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Limiting global warming to 1.5 °C will lower increases in inequalities of four hazard indicators of climate change

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Supplementary material for this article is available online

Abstract

Clarifying characteristics of hazards and risks of climate change at 2 °C and 1.5 °C global warming is important for understanding the implications of the Paris Agreement. We perform and analyze large ensembles of 2 °C and 1.5 °C warming simulations. In the 2 °C runs, we find substantial increases in extreme hot days, heavy rainfalls, high streamflow and labor capacity reduction related to heat stress. For example, about half of the world's population is projected to experience a present day 1-in-10 year hot day event every other year at 2 °C warming. The regions with relatively large increases of these four hazard indicators coincide with countries characterized by small CO_2 emissions, low-income and high vulnerability. Limiting global warming to 1.5 °C, compared to 2 °C, is projected to lower increases in the four hazard indicators especially in those regions.

Introduction

The Paris Agreement sets a goal of 'holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change' (United Nations Framework Convention on Climate Change (UNFCCC 2015). The most vulnerable and least developed countries have been calling for the 1.5 °C limit for many years, to reduce risk of dangerous anthropogenic interference with the climate system (Tschakert 2015, Schleussner *et al* 2016a). Since the adoption of the agreement, a range of studies have examined how changes in extreme weather events and impacts would be lowered by limiting global warming to 1.5 °C, compared to 2 °C (Tschakert 2015, Rogelj and Knutti 2016, Schleussner *et al* 2016b, Mitchell *et al* 2016, King *et al* 2017, Lewis *et al* 2017, Hoegh-Guldberg *et al* 2018).

In the Paris Agreement, the issues of equity and climate justice are inherent in discussions of climate change adaptation, loss and damage, as well as mitigation (Okereke and Coventry 2016, Morgan and Northrop 2017). The 1.5 °C special report of the Intergovernmental Panel on Climate Change (IPCC) (Hoegh-Guldberg *et al* 2018) concluded that, with respect to the 'distribution of impacts', a transition from moderate to high risk is located between 1.5 °C and 2 °C of global warming. 'Risk of climate-related impacts results from the interaction of climate-related hazards with the vulnerability and exposure of human and natural systems' (Field *et al* 2014). Vulnerability and adaptive capacities are unevenly distributed. In general, the least developed countries in tropical and subtropical areas are among the most vulnerable (African Development Bank *et al* 2003, Field *et al* 2014, Department of Economic and Social Affairs of the United Nations Secretariat 2016). The ability to cope with the impacts of climate variability and extreme weather events depends strongly on the level of economic development and governance (Field *et al* 2014, Tschakert 2015). The differential vulnerability and adaptation capability is projected to lead to relatively larger impacts in the least developed countries that have emitted less CO_2 and have fewer financial resources (i.e. relatively little mitigation capacities) (Field *et al* 2014). There are also spatial heterogeneities in the future changes of extreme weather events (hazards). Some studies have suggested that the frequencies of hot days will increase more rapidly in the poorest countries in the tropics than in countries in mid-to-high-latitude regions (Mahlstein *et al* 2011, Harrington *et al* 2016, Hoegh-Guldberg *et al* 2018). It has been suggested that 1.5 °C–2 °C differences of increases in heatwave exposure (Russo *et al* 2019), high streamflow (Döll *et al* 2018) and multi-sector (water, energy, food and environment) risks (Byers *et al* 2018) are larger for low-income countries/populations than high-income countries/populations.

The aim of this study is to investigate whether keeping global warming to 1.5 °C, compared to 2 °C, lowers changes in extreme weather events (extreme daily temperature and precipitation events), high streamflow and heat-related labor capacity reduction (LCR) from the present climate. We also examine if keeping global warming to 1.5 °C limits the unequal distribution of these hazard indicators in terms of not only incomes of countries but also their responsibilities and vulnerabilities.

Global climate model simulations

The large variability of the four hazard indicators cause challenges in distinguishing 2 °C from 1.5 °C when using small ensembles of climate model simulations. Furthermore, the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor *et al* 2012) that contributed to the previous IPCC report was not designed to compare changes in climate at the 1.5 °C and 2 °C stabilization levels (Tschakert 2015, Rogelj and Knutti 2016). Although it is possible to extract anomalies of climate variables at 1.5 °C and 2 °C from the *transient* scenario experiments of CMIP5, those can be different from anomalies in *stabilized* 1.5 °C and 2 °C simulations (e.g. figure 1 of Mitchell *et al* 2016).

To overcome these challenges and inform policy dialogues, a multi atmosphere-land global climate model (AGCM) intercomparison project, the Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI), was proposed (Mitchell *et al* 2016, 2017). In the HAPPI project, we have performed 10 year time-slice ensembles for the present (2006–2015, Hist), 1.5 °C and 2 °C warming climates relative to preindustrial levels using 6 AGCMs (supplementary table 1 is available online at stacks.iop.org/ERL/14/124022/mmedia, supplementary methods). This design enables us to examine anomalies of climate variables of the 1.5 °C and 2 °C stabilized simulations. Furthermore lower computing costs of AGCM than fully coupled models make it easier to perform large ensembles. The ensemble sizes for each experiment range from 83 to 125. These sizeable ensembles enable us to robustly examine the effects of a 0.5 °C difference in global warming on changes in the four hazard indicators.

Changes in the frequencies of extreme weather events

We investigate the annual warmest daily maximum temperatures (TXx) and the annual maximum consecutive 5 d precipitation (Rx5day) obtained from the HAPPI simulations (supplementary methods). Figures 1(a) and (d) show the values of TXx and Rx5day at the 10 year return level linked to the 2006–2015 state of the climate, respectively. Figures 1(b) and (c) show the factors by which 'frequencies of TXx exceeding the present-day 1-in-10 year values' increase in the 1.5 °C and 2.0 °C runs (probability ratio, PR(TXx)):

$$\mathrm{PR} = P_1/P_0, \qquad (1)$$

where P_0 and P_1 are the probabilities of extreme events under present-day conditions (1-in-10 year) and in the future, respectively. PR(TXx) is large in the tropics. In the tropical part of South America and large parts of Africa, PR(TXx) exceeds a factor of 7 in the 2.0 °C

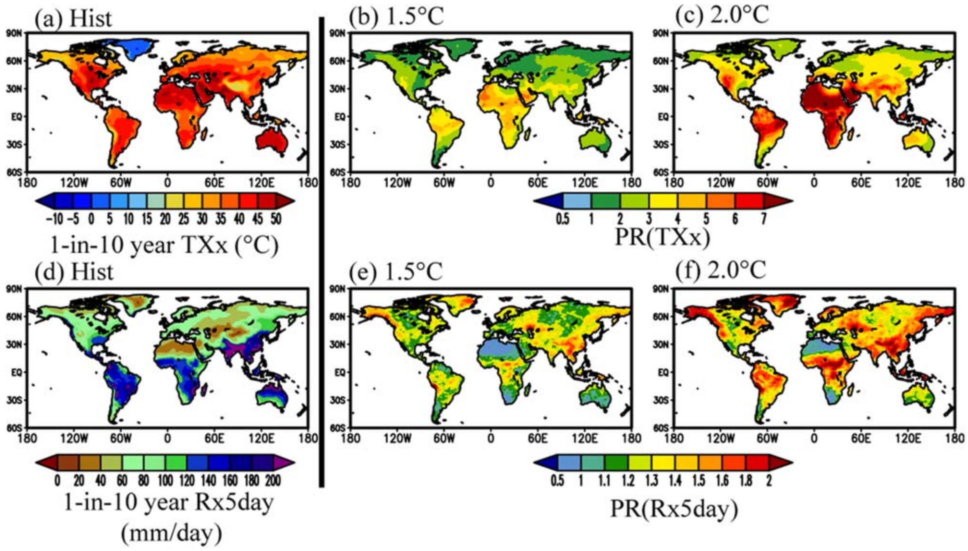

Figure 1. Changes in the frequency of the 1-in-10 year TXx and Rx5day values for the AGCM mean. (a) The 1-in-10 year TXx values under present-day conditions (°C). (b), (c) The PR(TXx) values for the 1.5 °C and 2.0 °C runs, respectively. (d) The 1-in-10 year Rx5day values under present-day conditions (mm d^{-1}). (e), (f) The PR(Rx5day) values for the 1.5 °C and 2.0 °C runs, respectively.

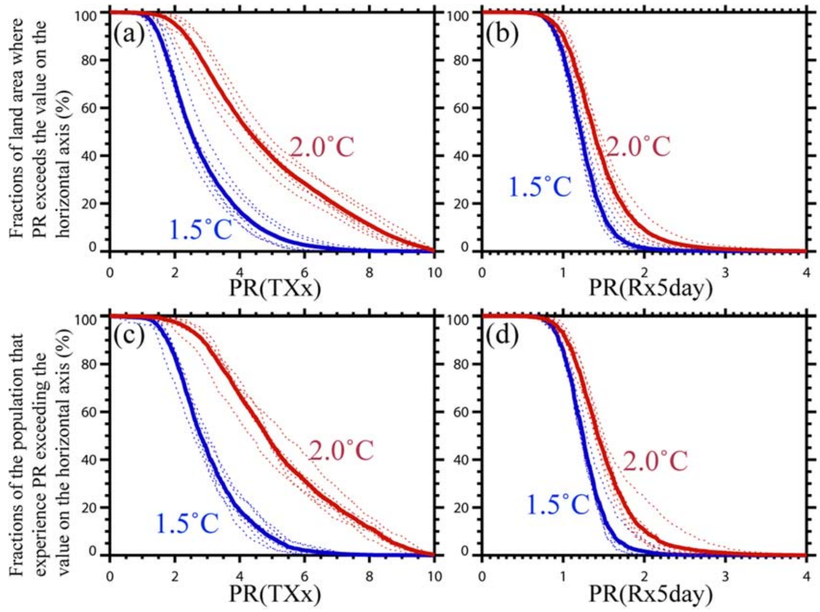

Figure 2. Fractions of land areas and populations where the PR(TXx) and PR(Rx5day) values exceed a given threshold. (a) The solid blue and red lines denote the fractions of the land area where PR(TXx) exceeds the values shown on the horizontal axis for the multi-AGCM averages of the 1.5 °C and 2.0 °C runs, respectively. The dotted lines indicate each AGCM. (b) As panel (a) but for PR(Rx5day). (c), (d) As the top panels, but the vertical axes indicate the fractions of the population that experience (c) PR(TXx) and (d) PR(Rx5day) values that exceed the values shown on the horizontal axes.

runs. In contrast, in the 1.5 °C runs, PR(TXx) values are below a factor of 4 in those regions.

Figures 1(e) and (f) indicate the factors by which 'frequencies of Rx5day exceeding the present-day 1-in-10 year values' increase in the 1.5 °C and 2.0 °C runs (PR(Rx5day)). PR(Rx5day) increases by a factor of 1.8 in many tropical countries in the 2.0 °C runs and by a factor of 1.4 in the 1.5 °C runs, relative to present levels. PR(TXx) and PR(Rx5day) are large in tropical countries because the variance of the natural variability is small at low latitudes (supplementary figure 1) (Mahlstein *et al* 2011, Harrington *et al* 2016, Hoegh-Guldberg *et al* 2018).

We investigate the exposure ratios of land areas (which are important for identifying impacts on natural systems) and populations to extreme weather events (figure 2). Figure 2(a) indicates the fraction of the global land area where PR(TXx) exceeds a given threshold (shown on the horizontal axis). We omit the Antarctic region from this analysis because of its insignificant population. In the multi-AGCM average of the 2.0 °C runs, PR(TXx) exceeds a factor of 5 (i.e.

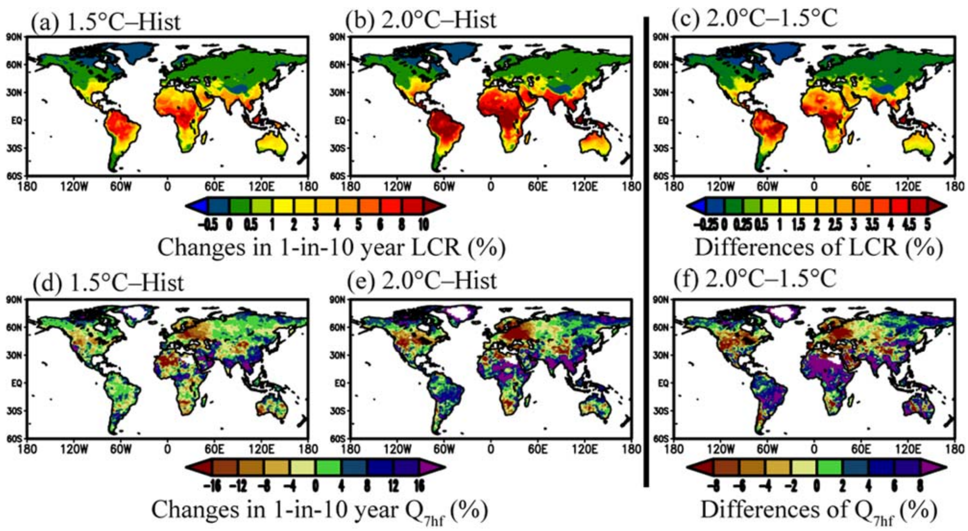

Figure 3. Ensemble mean changes in 1-in-10 year LCR and Q_{7hf} values. (a), (b) ΔLCR for 1.5 °C and 2.0 °C, respectively (%). (c) Percentage point difference between ΔLCR for 2.0 °C and 1.5 °C (%). (d), (e) ΔQ_{7hf} for the 1.5 °C and 2.0 °C runs, respectively. (f) Percentage point difference between ΔQ_{7hf} for 2.0 °C and 1.5 °C (%).

frequencies of extreme events increase by factors of >5) over 39% of the global land area (the min–max range of the AGCMs is 31%–47%). In contrast, under the 1.5 °C runs, the fraction of the land area where PR(TXx) exceeds a factor of 5 declines to 7% (3%–13%). The results for PR(Rx5day) are not as drastic as those for PR(TXx), but the changes in the frequency of the extreme rains are not negligible (figure 2(b)). The fraction of the land area where PR(Rx5day) exceeds a factor of 1.5 is 37% (28%–46%) and 15% (9%–23%) for the 2.0 °C and 1.5 °C runs, respectively.

Figures 2(c) and (d) show the fractions of the population in 2100 (Jones and O'Neill 2016) (supplementary figure 2) that experience PR(TXx) and PR(Rx5day) exceeding the horizontal axis values, respectively. Forty-six percent (38%–56%) and 7% (3%–12%) of the population face PR(TXx) values exceeding a factor of 5 for the 2.0 °C and 1.5 °C runs, respectively. Forty-three percent (35%–50%) and 16% (11%–29%) of the population experience PR(Rx5day) values exceeding a factor of 1.5 for the 2.0 °C and 1.5 °C runs, respectively. Because the low-latitude regions have a relatively large population compared to the high-latitude regions (supplementary figure 2), figures 2(c), (d) show greater changes in extreme events than figures 2(a), (b) (Lehner and Stocker 2015, Lehner *et al* 2018).

Labor capacity reduction

We examine heat-related LCR. To keep core body temperature within a safe range in hot environments, per-hour amount of physical activity must be limited (NIOSH 2016, ISO 2017), which means LCR. The future warming will increase LCR. If workers decrease their actual working time according to LCR, it leads to economic losses (Takakura *et al* 2017, 2018). If they do not, the risk of heat-related hazards, some of which are fatal, will be elevated. LCR can be one of the dominant sources of the expected total economic loss caused by climate change amongst many other climate-induced effects (Takakura *et al* 2019). Thus, LCR would be a good indicator to gauge potential effects of high temperature on humans whereas this indicator alone does not consider the difference in vulnerability among regions. We estimate the annual LCR for outdoor workers with moderate physical activity (300 W) in the present, +1.5 °C and +2.0 °C climates (supplementary methods). Figures 3(a), (b) indicate changes in 1-in-10 year LCR (ΔLCR) for the 1.5 °C and 2.0 °C runs from Hist, respectively. ΔLCR is greater than 8% in some tropical countries (greater positive values indicate more reduction of labor capacity) in the 2.0 °C runs, and the difference between the 1.5 °C and 2.0 °C runs (figures 3(c) and (a)) is largest in those tropical countries.

High streamflow

We also investigate annual highest 7 d streamflow (Q_{7hf}), calculated by Döll *et al* (2018) using two hydrological models and the HAPPI runs of four AGCMs (supplementary methods). We investigate 1-in-10 year Q_{7hf}, which may lead to inundations. Human assets can be damaged by inundation, while floodplain habitat requires inundation. Figures 3(d), (e) show the relative changes in 1-in-10 year Q_{7hf} (ΔQ_{7hf}) for the 1.5 °C and 2.0 °C runs compared to the Hist runs, respectively (supplementary methods). In the 2.0 °C runs, increases in Q_{7hf} of more than 8% compared to the Hist runs occur in the many tropical countries while decreases of Q_{7hf} are found in some

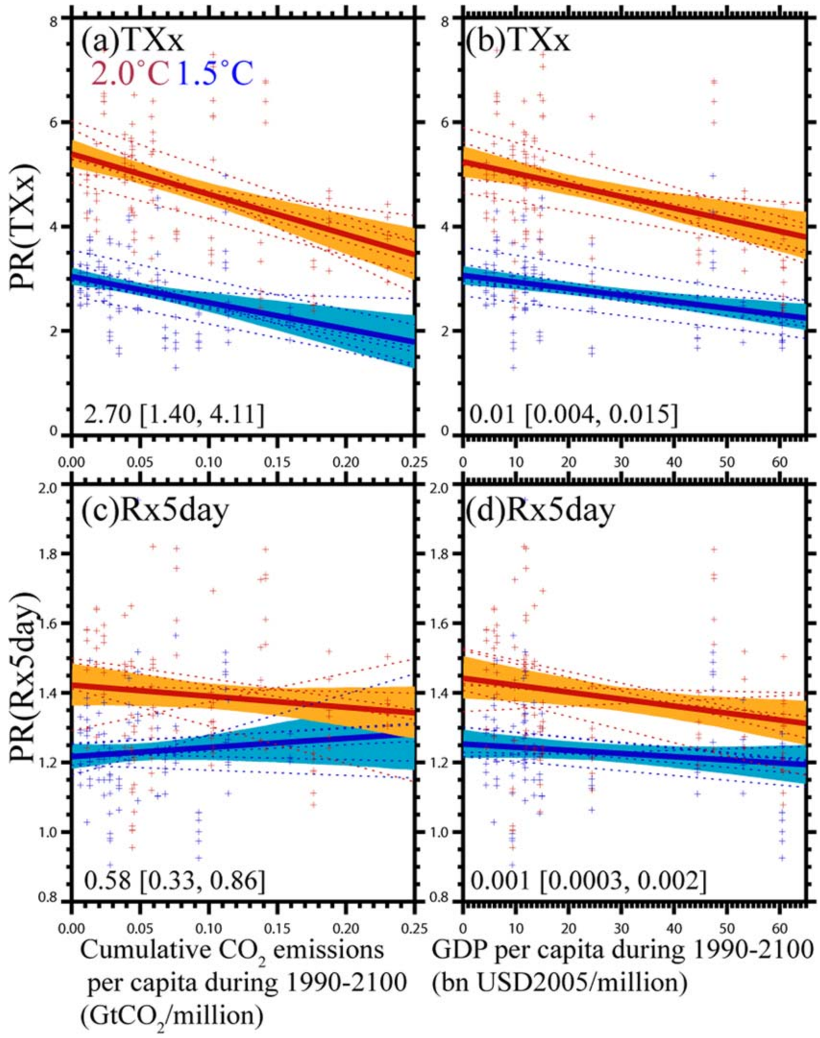

Figure 4. Uneven distributions of the increases in extreme events considering mitigation responsibilities and capabilities. (a) The horizontal axis represents the per capita cumulative CO_2 emissions in 1990–2100 ($GtCO_2$ million^{-1}). The vertical axis is the area-averaged PR(TXx), weighted by the population in 2100. Blue and red crosses indicate the PR(TXx) values of each region in the 1.5 °C and 2.0 °C runs, respectively. The solid lines indicate the regression lines when all the AGCM data are used. The dashed lines are the regression lines for each AGCM. The orange and light blue shaded areas indicate the 5%–95% confidence intervals of the solid blue and red lines (supplementary methods). The numbers at the bottom of each panel indicate the difference in the slopes of the solid lines (1.5 °C minus 2.0 °C) and the 5%–95% confidence interval of the difference (supplementary methods). (b) As (a) but for per capita GDP (bn USD 2005 million^{-1}). (c), (d) As (a), (b) but for PR(Rx5day).

high-latitude regions. The amplitudes of increases in Q_{7hf} are smaller in the 1.5 °C runs than the 2.0 °C runs in the tropical regions (figures 3(f) and (d)) (Döll *et al* 2018).

Uneven distributions of the four hazard indicators

Next, we investigate distributions of PR(TXx), PR(Rx5day), ΔLCR and ΔQ_{7hf} by plotting their changes against selected socio-economic indices. The horizontal axis of figure 4(a) indicates 'cumulative CO_2 emissions per capita' for the 17 regions of the world from 1990 to 2100 (supplementary methods). The horizontal axis of figure 4(b) indicates 'gross domestic product (GDP) per capita'. In previous studies of equitable mitigation efforts, 'cumulative CO_2 emissions per capita' and 'GDP per capita' have been used as indicators of the 'Common but Differentiated Responsibilities' (i.e. countries with higher per capita emissions have greater responsibility) and 'Respective Capabilities' (i.e. countries with higher per capita GDP have greater mitigation capability) principles of the UNFCCC (1992) (Clarke *et al* 2014, du Pont *et al* 2017). The vertical axes of figures 4(a) and (b) show the area-averaged PR(TXx) weighted by the population density (supplementary methods). The negative slopes of the red regression lines of figures 4(a), (b) indicate uneven distributions in the 2.0 °C runs: regions with lower mitigation responsibilities and capabilities have larger PR(TXx) values. Mahlstein *et al* (2011) performed a similar analysis for summer mean temperature changes relative to inter-annual variability under a single scenario (SRES A1B) and the CO_2 emissions per capita in 2009 and arrived

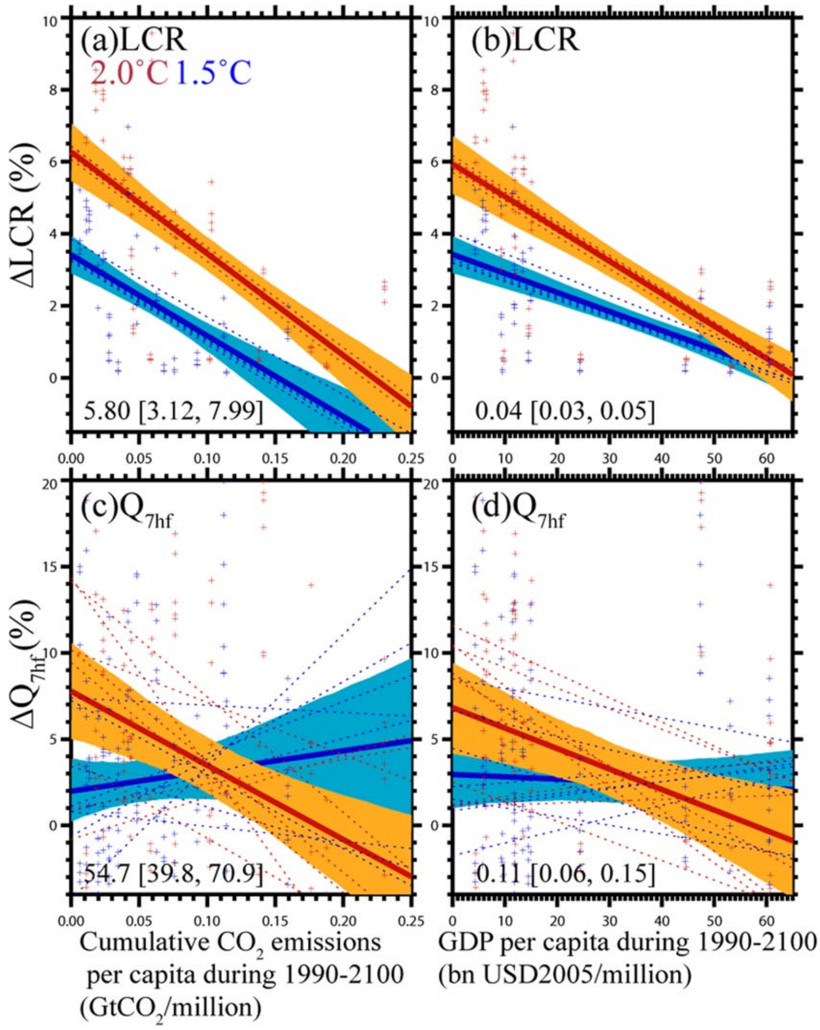

Figure 5. Uneven distributions of ΔLCR and ΔQ_{7hf} considering mitigation responsibilities and capabilities. (a) The horizontal axis represents the per capita cumulative CO_2 emissions in 1990–2100 ($GtCO_2$ million^{-1}). The vertical axis is the area-averaged ΔLCR, weighted by the population in 2100. Blue and red crosses indicate the ΔLCR values of each region in the 1.5 °C and 2.0 °C runs, respectively. The solid lines indicate the regression lines when all the AGCM data are used. The dashed lines are the regression lines for each model. The orange and light blue shaded areas indicate the 5%–95% confidence intervals of the solid blue and red lines (supplementary methods). The numbers at the bottom of each panel indicate the difference in the slopes of the solid lines (1.5 °C minus 2.0 °C) and the 5%–95% confidence interval of the difference (supplementary methods). (b) As (a) but for per capita GDP (bn USD 2005 million^{-1}). (c), (d) As (a), (b) but for ΔQ_{7hf}.

at the same conclusion. We further indicate that, compared to the 2.0 °C goal, meeting the 1.5 °C goal both decreases PR(TXx) (the blue lines are lower than the red lines) and limits the increases of the inequalities: the amplitudes of the decreases in PR(TXx) are larger in lower-income regions with smaller emissions.

Changes in LCR are greater in the lower-income regions with smaller emissions in 2.0 °C (figures 5(a), (b)). The differences of ΔLCR between 1.5 °C and 2.0 °C are larger in those regions.

There are uneven distributions in PR(Rx5day) in the 2.0 °C runs, but not so evident than those in PR(TXx) and ΔLCR (figures 4(c) and (d)). Although the solid red regression lines obtained using the 2.0 °C simulations of all the AGCMs have negative slopes (i.e. apparent unequal distributions), some of the AGCMs have positive slopes. Nevertheless, one important finding holds: the reductions in PR(Rx5day) from a 2.0 °C warming to a 1.5 °C warming are greater in the regions with smaller emissions and lower-income.

Similar to PR(Rx5day), ΔQ_{7hf} does not decrease with increasing emissions/wealth in case of a 1.5 °C world, while it clearly decreases in case of a 2 °C world, where it would increase uneven distributions (note that the differences of the regression slopes between 1.5 °C and 2.0 °C are statistically significant) (figures 5(c), (d)).

We also use the University of Notre Dame Global Adaptation Initiative (ND-GAIN) Country Index (Chen *et al* 2015), which summarizes the vulnerability of countries to climate change and other global challenges (in the food, water, health, ecosystem services, human habitat and infrastructure sectors), combined with the readiness of countries to improve their resilience in 2015 (figures 6, 7). Lower values indicate

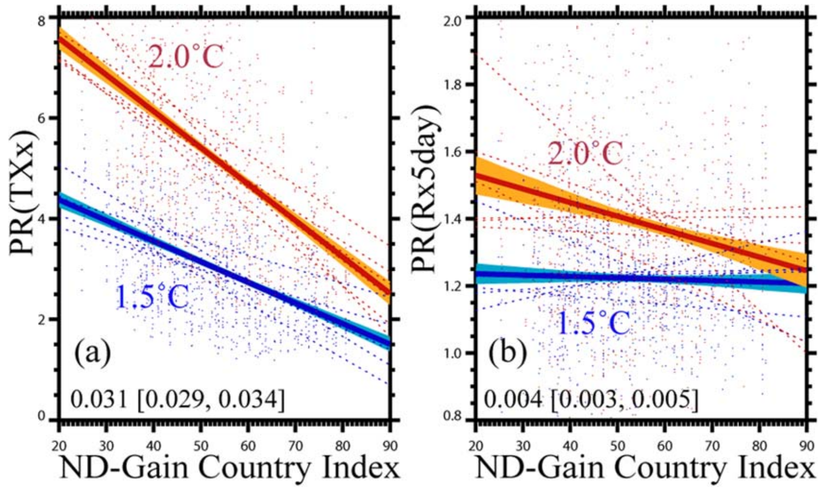

Figure 6. Uneven distributions of the increased frequencies of hot days and heavy rains considering the ND-GAIN Country Index. The horizontal axes show the ND-GAIN Country Index. The vertical axes show the country-averaged (a) PR(TXx) and (b) PR(Rx5day) values, weighted by the population in 2100. The blue and red dots indicate the values corresponding to each country in the 1.5 °C and 2.0 °C runs, respectively. Solid lines indicate the regression lines that are obtained when all of the AGCM data are used. The dashed lines are the regression lines for each AGCM. The orange and light blue shaded areas represent the 5%–95% confidence intervals of the solid blue and red lines (supplementary methods). The numbers at the bottom of each panel indicate the differences in the slopes of the solid lines (1.5 °C minus 2.0 °C) and the 5%–95% confidence intervals of the differences (supplementary methods).

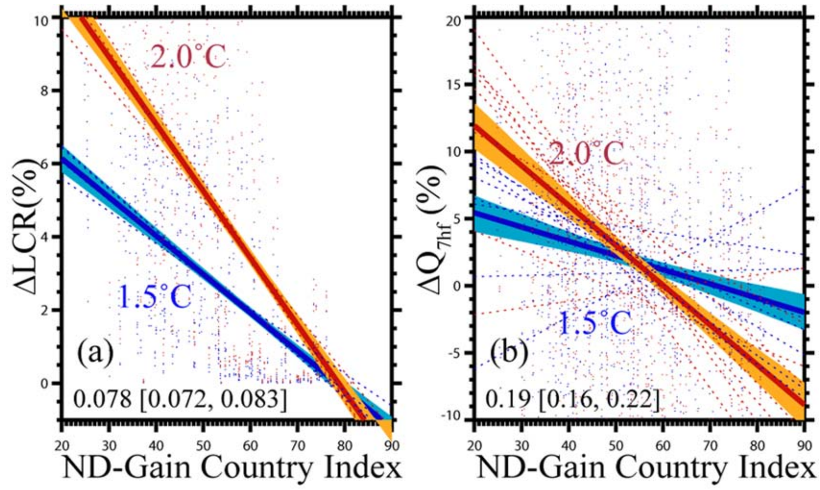

Figure 7. Uneven distributions of ΔLCR and ΔQ_{7hf} considering the ND-GAIN Country Index. The horizontal axes show the ND-GAIN Country Index. The vertical axes show the country-averaged (a) ΔLCR and (b) ΔQ_{7hf} values (%), weighted by the population in 2100. The blue and red dots indicate the values corresponding to each country in the 1.5 °C and 2.0 °C runs, respectively. Solid lines indicate the regression lines that are obtained when all of the model data are used. The dashed lines are the regression lines for each model. The orange and light blue shaded areas represent the 5%–95% confidence intervals of the solid blue and red lines (supplementary methods). The numbers at the bottom of each panel indicate the differences in the slopes of the solid lines (1.5 °C minus 2.0 °C) and the 5%–95% confidence intervals of the differences (supplementary methods).

greater vulnerability and lower readiness. There are obvious inequalities in the 2.0 °C runs: countries with lower ND-GAIN values (i.e. more vulnerable countries) are projected to suffer greater increases in extreme hot days, heavy rains and LCR. The severity of these inequalities is lower for these three indices when global warming is limited to 1.5 °C, rather than 2 °C.

In the 2 °C runs, 1-in-10 year Q_{7hf} largely increases in countries with low ND-GAIN values, and decreases in countries with high ND-GAIN values (figure 7(b)). The slope of the 1.5 °C runs is approximately zero. When we consider the human assets that can be damaged by inundation, the associated inequalities in the 1.5 °C world are lower than those in the 2.0 °C world, while that may not be the case for floodplain habitat requiring inundation.

Summary and discussion

By performing 2 °C and 1.5 °C warming runs of AGCMs, computing LCR and analyzing the outputs of the global hydrological model simulations, we show that keeping global warming to 1.5 °C, rather than

2.0 °C, lowers PR(TXx), PR(Rx5day), ΔLCR and ΔQ_{7hf}. Here we also examine the distributions of these four hazard indicators in relation to per capita CO_2 emissions, per capita GDP and ND-GAIN. There are uneven distributions: the regions with large increases of these four hazard indicators are characterized by small responsibility (small emissions/capita), low capability (low-income/capita) and high vulnerability (low-ND-GAIN). Keeping global warming to 1.5 °C, rather than 2.0 °C, limits these uneven distributions.

King and Harrington (2018) indicated that the ratios of annual mean temperature differences (2.0 °C minus 1.5 °C) and the internal variability are larger in lower-income countries. Russo *et al* (2019) suggested that heatwave exposure and an illustrative heatwave risk index (the product of the probability of heatwave occurrence, exposure and a proxy for vulnerability) at the 1.5 °C warming level for the population living in low development countries is expected to be greater than those at the 2 °C warming level for the population living in very high development countries. Döll *et al* (2018) showed that the effect on ΔQ_{7hf} of meeting the 1.5 °C goal rather than the 2.0 °C would be felt more strongly in the low-income country groups than other country groups. Our results are consistent with these previous studies. Furthermore we suggest that meeting the 1.5 °C goal limits the uneven distributions of the four hazard indicators in relation to not only GDP, but also CO_2 emissions and ND-GAIN values.

Our results are also consistent with Byers *et al* (2018) that analyzed distributions of a broader set of hazards and vulnerability indicators. They showed that global population exposure to multi-sector (water, energy, food and environment) risks approximately doubles between 1.5 °C and 2 °C warming. Large parts of global exposure to the multi-sector risks fall to Asian and African regions where the most of exposed and vulnerable population (income <$10/day) exist. Our four hazard indicators (not examined by Byers *et al* 2018) also have the largest changes in countries with low-income as well as low-emission and high-vulnerability, providing more evidence that a 2 °C warming is projected to increase the uneven distributions of hazard indicators compared to a 1.5 °C warming. On the other hand, the current mitigation policies of nations would lead to global warming of approximately 3 °C by 2100 (United Nations Environment Program 2018). A 3 °C warming would induce further changes in hazards (Lo *et al* 2019, Shiogama *et al* 2019) and a risk of additional increases in uneven distributions of some hazard indicators.

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Data availability

The AGCM and hydrological model simulation data are available from http://happimip.org and https://dkrz.de/WDCC/ui/cerasearch/q?query=cera%20happi&page=0&rows=15. We downloaded the ND-GAIN Country Index data from https://gain.nd.edu/our-work/country-index/ and the population data from http://sedac.ciesin.columbia.edu/data/set/popdynamics-pop-projection-ssp-2010-2100. The other datasets generated as part of the current study are available from the corresponding author upon reasonable request.

Code availability

The compute codes used to generate results presented in this paper are available from the corresponding author upon reasonable request.

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