

# Future population exposures to unprecedented climatic risks

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Physical Sciences - Article

Keywords:

Posted Date: November 9th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-101046/v1>

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# Abstract

Anthropogenic climate change is causing shifts in the frequencies of extreme weather events. There is an urgent need to quantify future unprecedented risks from extreme temperatures and precipitation, and the geographic distributions of at-risk areas. Here, we define the rim of two-dimensional (2D) risk histograms for 20-year extreme temperatures and precipitation as a climatic risk boundary. We found that nearly a quarter of the world population in South Asia, sub-Saharan Africa, and other regions of the world will transgress the climatic risk boundaries by the end of this century under RCP8.5 scenario, while under the future RCP2.6 scenario, only 5.8% of population will transgress the climatic risk boundaries. Some metropolitan areas, such as Delhi, Mumbai, and Tokyo, will also overstep the boundaries. While many large cities will remain within the climatic risk boundaries, they will still be exposed to unprecedented climatic risks in relation to the experiences of people in that region. This study will help refine public perceptions of extreme climatic risks and lead to more efficient policy making. In the future, unprecedented extreme weather risks should be properly considered in the impact assessments of climate change, and transfers of technologies and experiences gained in other regions to new at-risk regions should be supported to assist with adaptation to extreme climatic risks.

## Introduction

Human-induced climate change is increasing the frequency of heat waves and heavy rainfall<sup>1,2,3,4,5,6,7</sup>. These impacts have begun to manifest themselves in the form of various health hazards<sup>8,9,10</sup>, wildfires<sup>11</sup>, floods<sup>12</sup>, and other types of damaging events<sup>13,14,15,16</sup>. Since the Paris Agreement, in addition to mitigation efforts that act to slow the progression of climate change, adaptation efforts that symptomatically reduce the damage caused by climate-related events have been promoted<sup>1,3,6</sup>, but the limitations of these measures are of concern<sup>17</sup>.

Since climatic conditions change to levels unfamiliar to the flora and fauna of various regions, organisms will either need to adapt to the new climate conditions or change their habitats and behaviours to survive<sup>18,19</sup>. Humans are no exception here, and people are working to transform their socioeconomic systems to adapt to the changing climate, such as introducing different varieties of crops from other regions<sup>20,21</sup>. However, human society's ability to adapt is not always sufficient in relation to the speed of climate change<sup>22</sup>. In recent years, there has been an increase in the number of physical health problems caused by extreme weather events<sup>8,9,10,11,22</sup>.

Significant risks can arise when the magnitudes of climate change exceed the adaptive capacity of a region<sup>1,3,6,17</sup>. Previous studies have noted that an unprecedented climatic risk could have potentially serious impacts on socioeconomic systems<sup>1,3,6,17,23,24,25</sup>. These studies identified when and from which region climate departures from a range of past changes will occur<sup>23,24</sup>, and how human habitation niches will shift as a result of climate change<sup>26</sup>. For each region, the magnitude and the speed of the changing climate within the region was of the utmost interest<sup>3</sup>. However, for humanity as a whole, departure from

known climatic conditions would be highly problematic. Indeed, it is the extreme weather events that have the potential to adversely affect human health<sup>8,9,10</sup> and physical safety<sup>11,12</sup> that deserve heightened attention.

Here, we used changes in temperature and precipitation, which represent the most fundamental, representative, and influential climatic elements, to identify climatic risk boundaries outside of which the combined risks of extremely high temperatures and intense precipitation will be greater than those of current climatic conditions and virtually no human being has ever lived with such risks before. Then, we estimated the number of people who will live in such regions in the future under different representative concentration pathways<sup>27</sup> and socioeconomic scenarios<sup>28</sup>.

In this study, data from four general circulation models (GCMs)<sup>29,30,31,32</sup> employed in the Coupled Model Intercomparison Project Phase 6 (CMIP6)<sup>33</sup> were used to predict the changes in extreme temperature and precipitation, and the relationships between these data and human settlements are discussed. The combined risk of extreme temperature and precipitation in each grid within human settlements was estimated for the present climatic conditions (1980–2009) and for future climatic conditions (2070–2099) under two scenarios (RCP8.5-SSP5 and RCP2.6-SSP1, where RCP refers to the representative concentration pathway<sup>27</sup> and SSP refers to the shared socioeconomic pathway<sup>28</sup>, respectively). The rim of the 2D histogram of the present situation was regarded as the climatic risk boundary, and the people in the regions classified as outside of the climate risk boundaries will be exposed to unprecedented climate risks.

Supplementary Figure 1 shows the changes in the magnitude of once-in-20-year (hereafter 20-year) temperature and the coefficients of variation between the models for each scenario. Under the RCP8.5-SSP5 scenario, the 20-year temperature (Supplementary Figure 1a) is expected to rise significantly over the Northern Hemisphere mid-latitudes and the Amazon region with a maximum increase of ~6 °C. In the equatorial regions of Africa and Asia, the changes will be smaller but will still amount to nearly a 2 °C rise. Similarly, the predicted increase of the 20-year temperature under RCP2.6-SSP1 scenario (Supplementary Figure 1b) will be ~3 °C at maximum in the mid latitudes of the Northern Hemisphere and ~1 °C at minimum in the low latitudes of Africa and Asia.

The rate of increase in 20-year precipitation and the coefficients of variation among the models are shown in Supplementary Figure 2. Under the RCP8.5-SSP5 scenario, the increase in the 20-year precipitation in the Sahel and southern Arabian Peninsula will be more than double than that at present. Similarly, in the RCP2.6-SSP1 scenario, the increase rate will be ~1.5-times higher in the Sahel, Arabian Peninsula, and western India than that at present.

Figure 1 and Supplementary Figure 3 show the 2D histograms of the 20-year precipitation and temperature estimated for present and future conditions under the RCP8.5-SSP5 and RCP2.6-SSP1 scenarios, respectively. The colour density corresponds to the population under the climatic risks of 20-year temperature and precipitation. The blue histogram represents the present (1980–2009), and the red

histogram represents the future (2070–2099). A greater shift can be observed in the histogram from the present to the future under RCP8.5-SSP5 compared to that under RCP2.6-SSP1, and correspondingly, a larger population will transgress the climatic risk boundaries.

Figure 2 and Supplementary Figure 4 show the locations of the populations outside of the climatic risk boundaries around the world at the end of the 21st century under the RCP8.5-SSP5 and RCP2.6-SSP1 scenarios, respectively. Under the RCP8.5-SSP5 scenario, central India and portions of the Sahel region will overstep the climatic risk boundaries and be exposed to unprecedented climatic risks involving extreme temperatures and precipitation. Similarly, the Arabian Peninsula, northern India, and the Sahel region will be exposed to unprecedented extreme temperature risks. People in Southeast Asia and East Asia also will be exposed to unprecedented extreme precipitation risks. In total, there will be approximately 1.72 billion people, 23.3% of world population, living in areas that overstep the climatic risk boundaries under the RCP8.5-SSP5 scenario, whereas it will be approximately 401 million people, 5.81% of world population, under the RCP2.6-SSP1 scenario (Supplementary Table 1).

In this study, we have proposed a new concept of the climatic risk boundary<sup>34,35</sup>. This name was devised in relation to the so-called planetary boundaries, which are nine earth system limits that serve as prerequisites for sustainable development<sup>34,35</sup>. The climatic risk boundary concept is meant to supplement the idea of climatic elements within the planetary boundaries. According to the planetary boundary argument, exceeding these limits will lead to non-linear and abrupt changes within the system, with potentially catastrophic effects<sup>34,35</sup>. On the other hand, this study elucidates the data-driven boundaries of human settlements in terms of known climatic risks. Extreme weather events that occur beyond these boundaries are unknown to us and could cause direct catastrophic damage to humanity through health hazards and climatic disasters<sup>8,9,10,11,12,13,14,15</sup>. Under the RCP8.5-SSP5 scenario, more than 1.7 billion people, nearly a quarter (23.3 %) of the world population, will transgress the climatic risk boundaries and live under unprecedented climatic risks before the end of the 21st century. Mitigation measures can reduce the number of suffering people down to 401 million under RCP2.6-SSP1 and it corresponds to 5.81 % of the world population (Supplementary Table 1), however, still the significance of adaptation measures will remain.

Köppen's climate classification<sup>36,37,38</sup> and the Intergovernmental Panel on Climate Change's (IPCC) SREX report<sup>3</sup> estimates of changes in extreme weather events have used two basic climatic elements, viz. temperature and precipitation, for their assessments. This study also focused on the extremes of temperature and precipitation to delineate climatic risk boundaries. However, because we did not consider extremely low temperatures and precipitation, the climatic risk boundaries related to extremely low temperatures and/or droughts should be researched in the future<sup>39</sup>.

Human societies have been built to accommodate a variety of climatic factors, including wind speed, humidity, pressure, and sunshine hours<sup>40,41,42</sup>. Therefore, the construction of climatic risk boundaries that also consider the extremes of other climatic elements will make the potential risks of climate change

even clearer. In addition, extremes of longer time scales, in particular for precipitation, should be considered for continental scale floods and droughts<sup>43</sup>.

In this study, uncertainty in climate models has been taken into account. Besides that, climatic risk boundaries may depend on the definition of the return period and 'precedented' risk. Therefore, climatic risk boundaries should be set with regard to the intent of the assessment. Furthermore, it should be noted that even within the climatic risk boundary proposed in this study, i.e. the domain of known weather risk, the damage may not be necessarily minor if climate change progresses rapidly and the changes are significant<sup>44,45</sup>.

We must also mention that we presumed that the known climate risks can be adapted to if the risk has been experienced by human beings somewhere in the world, without considering any barriers to the transfer of adaptation measures. However, there is no guarantee that weather risks can be effectively managed by learning best practices from the people in the regions already under higher extreme risks. Cultural, social, or economical gaps may also prevent smooth transfer of knowledge and experiences from the regions where extremely high climatic risks have been managed to the regions that will be exposed to the risks for the first time<sup>17</sup>.

For example, the existence of people living under the risk of hotter and wetter weather does not necessarily mean that people in other parts of the world will be satisfied with the way they adapt to weather risks. The acceptability of the adaptations currently being employed by people in other regions cannot escape the influence of cultural and social aspects<sup>17</sup>. Figure 3 shows climatic risk boundaries of populations in Europe, East North America, East Asia, and South Asia. The change in climatic risks for some large cities are shown as arrows. Compared to the histogram for the entire world in Figure 3, it can be seen that the majority of the population in each region will be still within the climatic risk boundaries of 20-year temperature and precipitation. Nonetheless, the histograms for the present and future are almost exclusive for each region, and results indicate that most of the population will be living outside of the current climatic risk boundaries for that particular region. For example, many large cities in Central Europe will overstep the climatic risk boundaries for people living in Central Europe and people in those cities will be exposed to unprecedented risks, even though these are known risks for humanity as a whole (Figure 3a). Similarly, people in each city on the East Coast of the United States will be exposed to unprecedented climatic risks for that region, but some people in the world may have already been exposed to the similar risks (Figure 3b). On the other hand, the results show that some cities in East Asia and South Asia will be exposed to truly unprecedented extreme climatic risks (Figures 3c and 3d).

These figures allow us to judge whether the future extreme climatic risks are unprecedented. If the risks are known, we can ascertain which cities are currently experiencing the climatic risk and learn appropriate adaptation measures. More reasonable assessments of the risks will also be enabled by considering the transferability of knowledge and technologies in relation to social and economic disparities<sup>17</sup>. These findings highlight the importance of smooth exchanges of knowledge and technologies through global

partnerships based on multilateralism for implementing applicable adaptation measures to climate change.

## Methods

We calculated the magnitude of extreme weather events from four GCMs<sup>29,30,31,32</sup> employed in CMIP6<sup>33</sup>, and these were selected according to the availability of temperature and precipitation output data for all of the results of the RCP8.5-SSP5 scenario and RCP2.6-SSP1 scenario, as well as historical experiments when this study was initiated. However, different versions of GCMs from the same institutions cannot be considered as independent; here, only the latest ones were used even though there were multiple submissions for different versions of the GCMs. For the distribution of the annual maximum series of temperature and precipitation, the best-fit distribution was selected for each grid among the Generalized extreme value distribution, Gumbel distribution, Normal distribution, and Log Normal distribution, and then, the probabilistic values were calculated<sup>46</sup>. Because the sample data for the GCMs had a relatively small duration (30 years), the parameters of each distribution were estimated by using the Probability Weighted Moment method<sup>47</sup>. The goodness of fit of the distribution was evaluated by using the c-AIC (Akaike Information Criterion)<sup>47</sup>, and the best fit distribution was used for each type of experiment and grid. Because the four GCMs had different resolutions<sup>29,30,31,32</sup>, the estimated intensity of extreme weather events was interpolated to an equal-area grid with a resolution of 0.5° longitudinally and latitudinally, i.e. approximately 50 km × 50 km, and averaged. Because each of the GCM's output was considered to have a different bias, bias correction was conducted by using the extremes of temperature and precipitation calculated from the Climate Prediction Centre's (CPC) Unified Precipitation Project's product<sup>48</sup>.

The 2D histograms of 20-year temperature and precipitation weighted by population data under each scenario per grid with a resolution of 0.125° × 0.125° longitudinally and latitudinally in the grids were created<sup>49</sup>. The rim of the two-dimensional histogram was defined as a climatic risk boundary. To identify unprecedented climatic risks, from future histograms, the grids with a present value of the 20-year temperature and precipitation and the grids with a value smaller than 1 standard deviation above the mean of the present were excluded in order to eliminate small defects in the 2D histograms. Then, the remaining future grids that satisfied the condition of having a 20-year weather risk over 1 standard deviation above the mean value of the present 20-year value for both temperature and precipitation were defined as the grids exposed to unprecedented climatic risks; future grids that satisfied this condition for only temperature were deemed as the grids exposed to unprecedented extreme temperature risks, and future grids that satisfied this condition only for precipitation were deemed as the grids exposed to unprecedented extreme precipitation risks.

## Declarations

### Data availability

The gridded data of 20-year temperature and precipitation and the population data exposed unprecedented extreme climatic risk under each scenario are available at <http://hdl.handle.net/2261/00079735>

**Supplementary Information** is available in the online version of the paper.

## Acknowledgments

This work was supported by the Japan Society for the Promotion of Science [KAKENHI; 16H06291] and by the Environment Research and Technology Development Fund (JPMEERF20202005) of the Environmental Restoration and Conservation Agency of Japan. The authors are grateful for the supports on the data handling and bias correction by Drs. Hyungjun Kim and Satoshi Watanabe at The University of Tokyo.

## Author Contributions

TO and TS designed the research framework, TS conducted data analyses, and TO and TS developed and revised the manuscript.

## Competing Interests

N/A

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## Figures

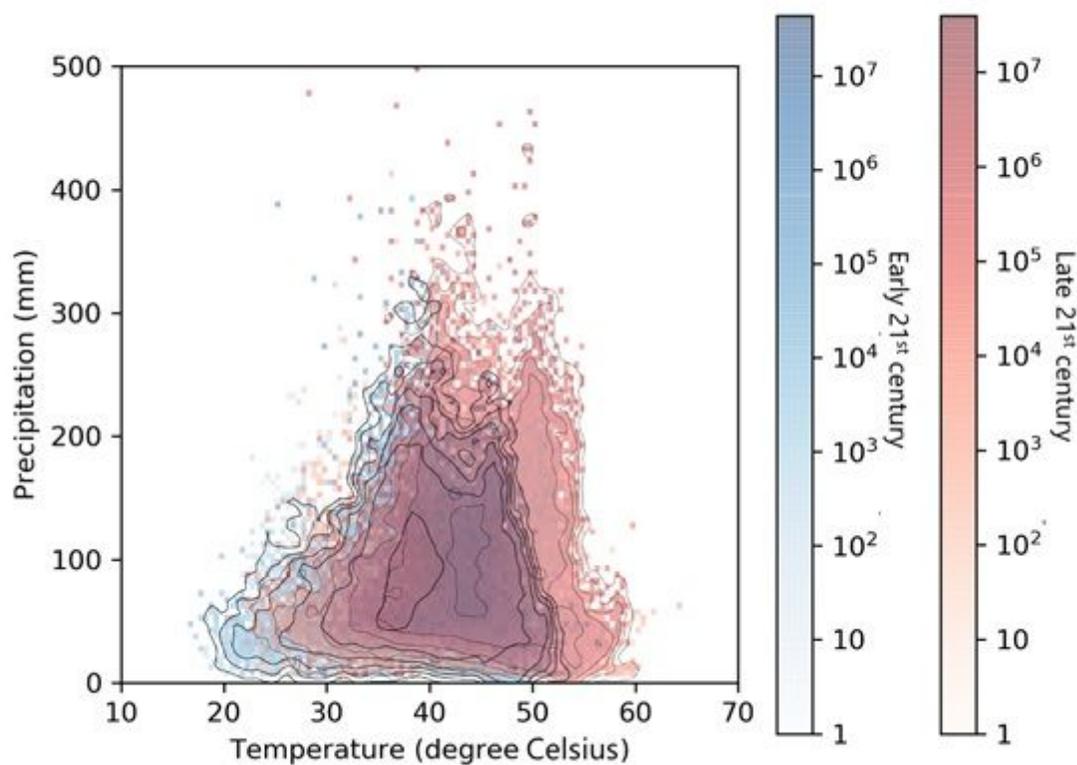
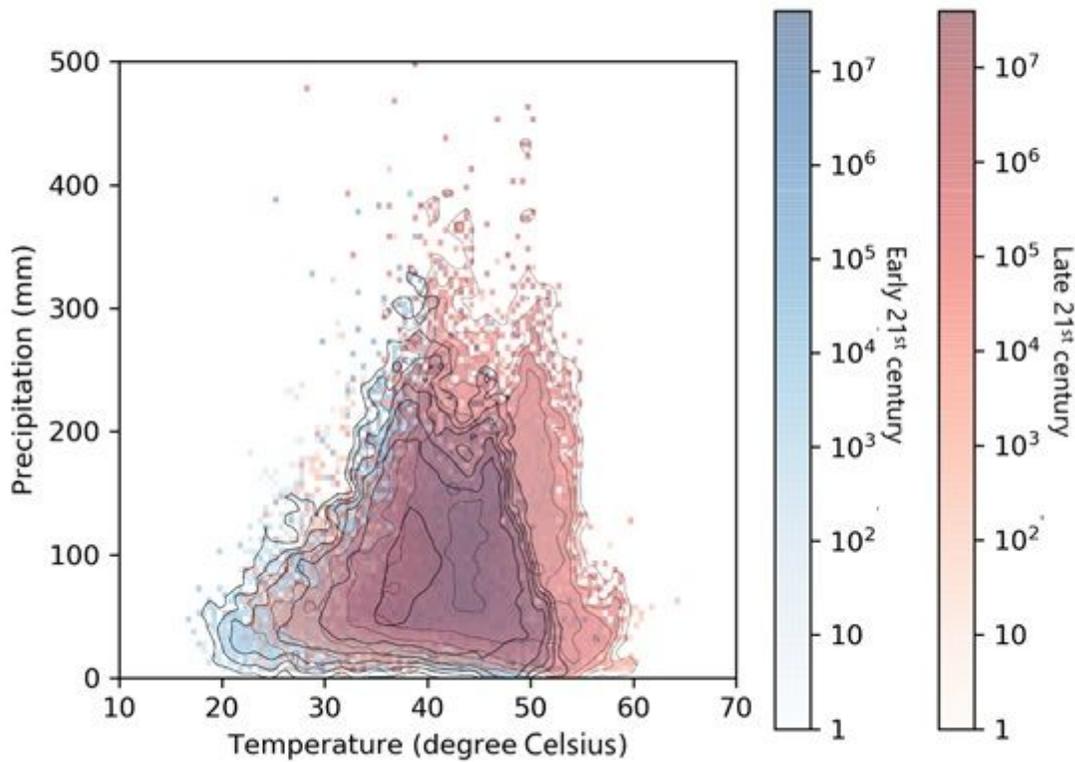


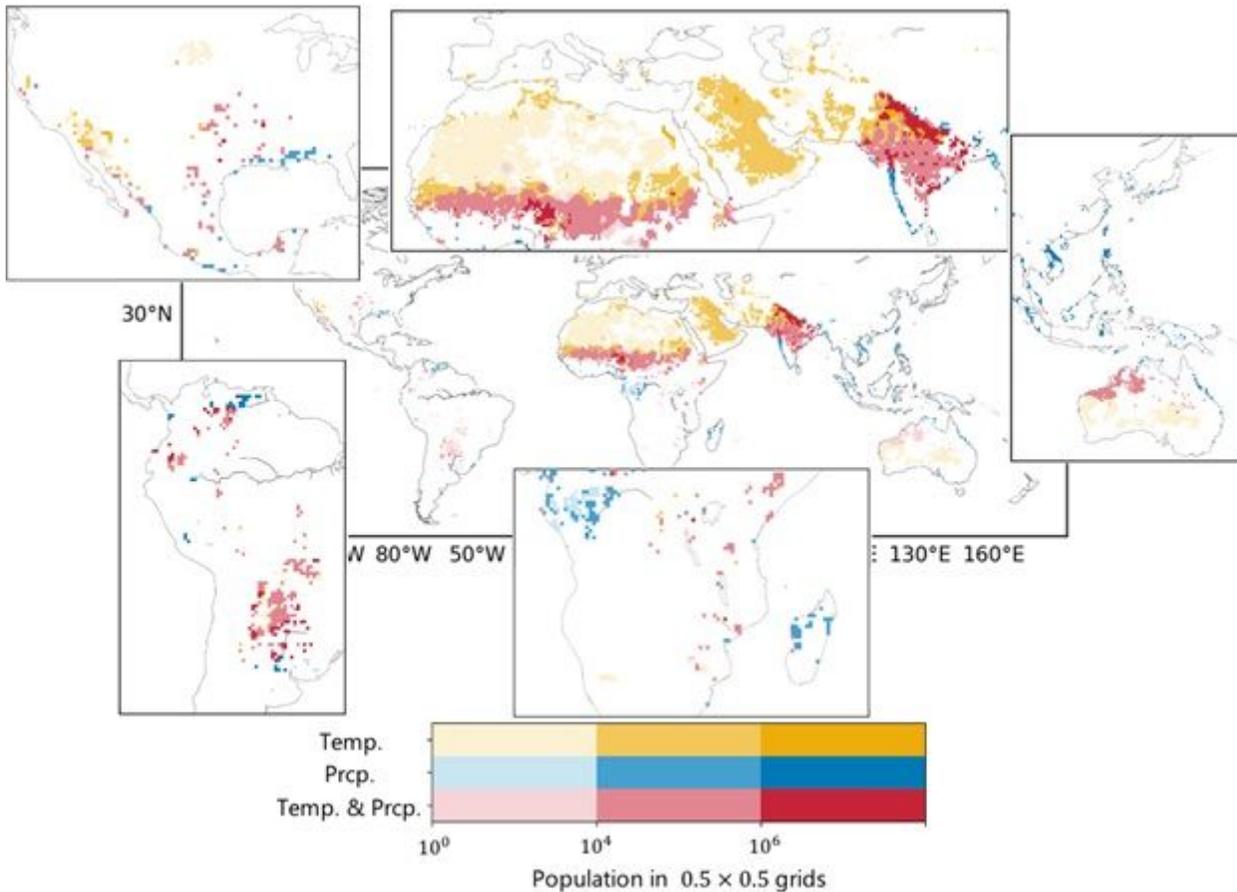
Figure 1

Projected change in the population exposed to extreme weather risks. Two-dimensional histogram representing the population exposed to the combination of extreme weather risks, calculated by the 20-year temperature and 20-year precipitation occurrences divided by bins of 0.5 °C and 10 mm, respectively. The blue histogram shows results for 1980–2009; the red histogram shows results for 2070–2099. These data are for the RCP8.5-SSP5 scenario. See Supplementary Figure 3 for a 2D histogram of the RCP2.6-SSP1 scenario.



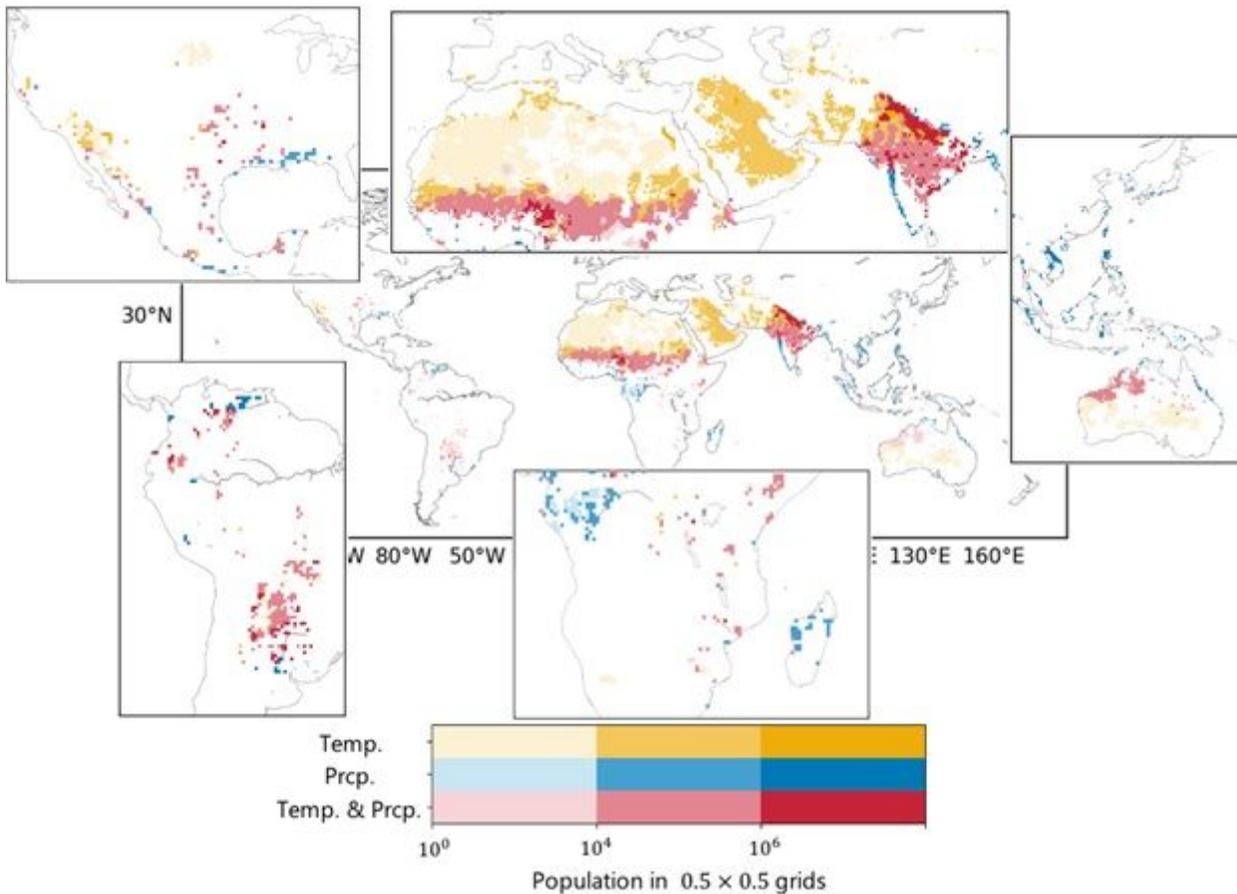
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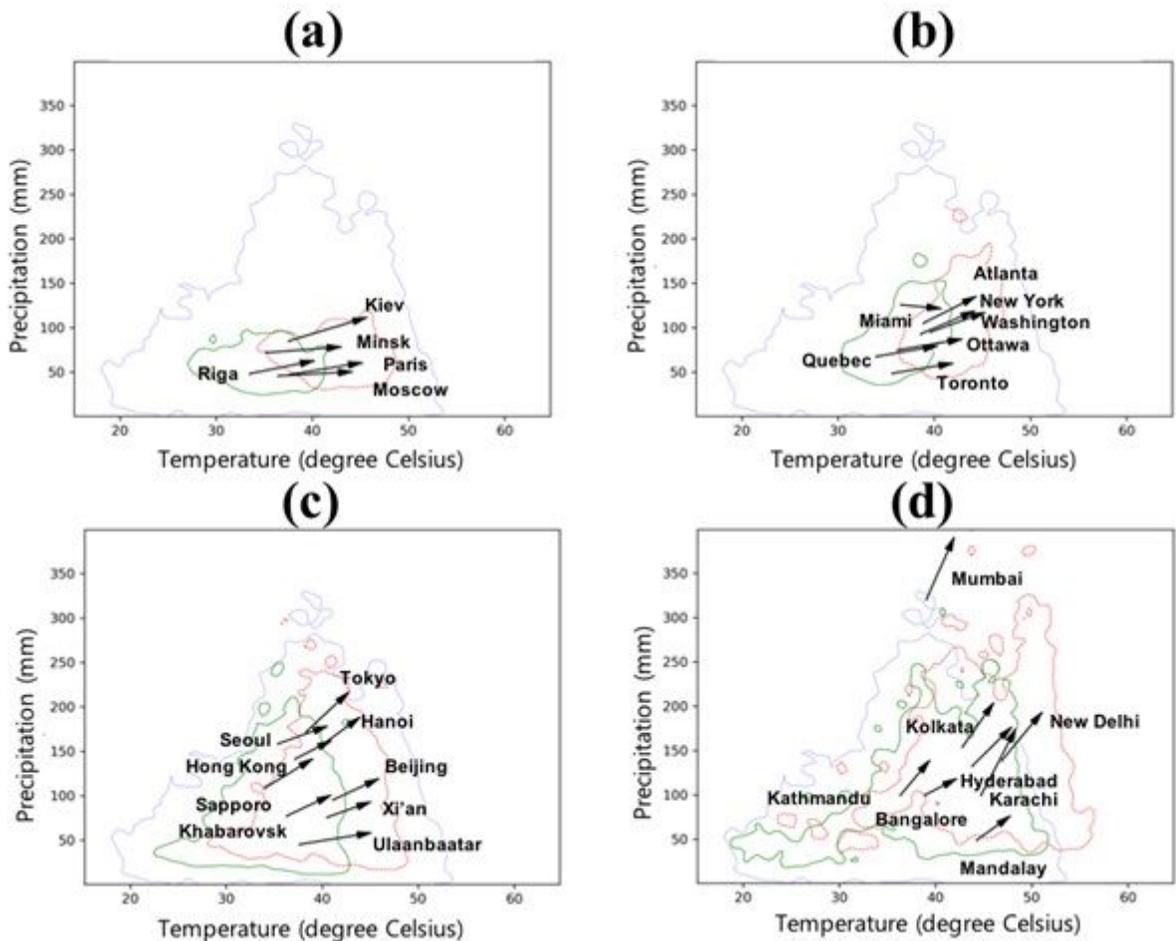
**Figure 2**

Enlarged map of the population expected to transgress the climatic risk boundaries and be exposed to unprecedented extreme climatic risks, with insets showing close-up views of the geographic distribution trends. In yellow and blue grids, people will be exposed to unprecedented extreme temperature and precipitation risks, respectively, while in the red grids, people will be exposed to a combination of unprecedented extreme climatic risks. Colour shades correspond to the density of residents; dark:  $>10^6$  people, mid-range:  $>10^4$  people, and light: at least 1 person in grids with spatial resolution of  $0.5^\circ \times 0.5^\circ$ , i.e. approximately  $50 \text{ km} \times 50 \text{ km}$ . See Supplementary Figure 4 for the original maps pertaining to the RCP8.5-SSP5 and RCP2.6-SSP1 scenarios.



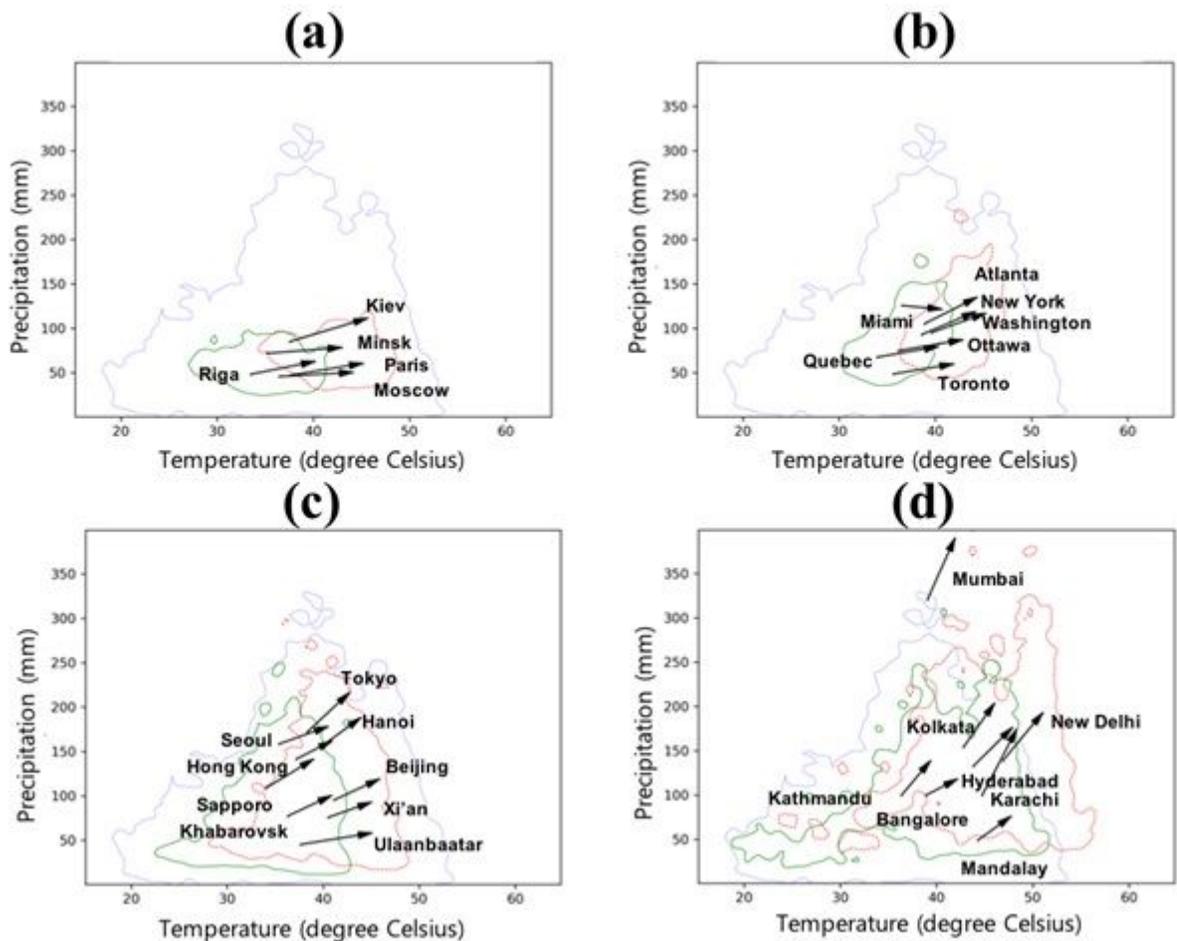
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**Figure 3**

Projected change in climatic risk boundaries of the 20-year temperature and precipitation in (a) Central Europe, (b) East North America, (c) East Asia, and (d) South Asia. Arrows show the shifts in extreme climatic risks in large cities represented by the direction of the arrow from the present climatic conditions (1980–2009) to the future climatic conditions (2070–2099) under RCP8.5-SSP5 scenario. See Supplementary Figure 5 for the regional classifications and Supplementary Figure 6 for the change in climatic risk boundaries of the 20-year temperature and precipitation in the other regions.



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