued increase of extreme El Niño frequency in a peak-and-decline scenario[50]. The imprints on such time-lagged systems for different 1.5°C worlds are not well constrained at present.

Assessing solar radiation management (SRM)

Compared to any mitigation options, climate interventions such as global solar radiation management (SRM) do not intend to reduce atmospheric CO_2 concentration per se but solely to limit global mean warming. Some studies[51,52,53] proposed that SRM may be used as a temporary measure to avoid global mean temperature exceeding 2°C. However, the use of SRM in the context of limiting temperature overshoot might create a new set of global and regional impacts, and could substantially modify regional precipitation patterns as compared to a world without SRM[54,55]. It would also have a high potential for cross-boundary conflicts because of positive, negative or undetectable effects on regional climate[56], natural ecosystems[57] and human settlements. Hence, while the global mean temperature might be close to a 1.5°C warming under a given global SRM deployment, the regional implications could be very different from those of a 1.5°C global warming reached with early reductions of CO_2 emissions and stabilization of CO_2 concentrations. In some cases, some novel climate conditions would be created because of the addition of two climate forcings with different geographical footprints. Hence, a similar mean global warming may have very different regional implications (see Fig. 1b for an illustration) and in the case of SRM would be associated with substantial uncertainties in terms of regional impacts. Furthermore, SRM would not counter ocean acidification, which would continue unabated under enhanced CO_2 concentrations. Finally, there is also the issue that the sudden discontinuation of SRM measures would lead to a "termination problem"[52,58]. Together, this implies that the aggregated environmental implications of an SRM world with 1.5°C mean global temperature warming, would probably be very different, and likely more detrimental and less predictable, from those of a 1.5°C warmer world in which the global temperature is limited to 1.5°C through decarbonisation alone. Nonetheless, regional-scale changes in surface albedo may be worthwhile considering in order to reduce regional impacts in cities or agricultural areas[21], although in-depth assessments on this topic are not yet available, and such modifications would be unlikely to substantially affect global temperature.

Risks in 1.5°C warmer worlds

1.5°C warmer worlds will still present climate-related risks to natural, managed, and human systems, as seen above. The magnitude of the overall risks and their geographical patterns in a 1.5°C warmer world will, however, not only depend on uncertainties in the regional climate that result from this level of warming. The magnitude of risk will also strongly depend on the approaches used to limit warming to 1.5°C and on the wider context of societal development as it is pursued by individual communities and nations, and global society as a whole. Indeed, these can result in significant differences in the magnitude and pattern of exposures and vulnerabilities[59,60].

For natural ecosystems and agriculture, low-emissions scenarios can have a high reliance on land use modifications (either for bioenergy production or afforestation[25,29,61]) that in turn can affect food production and prices through land use competition effects[29,31,62]. The risks to human systems will depend on the ambition and effectiveness of implementing accompanying policies and measures that increase resilience to the risks of climate change and potential trade-offs of mitigation. For example, large-scale deployment of BECCS could push the Earth closer to the planetary boundaries for land use change and freshwater, biosphere integrity and biogeochemical flows[30] (in addition to pressures associated to development goals[63]).

Also the timing of when warming can be stabilized to 1.5°C or 2°C will influence exposure and vulnerability. For example, in a world pursuing a strong sustainable development trajectory, significant increases in resilience by the end of the century would make the world less vulnerable overall[59]. Even under this pathway, rapidly reaching 1.5°C would mean that some regions and sectors would require additional preparation to manage the hazards created by a changing climate.

Commonalities of all 1.5°C warmer worlds

Because human-caused warming linked to CO_2 emissions is near irreversible for more than 1000 years[64,65], the cumulative amount of CO_2 emissions is the prime determinant to long-lived permanent changes in the global mean temperature rise at the Earth's surface. All 1.5°C stabilization scenarios require net CO_2 emissions to be zero and non-CO_2 forcing to be capped to stable levels at some point[64,66,67]. This is also the case for stabilization scenarios at higher levels of warming (e.g. at 2°C), the only differences would be the time at which the net CO_2 budget is zero, and the cumulative CO_2 emissions emitted until then. Hence, a transition to a decarbonisation of energy use is necessary in all scenarios.

Article 4 of the Paris Agreement calls for net zero global greenhouse gas emissions to be achieved in the second half of the 21st century, which most plausibly requires some extent of negative CO_2 emissions to compensate for remaining non-CO_2 forcing[13]. The timing of when net zero global greenhouse gas emissions are achieved strongly determines the peak warming. All presently published 1.5°C-warming compatible scenarios include CDR to achieve net-zero CO_2 emissions, to varying degrees. CO_2-induced warming by 2100 is determined by the difference between the total amount of CO_2 generated (which can be reduced by early decarbonisation) and the total amount permanently stored out of the atmosphere, for example by geological sequestration. Current evidence indicate that at least some measure of CDR will be required to follow a 1.5°C-compatible emissions trajectory.

Towards a sustainable "1.5°C warmer world"

Emissions pathways limiting global warming to 1.5°C allow to avoid risks associated with higher levels of warming, but do not guarantee an absence of climate risks at regional scale, and are also associated with their own set of risks with respect to the implementation of mitigation technologies, in particular related to land use changes associated with e.g. BECCS or competition for food production[29,30,31,33].

Important aspects to consider when pursuing limiting warming to or below a global mean temperature level relate to how this goal is achieved and to the nature of emerging regional and sub-regional risks[68,69,70]. Also relevant are considerations of how the policies influence the resilience of human and natural systems, and which broader societal pathways are followed in terms of human development. Many but not all of these can be influenced directly through policy choices[68,69,70]. Internal climate variability as well as regional climate sensitivity, which display a substantial range between current climate models, are also important components of how risk will be realized. Explicitly illustrating the full range of possible outcomes of 1.5°C warmer worlds is important for an adequate consideration of the implications of mitigation options by decision makers.

The time frame to initiate major mitigation measures varies in 1.5°C-compatible (or 2°C) scenarios (Table 1). However, given the current state of knowledge about both the global and regional climate responses and the availability of mitigation measures, if the potential to limit warming to below 1.5°C or 2°C is to be maximised, emissions reductions in CO_2 and other greenhouse gases would need to start as soon as possible, leading to a global decline in emissions following 2020 at the latest. At the same time, if potential competition for land and water between negative emission technologies, agriculture and biodiversity conservation is to be avoided, mitigation would need to be carefully designed and regulated to minimise these effects, which could otherwise act to increase food prices and reduce ecosystem services. The remaining uncertainties underscore the need for continuous monitoring of not just global mean surface temperature, but also of the deployment and development of mitigation options, the resulting emissions reductions, and in particular of the intensity of global and regional climate responses and their sensitivity to climate forcing. Together with the overall societal development choices, these various elements strongly co-determine the regional and sectoral magnitudes and patterns of risk at 2°C and 1.5°C global warming.

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Acknowledgements

S.I.S. and R.W. acknowledge the European Research Council (ERC) 'DROUGHT-HEAT' project funded by the European Community's Seventh Framework Programme (grant agreement FP7-IDEAS-ERC-617518). J.R. acknowledges the Oxford Martin School Visiting Fellowship programme for support. R.S. acknowledges the European Union's H2020 project CRESCENDO "Coordinated Research in Earth Systems and Climate: Experiments, kNowledge, Dissemination and Outreach" (grant agreement H2020-641816). O.H.G. acknowledges support of the Australia Research Council Laureate program. This work contributes to the World Climate Research Programme (WCRP) Grand Challenge on Extremes. We acknowledge the WCRP Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Data availability

Emission data is available from the database accompanying ref[15] which presents pathways in line with 1.9 W/m^2 of radiative forcing in 2100, limiting warming to below 1.5°C by 2100. Regional changes in climate extremes for different global warming levels derived following the methodology of refs[4,37] can be obtained from the associated database associated with the ERC DROUGHT-HEAT project (http://www.drought-heat.ethz.ch) and the software developed under ref[37].

Authors contributions

S.I.S. coordinated the design and writing of the article, with contributions from all co-authors. J.R. provided the emissions scenario data processed in Table 1. R.S. computed the scenario summary statistics of Table 1. R.W. computed the regional projections statistics of Table 1, as well as Figs. 2-4. S.I.S. prepared Fig. 1, with support from P.T. and J.R. J.R., R.S., M.A, M.C and R.M. co-designed the analyses of emissions scenarios. K.L.E, N.E, O.H.G., A.J.P., C.F.S., P.T. and R.F.W. provided assessments on physical, ecosystem and human impacts. S.I.S. drafted the first version of the manuscript, with inputs from J.R., R.S. and M.A. All authors contributed to and commented on the manuscript.

Author Information

The authors declare no competing financial interests. Correspondence and requests for material should be addressed to S.I.S (sonia.seneviratne@ethz.ch).

List of Tables

Table 1: Description of different worlds based on scenarios currently considered compatible with 1.5°C and 2°C warming[15], including projections of changes in regional climate associated with resulting global temperature levels derived following previous studies[4,37] (see Supplementary Information for corresponding estimates from scenarios assessed in the IPCC 5th assessment report[12,14] and for median estimates).

Table 1: Description of different worlds based on scenarios currently considered compatible with 1.5°C and 2°C warming[15], including projections of changes in regional climate associated with resulting global temperature levels derived following previous studies[4,37] (see Supplementary Information for corresponding estimates from scenarios assessed in the IPCC 5th assessment report[12,14] and for median estimates).

		SCEN_1p5C Emissions pathways currently considered in line with keeping warming below 1.5°C in 2100 with 66% chance (allowing for a higher peak in temperature earlier)		SCEN_2C Emissions pathways currently considered in line with keeping warming below 2°C during the entire 21st century with 66% chance	
		"probable" (66th percentile) outcome[a]	"worst-case" 10% (90th percentile) outcome[b]	"probable" (66th percentile) outcome[a]	"worst-case" 10% (90th percentile) outcome[b]
General characteristics of pathway	**Overshoot 1.5°C in 21st century with >50% likelihood[c,h]**	**Yes (13/13)**	**Yes (13/13)**	**Yes (10/10)**	**Yes (10/10)**
	Overshoot 2°C in 21st century with >50% likelihood[h]	**No (0/13)**	**Yes (10/13)**	**No (0/10)**	**Yes (10/10)**
	Cumulative CO_2 emissions up to peak warming (relative to 2016)[d]	720 (650, 750)	690 (650, 710)	1050 (1020, 1140)	1040 (930, 1140)
	Cumulative CO_2 emissions up to 2100 (relative to 2016)[d] [$GtCO_2$]	320 (200, 340)		1030 (910, 1140)	
	Global GHG emissions in 2030[d] [$GtCO_2$ y^{-1}]	22 (19, 31)		28 (24, 30)	
	Years of global net zero CO_2 emissions[d]	2070 (2067, 2074)		2088 (2085, 2092)	
Possible climate range at peak warming (reg+glob)	**Global mean temperature anomaly at peak warming [°C][i]**	**1.75°C (1.65, 1.81°C)**	**2.13°C (2.0, 2.2°C)**	**1.93°C (1.9, 1.94°C)**	**2.44°C (2.43, 2.46°C)**
	Warming in the Arctic[e] (TNn[f]) [°C]	5.04°C (4.45, 5.66°C)	6.29°C (5.47, 7.21°C)	5.70°C (4.90, 6.53°C)	7.25°C (6.51, 8.24°C)
	Warming in the contiguous United States[e] (TXx[f]) [°C]	2.57°C (2.04, 2.95°C)	3.09°C (2.71, 3.58°C)	2.83°C (2.34, 3.27°C)	3.63°C (3.23, 3.98°C)
	Warming in Central Brazil[e] (TXx[f]) [°C]	2.74°C (2.39, 3.22°C)	3.34°C (3.05, 3.92°C)	3.01°C (2.62, 3.50°C)	3.82°C (3.44, 4.15°C)
	Drying in the Mediterranean region[e] [std[f]] (-1: dry; -2: severely dry; -3: very severely dry)	-1.27 (-2.43, -0.45)	-1.40 (-2.64, -0.52)	-1.14 (-2.18, -0.50)	-1.42 (-2.74, -0.67)
	Increase in heavy precipitation events[f] in Southern Asia[e] [%]	9.69% (6.79, 14.90%)	12.87% (7.90, 22.78%)	10.01% (6.97, 17.11%)	17.45% (10.15, 24.03%)
Possible climate range in 2100 (reg+glob)	**Global mean temperature warming in 2100 [°C][i]**	**1.44°C (1.44—1.48°C)**	**1.88°C (1.85—1.93°C)**	**1.89°C(1.88—1.91°C)**	**2.43°C (2.42—2.46°C)**
	Warming in the Arctic[g] (TNn[f]) [°C]	4.21°C (3.65, 4.71°C)	5.55°C (4.80, 6.35°C)	5.58°C (4.82, 6.38°C)	7.22°C (6.49, 8.16°C)
	Warming in the contiguous United States[g] (TXx[f]) [°C]	2.03°C (1.64, 2.49°C)	2.73°C (2.21, 3.22°C)	2.76°C (2.23, 3.24°C)	3.64°C (3.23, 3.97°C)
	Warming in Central Brazil[g] (TXx[f]) [°C]	2.25°C (2.02, 2.60°C)	2.92°C (2.55, 3.44°C)	2.94°C (2.58, 3.47°C)	3.80°C (3.43, 4.12°C)
	Drying in the Mediterranean region[g] [std[f]]	-0.96 (-1.94, -0.28)	-1.09 (-2.16, -0.48)	-1.10 (-2.15, -0.46)	-1.41 (-2.69, -0.64)
	Increase in heavy precipitation events[f] in Southern Asia[g] [%]	8.29% (4.52, 11.98%)	10.59% (6.75, 16.64%)	10.55% (6.83, 16.64%)	17.21% (10.24, 24.03%)

[a] 66th percentile for global temperature (i.e. 66% likelihood of being at or below values)
[b] 90th percentile for global temperature (i.e. 10% likelihood of being at or above values)
[c] All 1.5°C scenarios include a substantial probability of overshooting above 1.5°C global warming before returning to 1.5°C.
[d] The values indicate the median and the interquartile range in parenthesis (25th percentile and 75th percentile)
[e] The regional projections in these rows provide the range [median (q25, q75)] associated with the *median* global temperature outcomes of the considered mitigation scenarios at *peak warming* (see Box 1 and Suppl. Info. for details).
[f] TNn: annual minimum night-time temperature; TXx: annual maximum day-time temperature; std: drying of soil moisture expressed in units of standard deviations of pre-industrial climate (1861-1880) variability; Rx5day: annual maximum consecutive 5-day precipitation
[g] Same as footnote e, but for the regional responses associated with the *median* global temperature outcomes of the considered mitigation scenarios *in 2100* (see Box 1 and Suppl. Info. for details).
[h] Red and yellow colors indicate whether scenarios lead to overshoot a given level of warming or not.
[i] Green, yellow and red colors indicate whether the global mean temperature remains below 1.5°C, between 1.5°C and 2°C, or exceeds 2°C.

List of Figures

Figure 1. Temporal and spatial dimensions 1.5°C warmer worlds. a. *Typical pathways of Earth's climate towards stabilization at 1.5°C warming. Pre-industrial climate conditions are the reference for the determined global warming. Present-day warming corresponds to 1°C compared to pre-industrial conditions. All "1.5°C-warming compatible emissions pathways" currently available in the literature[12,13,14,15] include overshooting over 1.5°C warming prior to stabilization or further decline. We here illustrate the example of temperature stabilization at 1.5°C in the long-term, but temperatures could also further decline below 1.5°C.* ***b.*** *Not all conceivable "1.5°C warmer climates" are equivalent. These conceptual schematics illustrate the importance of the spatial dimension of distributed impacts associated with a given global warming, at the example of a simplified world with two surfaces of equal area (the given temperature anomalies are chosen for illustrative purposes and do not refer to specific 1.5°C scenarios). (left) Reference world (without warming); (top right) world with 1.5°C mean global warming that is equally distributed on the two surfaces; (bottom right) world with 1.5°C mean global warming with high differences in regional responses.*

Figure 2: Possible outcomes with respect to global temperature and regional climate anomalies from typical 1.5°C-warming and 2°C-warming compatible scenarios at peak warming. *(a) Net $GtCO_2$ emitted until time of peak warming relative to 2016 (including carbon dioxide removal from the atmosphere) in considered scenarios from Table 1 (25^{th}quantile (q25), median (q50), and 75^{th} quantile (q75)). (b) Global mean temperature anomaly at peak warming (q25, q50, q75). (c-e): Regional climate anomalies at peak warming compared to the pre-industrial period corresponding to the median global warming of the 2^{nd} row (full range associated with different regional responses within CMIP5 multi-model ensemble displayed as violin plot; the median and interquartile ranges are indicated with horizontal dark gray lines). See Table 1 for more details.*

Figure 3: Possible outcomes with respect to global temperature and regional climate anomalies from typical 1.5°C-warming and 2°C-warming compatible scenarios in 2100. *(a) Net $GtCO_2$ emitted by 2100 relative to 2016 (including carbon dioxide removal from the atmosphere) in considered scenarios from Table 1 (25^{th}quantile (q25), median (q50), and 75^{th} quantile (q75)). (b) Global mean temperature anomaly in 2100 (q25, q50, q75). (c-e) Regional climate anomalies at peak warming compared to the pre-industrial period corresponding to the median global warming of the 2^{nd} row (full range associated with different regional responses within CMIP5 multi-model ensemble displayed as violin plot; the median and interquartile ranges are indicated with horizontal dark gray lines). See Table 1 for more details.*

Figure 4: The stochastic noise and model-based uncertainty of realized climate at 1.5°C. *Temperature with 25% chance of occurrence at any location within 10-year time frames corresponding to $\Delta Tglob=1.5°C$ (based on CMIP5 multi-model ensemble). The plots display at each location the 25^{th} percentile (Q25; a, c, e) and 75^{th} percentile (Q75; b, d, f) values of mean temperature (Tmean; a, b), yearly maximum day-time temperature (TXx; c, d), and yearly minimum night-time temperature (TNn; e, f), sampled from all time frames with $\Delta Tglob=1.5°C$ in all RCP8.5 model simulations of the CMIP5 ensemble (see Box 1 for details).*

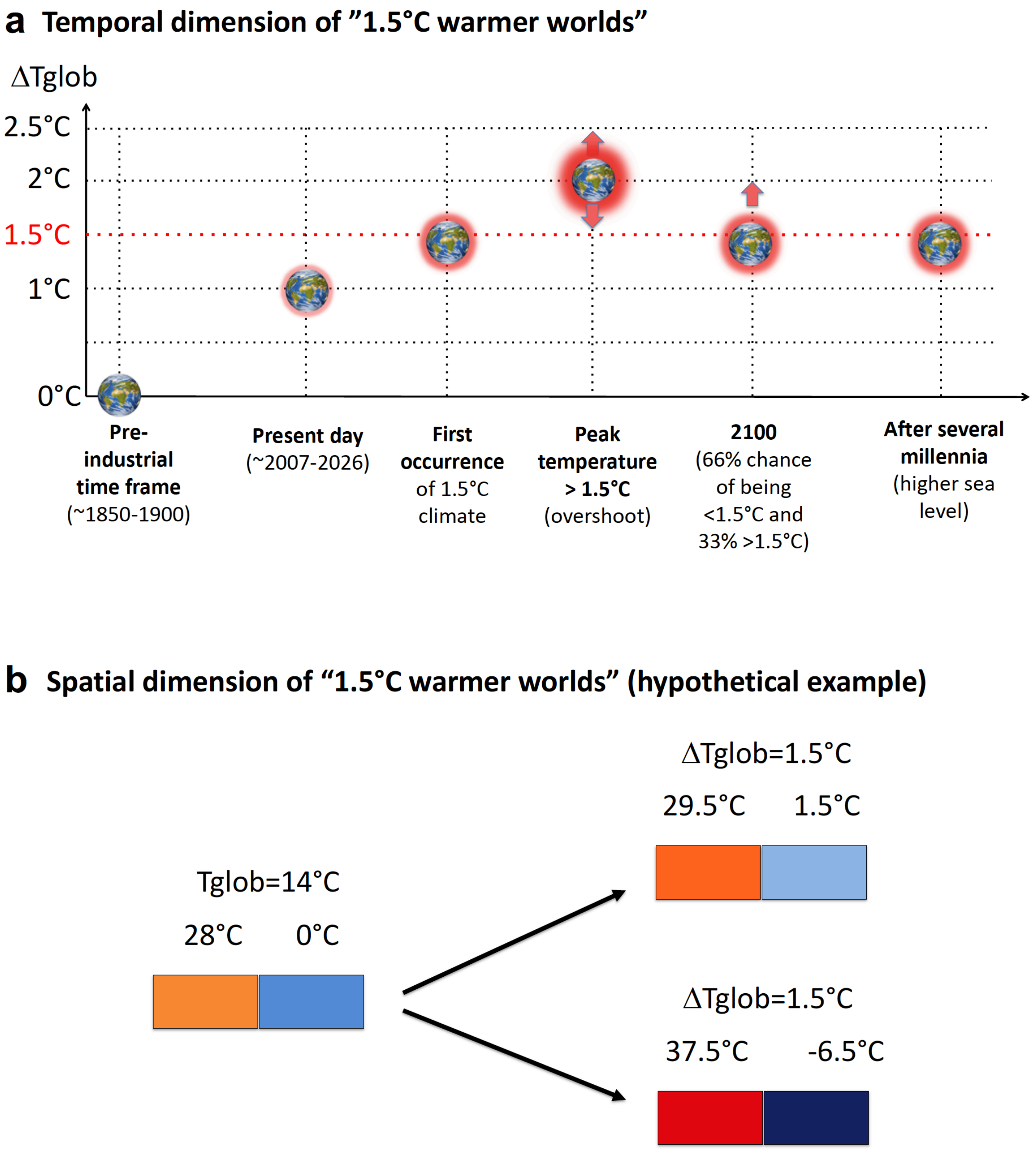

Figure 1. Temporal and spatial dimensions 1.5°C warmer worlds. a. *Typical pathways of Earth's climate towards stabilization at 1.5°C warming. Pre-industrial climate conditions are the reference for the determined global warming. Present-day warming corresponds to 1°C compared to pre-industrial conditions. All "1.5°C-warming compatible emissions pathways" currently available in the literature[12,13,14,15] include overshooting over 1.5°C warming prior to stabilization or further decline. We here illustrate the example of temperature stabilization at 1.5°C in the long-term, but temperatures could also further decline below 1.5°C.* ***b.*** *Not all conceivable "1.5°C warmer climates" are equivalent. These conceptual schematics illustrate the importance of the spatial dimension of distributed impacts associated with a given global warming, at the example of a simplified world with two surfaces of equal area (the given temperature anomalies are chosen for illustrative purposes and do not refer to specific 1.5°C scenarios). (left) Reference world (without warming); (top right)*

world with 1.5°C mean global warming that is equally distributed on the two surfaces; (bottom right) world with 1.5°C mean global warming with high differences in regional responses.

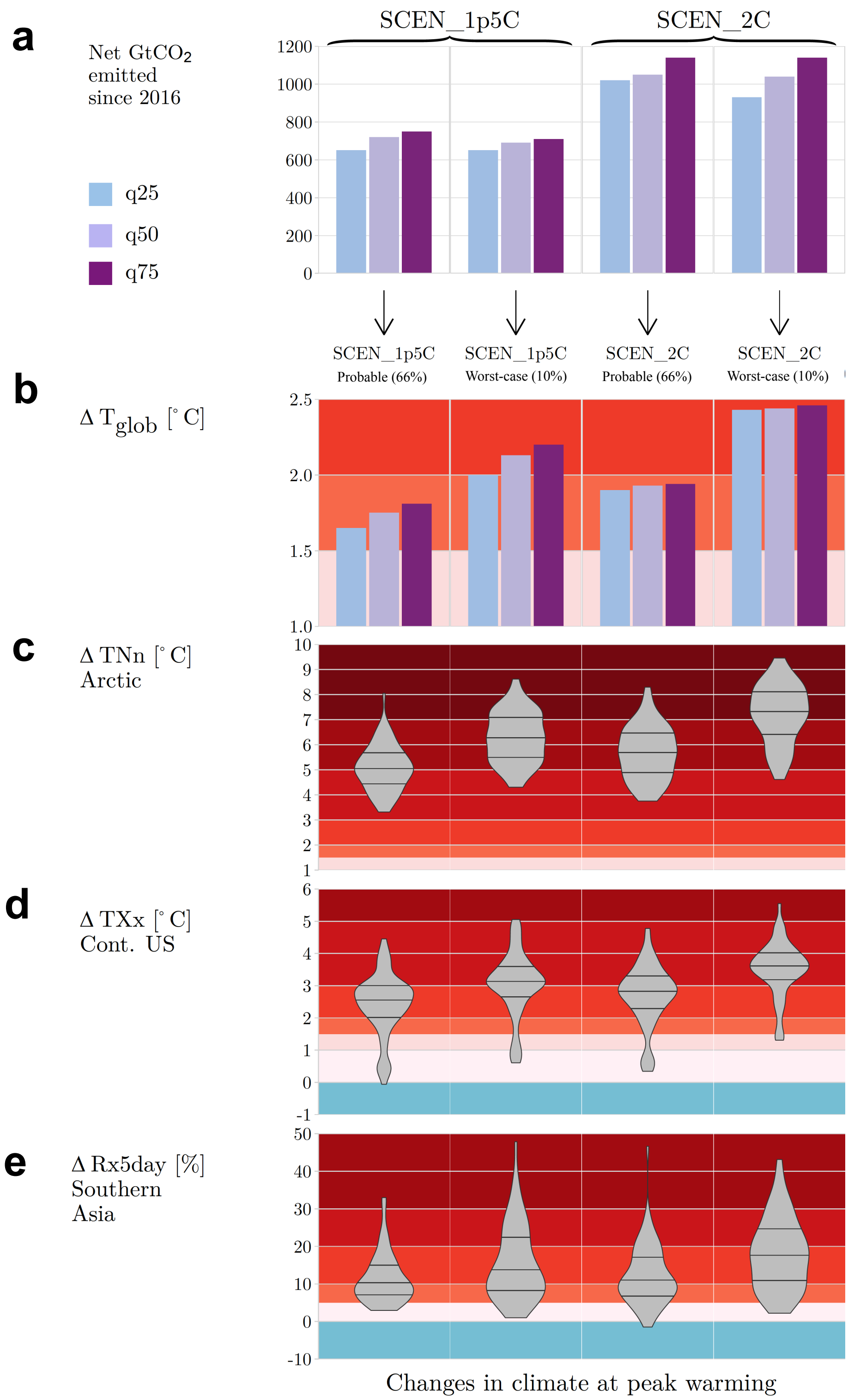

Figure 2: Possible outcomes with respect to global temperature and regional climate anomalies from typical 1.5°C-warming and 2°C-warming compatible scenarios at peak warming. *(a) Net $GtCO_2$ emitted until time of peak warming relative to 2016 (including carbon dioxide removal from the atmosphere) in considered scenarios from Table 1 (25^{th}quantile (q25), median (q50), and 75^{th} quantile (q75)). (b) Global mean temperature anomaly at peak warming (q25, q50, q75). (c-e): Regional climate anomalies at peak warming compared to the pre-*

industrial period corresponding to the median global warming of the 2nd row (full range associated with different regional responses within CMIP5 multi-model ensemble displayed as violin plot; the median and interquartile ranges are indicated with horizontal dark gray lines). See Table 1 for more details.

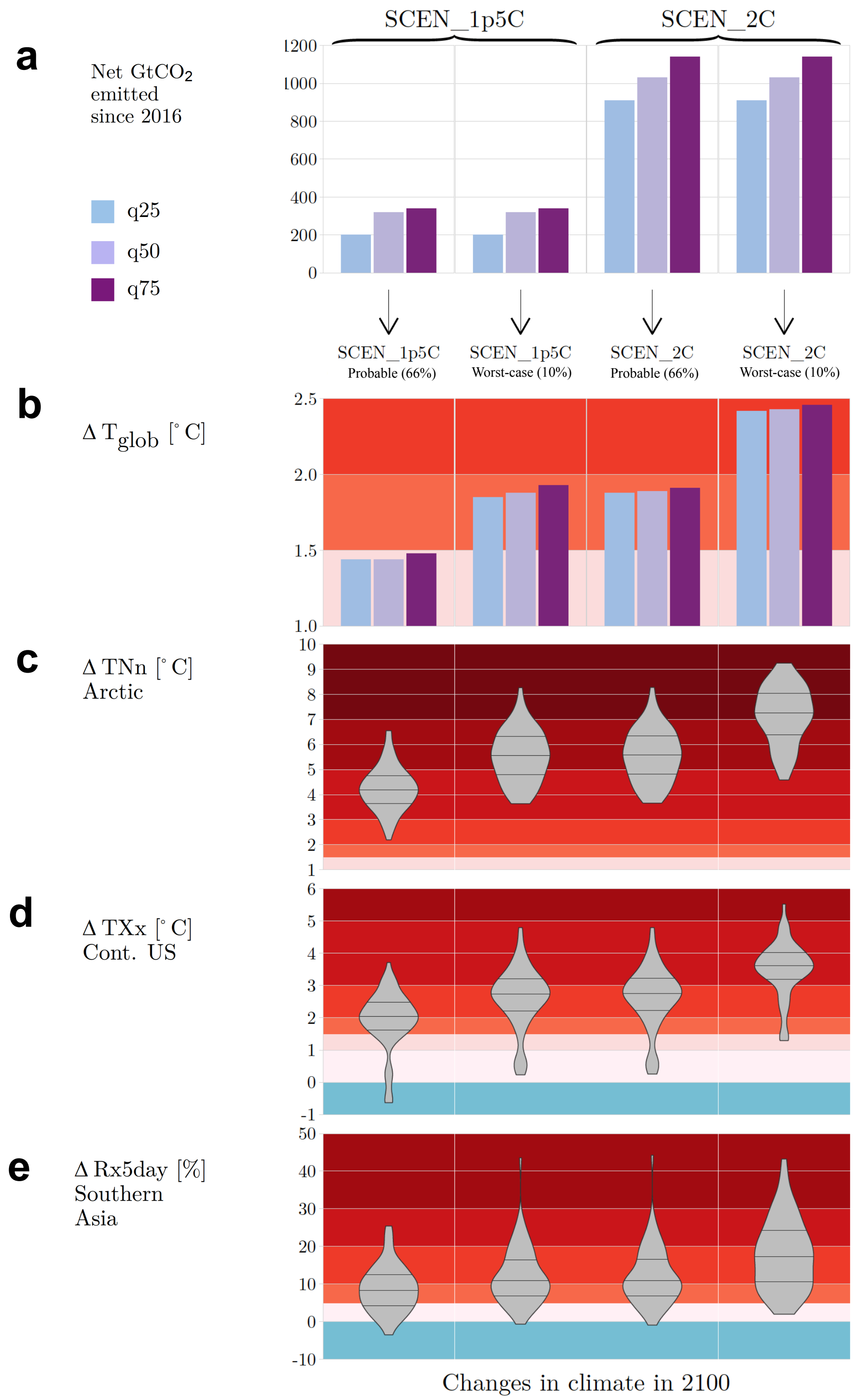

Figure 3: Possible outcomes with respect to global temperature and regional climate anomalies from typical 1.5°C-warming and 2°C-warming compatible scenarios in 2100. *(a) Net $GtCO_2$ emitted by 2100 relative to 2016 (including carbon dioxide removal from the atmosphere) in considered scenarios from Table 1 (25th quantile (q25), median (q50), and 75th quantile (q75)). (b) Global mean temperature anomaly in 2100 (q25, q50, q75). (c-e) Regional climate anomalies at peak warming compared to the pre-industrial period corresponding to the median global warming of the 2nd row (full range associated with different regional*

responses within CMIP5 multi-model ensemble displayed as violin plot; the median and interquartile ranges are indicated with horizontal dark gray lines). See Table 1 for more details.

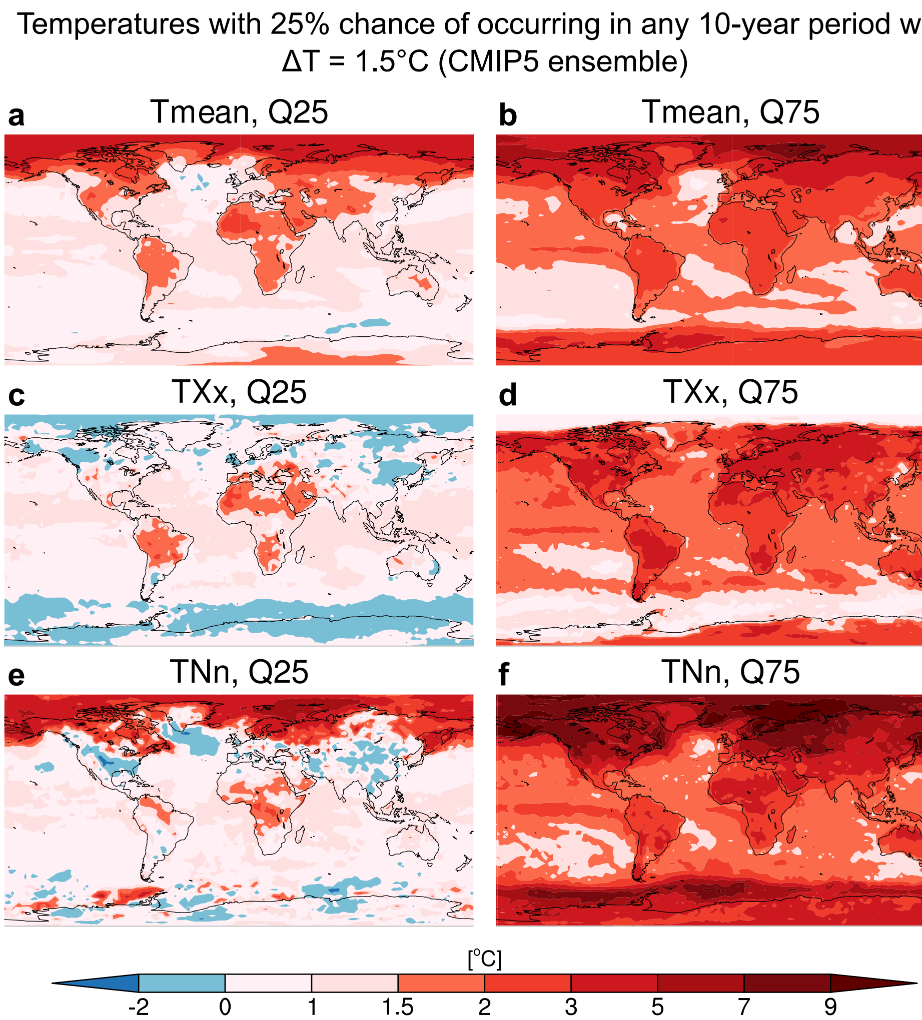

Figure 4: The stochastic noise and model-based uncertainty of realized climate at 1.5°C. *Temperature with 25% chance of occurrence at any location within 10-year time frames corresponding to ΔTglob=1.5°C (based on CMIP5 multi-model ensemble). The plots display at each location the 25th percentile (Q25; a, c, e) and 75th percentile (Q75; b, d, f) values of mean temperature (Tmean; a, b), yearly maximum day-time temperature (TXx; c, d), and yearly minimum night-time temperature (TNn; e, f), sampled from all time frames with ΔTglob=1.5°C in all RCP8.5 model simulations of the CMIP5 ensemble (see Box 1 for details).*

Box 1. Emissions budgets and regional projections for 1.5°C and 2°C global warming

The emissions budget estimates of Table 1 are based on scenarios currently considered compatible with limiting global warming (dTglob) to 1.5°C and 2°C, either in 2100 or during the entire 21st century[15]. The emissions pathways are determined based on their probability of limiting dTglob below 1.5°C or 2°C by 2100 using the probabilistic outcomes of a simple climate model (MAGICC[71]) exploring the range of climate system response as assessed in the IPCC AR5[72]. The 50th (Suppl. Info.), 66th and 90th percentile (Table 1) MAGICC global transient climate response (TCR) values in the scenarios are 1.7, 1.9, and 2.4 [°C], respectively, overall consistent with the assessed range for this parameter (>66% in the 1-2.5 [°C] range, less than 5% greater than 3 [°C]) in the IPCC AR5[72]. The current airborne fraction (ratio of accumulated atmospheric CO_2 to CO_2 emissions over the decade 2011-2020) in these scenarios with this MAGICC version has been estimated at 0.55, which is 20% higher than the central estimate for the most recent decade given in refs[73,74], but ref[74] emphasizes that this quantity is uncertain and subject to variability over time. The provided estimates are consistent with corresponding values from scenarios assessed in the IPCC AR5[12,14] (see Suppl. Table S1), but have slightly larger estimates for the remaining cumulative CO_2 budgets, consistent with other recent publications[34,35,36]. Both sets of scenarios imply that for limiting dTglob below 1.5°C by 2100 strong near-term mitigation measures are needed supported by technologies capable of enabling net-zero global CO_2 emissions near to mid-century.

Table 1 and Figures 2-3 also provide estimates of regional responses associated with given dTglob levels (at peak warming and in 2100). The values are computed based on decadal averages of 26 CMIP5 global climate model simulations and all four Representative Concentrations Pathways (RCP scenarios) following the approach from refs[4,37] (see Suppl. Info. for more details). Decades corresponding to a 1.5°C or 2°C warming are those in which the last year of the decade reaches this temperature, consistent with previous publications[3,4,37]. Corresponding regional responses for the median estimates of the considered scenarios are provided in Suppl. Table S2 and Suppl. Figures S1 and S2. Respective estimates of spread for recent (0.5°C) and present-day (1°C) global warming are provided in the Suppl. Figure S3.

Figure 4 is based on the same 26 CMIP5 models' subset as used for Table 1 and Figures 2-3, but uses RCP8.5 simulations only. For each simulation, the ensemble percentiles are calculated for the time step corresponding to the decade at which a 1.5°C warming occurs for the first time. Statistics are computed over all 26 climate models and all years within the given decade.

The databases underlying the analyses of Table 1 and Figs. 2-3 are described under the data availability statement. The R code used to analyze MAGICC outputs in this paper is available from R.S. on reasonable request. The scripts used for the regional analyses provided in Table 1 and Figs 2-4 are available from R.W. and S.I.S. upon request.

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