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Every year, millions of people around the world are being displaced from their homes due to climate-related disasters. River flooding is responsible for a large part of this displacement. Previous studies have shown that river flood risk is expected to change as a result of global warming and its effects on the hydrological cycle. At the same time, future scenarios of socio-economic development imply substantial population increases in many of the areas that presently experience disaster-induced displacement. Here we show that both global warming and population change are projected to lead to substantial increases in flood-induced displacement risk over the coming decades. We use a global climate-hydrology-inundation modelling chain, including multiple alternative climate and hydrological models, to quantify the effect of global warming on displacement risk assuming either current or projected future population distributions. Keeping population fixed at present levels, we find roughly a 50% increase in global displacement risk for every degree of global warming. Adding projected population changes further exacerbates these increases globally and in most world regions, with the relative global flood displacement risk is increasing by roughly 350% at the end of the 21st century, compared to an increase of 150% without the contribution of population change. While the resolution of the global models is limited, the effect of global warming is robust across greenhouse gas concentration scenarios, climate models and hydrological models. These findings indicate a need for rapid action on both climate mitigation and adaptation agendas in order to reduce future risks to vulnerable populations.

1. Introduction

Since 2008, disasters caused by natural hazards have caused 288 million people to be displaced⁶, three times more than the number of people that have been displaced within their countries as a result of wars, conflicts and violence [1]. Floods are the largest cause of displacement, accounting for about half of all disaster displacements; floods alone have caused 63% more displacement than conflict and violence [1].

⁶Note that these numbers throughout this paper also include people displaced repeatedly.

Displacements may be brief, such as precautionary evacuation before an impending flood. Yet if there is significant damage to people's homes and community infrastructure, and/or disruption of livelihoods and community services, displacement can be prolonged.

Displacement poses many hardships. These hardships often fall most heavily on socio-economically vulnerable groups, who tend to live in more hazard-prone areas [2–4] and lack the resources to cope with displacement. Displaced people face heightened risks to their physical and mental health, livelihoods, land tenancy, personal security, and many other aspects of their well-being [5–9]. Under normal circumstances,

displaced people are at heightened risk of disease and other health problems, as sanitation is difficult to maintain and access to health care is often limited [10]. At the time of this writing, the ongoing COVID-19 pandemic poses additional risks both to those who are displaced and to the societies of which they are a part. It is very difficult to maintain appropriate physical distancing and other protective measures during mass evacuations and temporary sheltering [11–13]. These heightened risks at the intersection of disaster displacement and the COVID-19 crisis may well lead to disproportionate impacts on already-marginalised populations [14].

From a long-term perspective, displaced people are among those most at risk of being ‘left behind’ by economic development and who need special consideration in order to achieve the Sustainable Development Goals. While governments and the United Nations (UN) have adopted global compacts for refugees and migrants, there has been a relative lack of attention on those displaced by disasters, something that will be addressed by the UN secretary-general’s recently formed high-level panel on internal displacement [15]. In fact, according to the secretary-general, displacement and climate change represent the key challenges we face as a global community [16, 17]. Progress is needed in order to break the cycle in which disaster displacement comes about due to people’s underlying exposure and vulnerability to natural hazards, then also exacerbates those same factors [18].

Because floods are a major driver of displacement [18] and due to the fact that they are influenced by climate change, it is imperative that we have a better understanding of the future flood displacement risk and how climate change and demographic and socio-economic factors will influence it. The Intergovernmental Panel on Climate Change (IPCC) aims to address displacement within its next assessment report AR6 [19], but much more evidence is needed in order to yield confident conclusions. In the present study, we focus on the displacement due to riverine floods.

Disaster risk, or hereby specifically river flood risk, has been defined in terms of the following three elements: (a) the complex interactions of weather- and climate-related hazards; (b) the exposure of people, or economic, social, or cultural assets to the hazards; and (c) the vulnerability of those exposed people and socio-economic systems [20]. Previous efforts have already proposed a globally consistent framework to estimate the riverine flood risk [21, 22], and identify such risk in the present day climate [23, 24]. With further global warming, the frequency of floods is projected to increase in Southeast Asia, eastern Africa and in northern half of the Andes, while it is projected to decrease in some other parts of the world such as the European continent [25].

Other studies have assessed the potential future effects of projected riverine flood risk in terms of

monetary values and exposure of people due to both climate change and socio-economic development. Under the framework of the Paris Agreement, which aims at limiting the global temperature rise to 1.5 °C compared to the pre-industrial level [26], the number of people exposed to flood will increase by around 50%–60% globally, depending on the socio-economic scenario [27]. Another similar study found that gross domestic product (GDP) damage due to flood could increase 20-times by the end of the century if no mitigation or adaptation measures are taken [28]. The same study also highlights that the increase of risk in Southeast Asia is mainly contributed by climate change, whereas in African countries it is mainly driven by socio-economic growth [28]. However, previous studies have not yet evaluated the effects on population displacement.

This study uses scenario-based projections to estimate the changing trend of river flood displacements globally and at the regional level. Such methods enable us to capture the dynamics of climate change and socio-economic development in the long run. Here we also examine whether flood displacement risk is driven by climate change, by social economic development, or by both.

2. Data and methods

We calculate population exposure to river floods by combining projections of flood hazard and population distribution, and then apply a vulnerability function to calculate displacement risk. The calculations are made using the open-source software CLIMADA (CLIMate ADAPtation) [29].

Flood hazard is derived from climate and hydrological models in the framework of the Inter-Sectoral Impact Model Intercomparison Project phase 2b [30]. To assess the effects of uncertainty regarding the response of the climate system to greenhouse gas (GHG) forcing as well as the response of terrestrial hydrology to climatic changes, we employ an ensemble of six different global hydrological models (GHMs) [31–37], each driven with weather variables simulated by four general circulation models (GCMs) within the Coupled Model Intercomparison Project phase 5 (CMIP5) [38]. Not all GCM-GHM combinations were simulated, resulting in a total of 21 alternative flood simulations (table S1 (available online at stacks.iop.org/ERL/16/044026/mmedia)). The resulting runoff time series are then distributed by the global river and floodplain model CaMa-Flood (v3.6.2) [39] to derive river discharge. For each of the projected flood events, the fraction of the grid cell area inundated was estimated using a bias-correction and downscaling technique [40]. For that we use the 300 year-long pre-industrial control runs of each GHM-GCM combination (no anthropogenic GHG forcing) and use annual maximum discharge to which we fit a generalized extreme value distribution to

derive, for each cell and model combination, a relation between discharge and annual return period, thereby reducing regional model bias. For each projected year we look up the flood depth corresponding to this return period from an observation-driven MATSIRO run [25]. In that, we assume a flood event to only occur when the return period exceeds the current local flood protection standard retrieved from the FLOPROS database [41]. Finally, the annual maximum flooded area and annual maximum flood depth were downscaled to a spatial resolution of 2.5' (about 5 kilometres at the equator) using flood-difference maps [39] thereby deriving the maximum annual flood fraction for each grid cell.

Two scenarios of GHG concentrations are used for the study, the IPCC representative concentration pathways (RCPs) 2.6 and 6.0, respectively [42]. RCP2.6 represents strong GHG mitigation efforts with a projected temperature rise compatible to the Paris Agreement of limiting global temperature rise to 1.5 °C [26]. RCP6.0, on the other hand, represents weak GHG mitigation efforts and constitutes a close estimation of the global temperature rise to 3 °C by 2100 [43]. We point out that RCP6.0 is not a worst-case scenario; substantially higher GHG concentrations are plausible under some of the shared socio-economic pathways (SSPs). However, RCP6.0 represents concentration levels attainable under all of the SSPs according to integrated assessment models, and thus serves here as the weak mitigation case, in contrast to the strong mitigation scenario RCP2.6 [44, 45].

As exposure dataset we use the spatially explicit population distribution in the 21st century [46] projected under the SSPs [44], downscaled to a spatial resolution of 1 kilometre and a temporal resolution of 10 years [47], which was retrieved from the National Center for Atmospheric Research. The raster files of the population distribution are remapped to the 2.5' resolution common with the hazard datasets. We consider two scenario combinations: RCP2.6 with SSP1 (commonly referred to as the 'Sustainability Development'), and RCP6.0 with SSP4 (the 'Inequality' or 'A Road Divided') [48, 49]. Both SSPs share the same baseline of population distribution in the year 2000.

Damage to people's housing due to flood water can lead to displacement of the residents. Typically, modelling approaches use a vulnerability (impact) function to relate the flooding hazard intensity to the expected damages to the exposed buildings [50]. Here, a previous study has shown that a static flood-water depth between 0.5 metre to 2 metre could cause substantial damage to a reinforced concrete frame building [51]. Another study found a steep increase of building damage ratio when the water depth above ground floor between 0 to 1 metre [52]. Some flood prone areas, such as Bangladesh, houses are usually 1 metre higher than the agricultural fields and

livestock sheds in order to adapt the floods [53]. Therefore, we use a 1 metre step function to relate flooding depth to displacement risk.

This modelling approach assumes that displacement will occur if the flood depth is above 1 metre but no displacement if the flood depth is below this threshold. While of course this does not capture all the physical and socio-economic factors that influence displacement, such a simplifying assumption is necessary in order to model displacement at the global scale. Here we also assume the populations are evenly distributed inside each cell. Therefore, the annual maximum number of people displaced in a grid cell is estimated by multiplying the number of people living in that cell with the flood fraction if the maximum flood depth is greater than or equal to 1 metre. As such, the annual maximum number of people displaced is defined as the displacement risk. We would like to point out that the use of the annual maximum flood depth and annual maximum flood fraction tends to overestimate the number of people displaced by river floods annually, we report the percentage change of displacement risk in the projected futures compared to a baseline value, detailed in the next paragraph.

We compute a 10 year average of the annual maximum displacement, holding population constant during that time interval. Then the 10 year average is divided by a baseline value, which is an average annual maximum displacement computed using the flood dataset for 1976–2005 with a constant population in 2000. This yields, a relative displacement risk for every decade. As such, a 0% change of flood displacement risk means no change of risk to the respective baseline, whereas a 100% means the risk is doubled, and so on.

In order to test the representability of this 1 metre step function, we ran the same displacement risk analysis using different flood depth thresholds ranging from 0.5 to 2 metres with an increment of 0.5 metre (supplementary information S2.1). We find that the percentage change of the global displacement risk varies by around 5% less and 15% more when using the displacement threshold is 0.5 metre flood depth and 2 metres flood depth compared to the 1 metre threshold, respectively (figure S2). Therefore, we keep the preferred 1 metre threshold in this study.

In addition to the 1 metre step function, we also test the sensitivity of the results using sigmoid logistic functions with growth rates of 10 and 30, respectively (supplementary information S2.2). The yielded percentage change of global displacement risk with sigmoid logistic functions are +292% and +268%, respectively, compared to +296% estimated by the 1 metre step function (figure S4). Here we present the results using the preferred 1 metre step function in the rest of the paper.

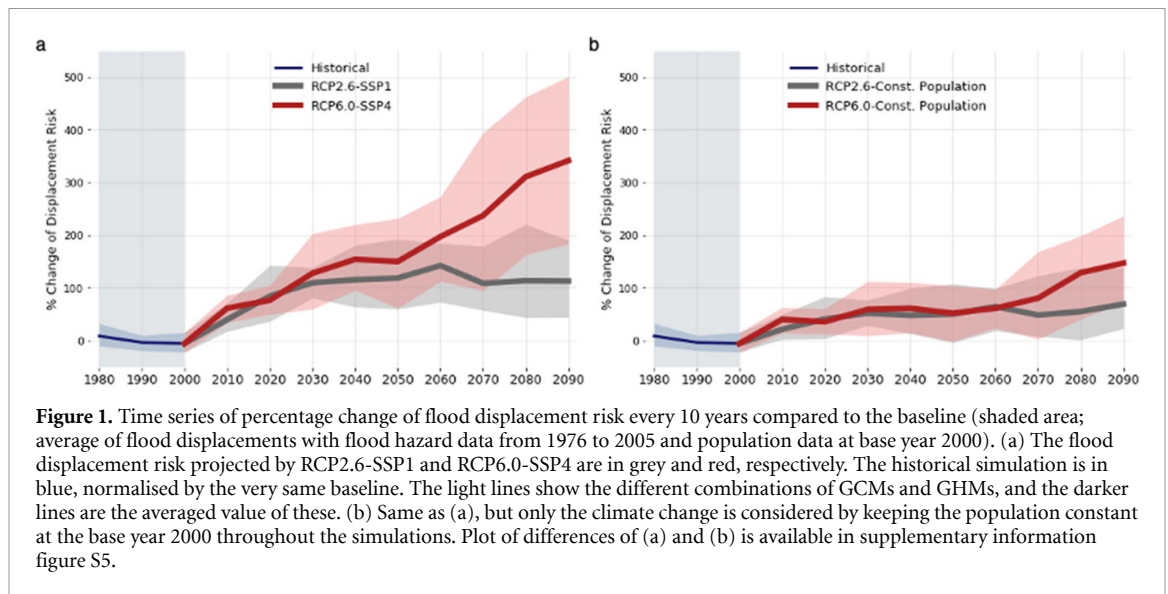


Figure 1. Time series of percentage change of flood displacement risk every 10 years compared to the baseline (shaded area; average of flood displacements with flood hazard data from 1976 to 2005 and population data at base year 2000). (a) The flood displacement risk projected by RCP2.6-SSP1 and RCP6.0-SSP4 are in grey and red, respectively. The historical simulation is in blue, normalised by the very same baseline. The light lines show the different combinations of GCMs and GHMs, and the darker lines are the averaged value of these. (b) Same as (a), but only the climate change is considered by keeping the population constant at the base year 2000 throughout the simulations. Plot of differences of (a) and (b) is available in supplementary information figure S5.

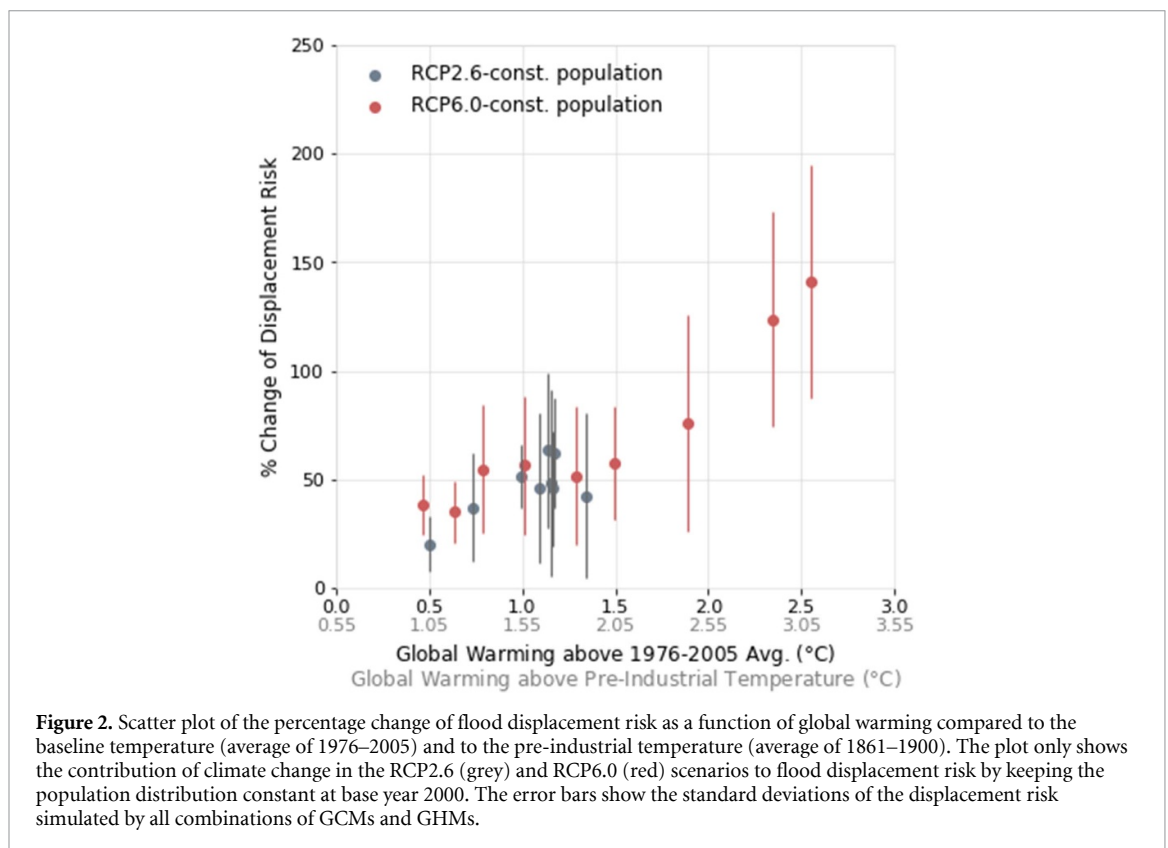


Figure 2. Scatter plot of the percentage change of flood displacement risk as a function of global warming compared to the baseline temperature (average of 1976–2005) and to the pre-industrial temperature (average of 1861–1900). The plot only shows the contribution of climate change in the RCP2.6 (grey) and RCP6.0 (red) scenarios to flood displacement risk by keeping the population distribution constant at base year 2000. The error bars show the standard deviations of the displacement risk simulated by all combinations of GCMs and GHMs.

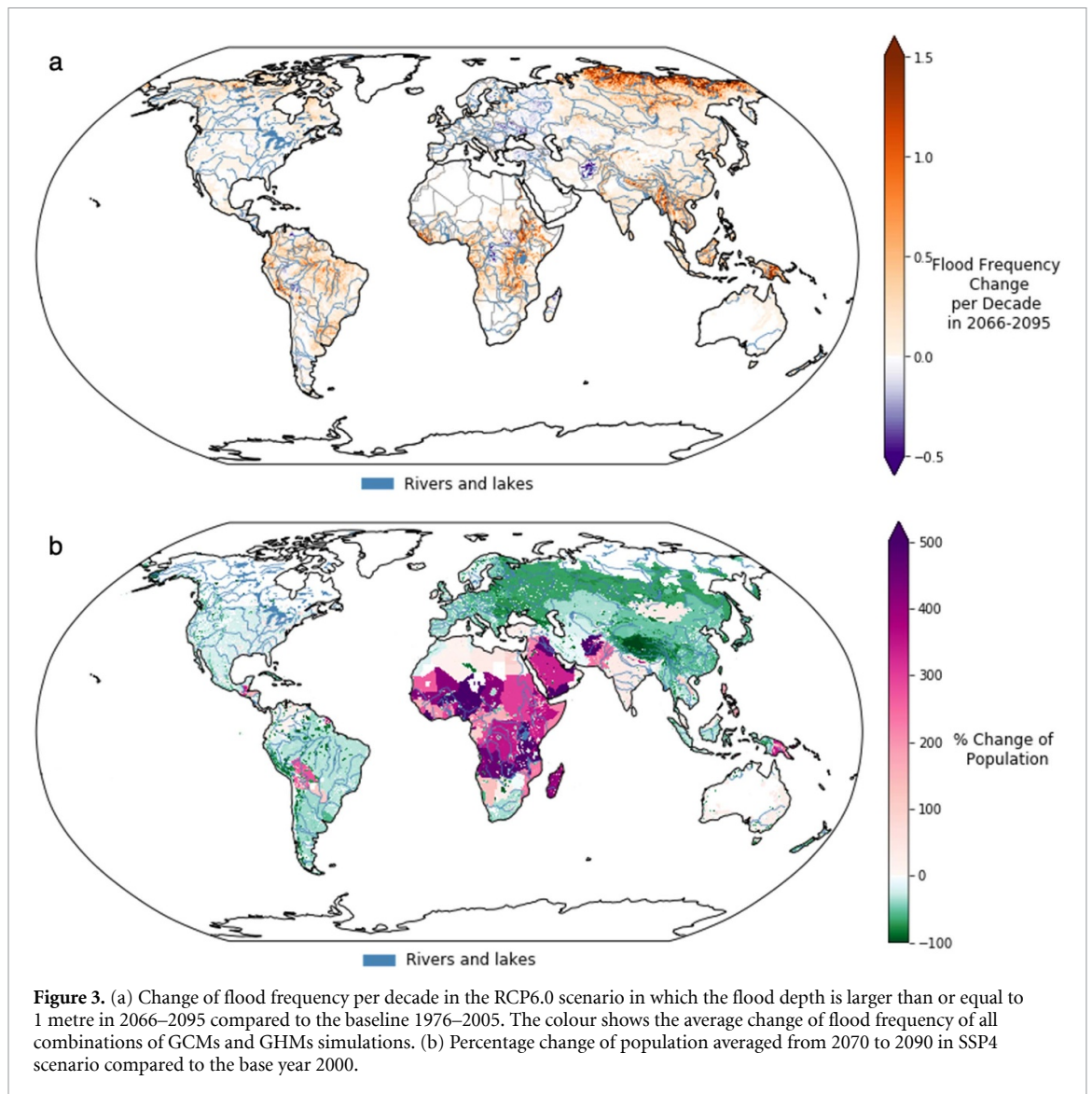
3. Results

3.1. Flood displacement risk at the global scale

The trend of flood displacement at the global scale is a compound effect of both the increasing intensity and frequency of flood hazard due to climate change as well as socio-economic development, represented by the RCP and SSP scenarios, respectively.

Figure 1(a) shows the relative change of flood displacement risk at the global scale with the coupled RCP and SSP simulations. The light lines represent each of the combinations of the GCM and

GHM simulations and the thick lines are the average of the combinations. With weak mitigation of climate change (RCP6.0) and the ‘inequality’ scenario of socio-economic development (SSP4; figure 1(a), red curves), the multi-model average displacement risk is estimated to rise steadily to +350% (range +183%–500%) compared to the baseline by the end of the century. Using the more optimistic combination of substantial mitigation of climate change (RCP2.6) and the ‘sustainability’ scenario of socio-economic development (SSP1; figure 1(a), grey curves), the multi-model average displacement risk is



projected to double by mid-century and then remain mostly steady to +110% by the end of the century.

To consider only the contribution of climate change to displacement risk, we also run simulations where only the flood hazard sets change with time but the population distribution is kept constant at the year 2000 baseline. By mid-century, both RCP2.6 and RCP6.0 result in similar projections of displacement risk at around +50% (figure 1(b)). At the end of the century, RCP6.0 shows a further rise to around +150% increase of displacement risk, whereas the risk in RCP2.6 remains more or less stable near +50%.

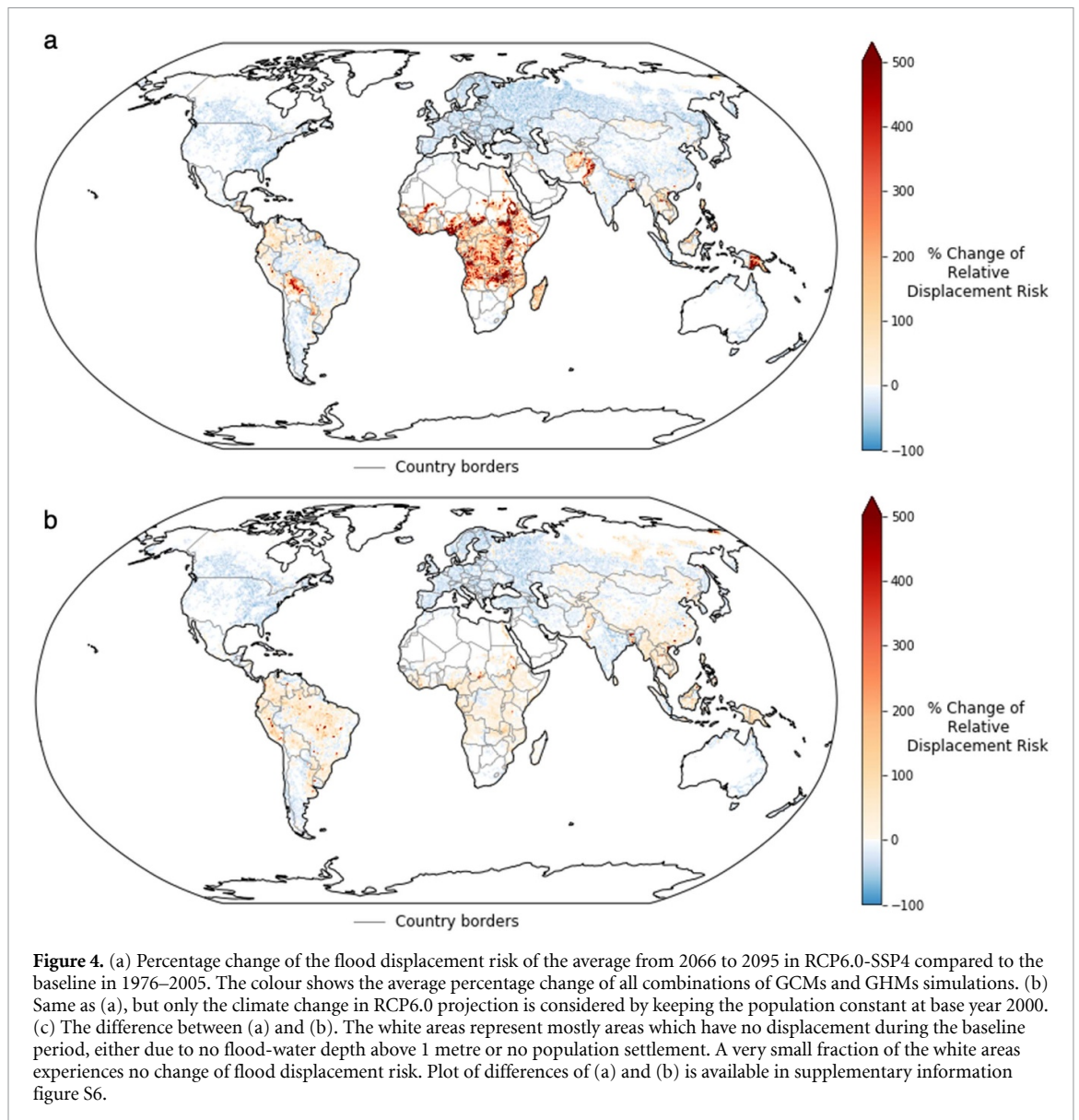
We also examine displacement risk as a function of the level of global warming, a framing that is relevant to the Paris Agreement framework [26]. Figure 2 shows the same results as figure 1, but as a function of the level of global warming rather than of time. Between a warming of 1.5 °C to 2 °C above the pre-industrial level, the displacement risk is expected to rise by approximately 50% in the multi-model mean, across both scenarios (figure 2). Warming of 2.5 °C

above the pre-industrial level results in a substantially larger rise of displacement risk of approximately 75%.

3.2. Flood displacement risk at the regional scale

In the previous section we have shown that flood displacement risk increases globally in both of the scenarios, but with different magnitudes. Here we investigate regional variation in changes in flood displacement risk using the RCP6.0-SSP4 scenario. The RCP2.6-SSP1 scenario shows similar regional patterns but with lesser magnitude, as presented in supplementary figures S5–S7.

Displacement would occur more frequently if the frequency of severe flooding that exceeds the 1 metre threshold increases in the populated area. We compute the frequency change of flooding exceeding the 1 metre threshold during the period 2066–2095 in the RCP6.0 scenario compared to the baseline period. Figure 3(a) presents the average of the flood simulations (combinations of GCMs and GHMs). Floods exceeding 1 metre are projected to occur more frequently in Siberia, southern and eastern Asia, the

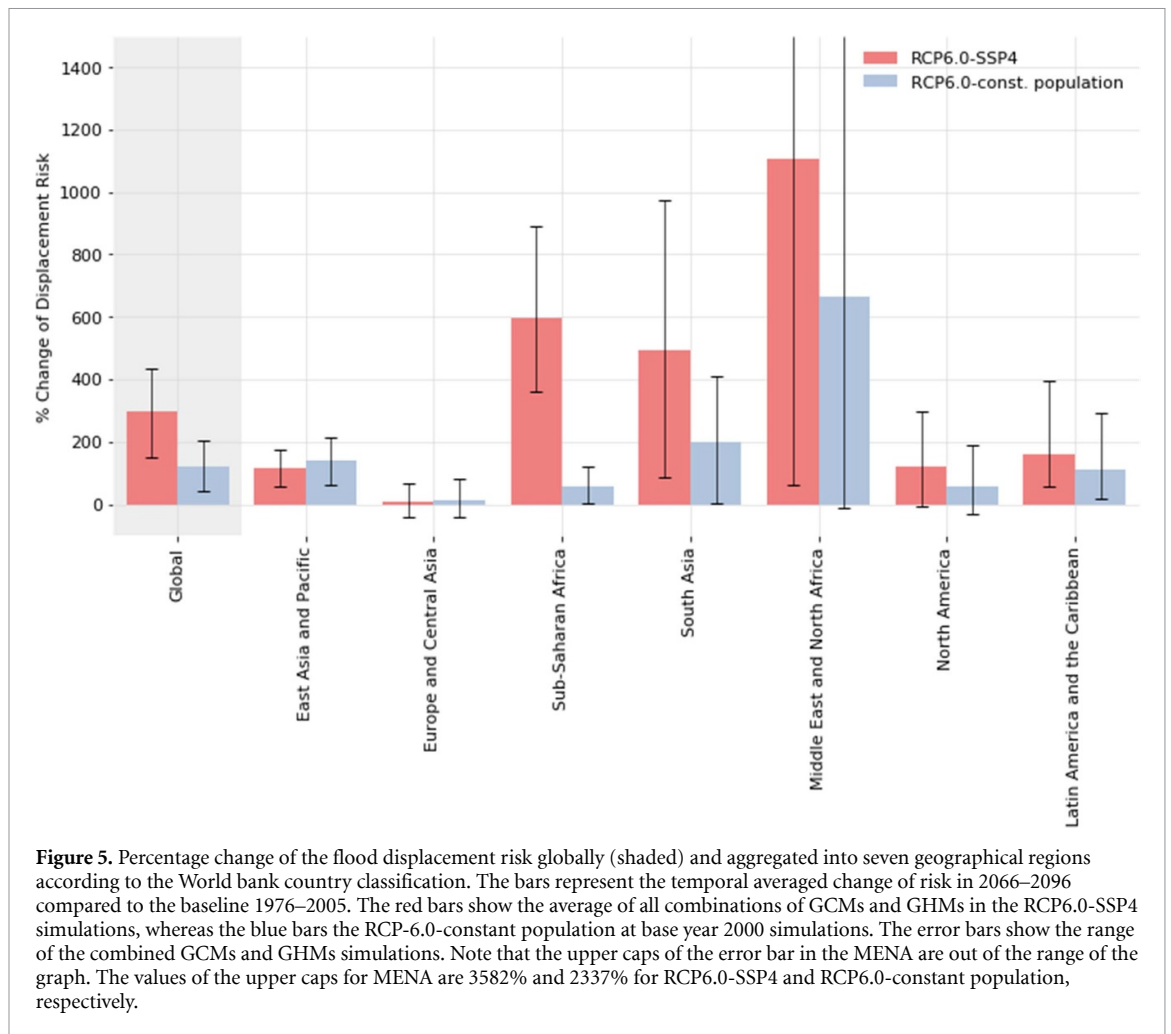


islands of Southeast Asia, central and east Africa, much of South America, and scattered areas in North America. In contrast, floods exceeding 1 metre are projected to occur less frequently in Europe and the highlands in Afghanistan. The distribution of flood frequency change is consistent with a previous study by Hirabayashi *et al* [54]; they however presented the flood frequency change in the RCP8.5 projection, a scenario which features a higher warming.

Apart from the frequency of flooding, population increase in flood-prone areas would also intensify displacement risk. Figure 3(b) shows the percentage change of population averaged from 2070 to 2090 in SSP4 relative to the base year 2000. Africa, the Middle East, Afghanistan and Pakistan are projected to have substantial increases in population. There are also some increases in Mongolia, India, Polynesia, coastal Australia, the Caribbean Islands, and a small area in central South America. In contrast, the

remaining part of the world generally has a decrease of population at risk by the end of the century.

Combining both regional changes in flood frequency and in population (figure 3), we estimate the average percentage change of flood displacement risk during 2066–2095 relative to the baseline period, as shown at 2.5' resolution in figure 4(a). Central and eastern Africa, Polynesia, and the Indus river basin area show the most significant increase in flood displacement risk. The estimated increase in displacement risk in these regions is less pronounced if we hold population constant and consider only flood hazard variations due to climate change (figure 4(b)). This implies that population growth contributes substantially to the overall increase in displacement risk in these regions. In contrast, in China flood displacement risk increases in the RCP6.0-constant population projection but decreases in the combined RCP6.0-SSP4 projection, indicating that the increase of displacement risk due to climate change



is compensated by the projected (SSP) decrease of population in the country. Most of the white areas in the figure (notably the Siberia, the Saharan Desert and Middle East, deserted area of Australia, northern Canada and Greenland) denote areas which displacement is zero during the baseline period, either there is no flood-water depth above the 1 metre threshold or no population settlement. Moreover, a very small fraction of the white areas experience no or very little change of flood displacement risk.

Figure 5 aggregates the results that are shown in maps in figure 4 at the level of the 7 geographic regions as defined by the World Bank Country Classification. For each region, the difference between the red and blue bars in figure 5 indicates the additional influence of population change on river flood displacement risk beyond that of climate change alone. Where the red bars (climate change and population change) are higher than the blue bars (climate change only), population change also increases river flood displacement risk. This is most pronounced in Sub-Saharan Africa, which has a large increase of displacement risk in the combined projection (+598%), but relatively small increase of displacement risk in the climate-change-only projection (+55%), implying that the population growth in the flood prone area is

the main driver of the increase in displacement risk in this region. South Asia and North America have increased risk in the combined RCP6.0-SSP4 simulation of about +493% and +120%, respectively, while the climate change only simulation roughly half of the numbers (+200% and +58%, respectively). Latin America and the Caribbean also have a larger increase in the combined simulation than the climate change only simulation, accounting for a respective +161% and +113%.

In contrast, where the blue bars (climate-change only) in figure 5 are higher than the red bars (climate change + population change), population change acts to counter the increase in displacement risk caused by climate change. This is the case in East Asia and the Pacific, which experiences a slightly higher flood displacement risk with only climate change (+141%) compared to the results that also include population growth (+115%), indicating that climate change is the main contribution of the risk in these regions.

While the Middle East and North Africa (MENA) have the largest percentage increase of displacement risk, an important caveat is that the number of flood events during the baseline period is small or even none; this may result in a very large percentage

increase with a few flood events with long return period occurs towards the end of the century. This paucity of baseline data in this region also results in a very large spread of the simulated results, indicated by the large error bars in figure 5.

4. Discussion and conclusion

In this study we show that the globally averaged risk of people being displaced by river floods is projected to double (+110%) by the end of this century under a more optimistic scenario that is in line with the targets of the Paris Agreement (RCP2.6-SSP1), while this displacement risk is projected to increase by 350% under a scenario more in line with 'business as usual' (RCP6.0-SSP4). These projections are based on an ensemble of multiple climate and hydrological models as well as scenarios of population change.

While more frequent flood events in a warming climate contribute to the increase of river flood displacement risk, the growth of population in flood-prone areas also increases this risk. We find that for most regions, both increased flooding and population growth contribute to increased risk of displacement by river floods. Regions such as Sub-Saharan Africa experience higher flood displacement risk that is mainly driven by the population growth, while the increase of risk in East Asia and Pacific and in Latin America and the Caribbean is more driven by the increase of flood events.

Although the changes in flood displacement risk will be distributed unevenly across the globe, the different scenarios also show that the risk of flood displacement can still be addressed and managed. There are a number of ways to manage this risk. One clear opportunity concerns urban planning, since the regions with the largest increases in displacement are those projected to become more urban over the coming decades. However, some countries such as those from the Sub-Saharan region have a relatively low human development index [55] but a large increase in flood displacement risk, that implies two things: first that there are potential synergies between efforts to address human development and flood displacement risk; and second, that the failure to realise these synergies could have dire outcomes in terms of high levels of displacement and socio-economic vulnerability.

There are several limitations intrinsic modelling global flood displacement risk. On the physical hazard side, uncertainties that are related to the input flooding projections under climate change are taken into account only to the extent that they are covered by our multi-model ensemble, while uncertainties about future population change are not examined here beyond comparing SSP1 and SSP4. Rare events with a high return period (i.e. beyond 100 year return period) may not be captured in this work very well. We only analyse approximately 100 year-long simulations with a limited number of models, the

sample size thus limiting the resolution of such rare events. On the societal impact side, the population projections do not consider future adaptation measures. Abandonment of settlements due to more severe and frequent river flood events are not considered in the population projections. In addition, the relationship of the flooding intensity and displacement is much more complex and context-dependent than our modelling assumption that displacement occurs when the flood depth reaches the 1 metre threshold. Such simplification is necessary in global modelling risk assessments. However, there could be floods that are very disastrous and destroy the transport networks so people could not evacuate to shelters. In addition, people may wish to remain in flooded areas, for diverse reasons. These and other aspects are not captured in our analysis.

Future research could explore how displacement risk may be reduced by adaptation measures such as new protective infrastructure and land-use planning to encourage development in areas less exposed to flooding hazard, as well as factors that may increase or decrease the effectiveness of these and other ways to manage flood risks [56, 57].

Here we have investigated the change in river flood displacement risk driven both by climate change and socio-economic development. The framework we use here, which combines hazards, population exposure and vulnerability to calculate risks, could be extended to include other hazards such as flash floods and coastal surges. Further future research is encouraged to be conducted in this vein.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

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