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Kaoru Kakinuma[1,2], Michael J Puma[3,4], Yukiko Hirabayashi[5], Masahiro Tanoue[6], Emerson A Baptista[1] and Shinjiro Kanae[7]

[1] Asian Demographic Research Institute, Shanghai University, Shanghai, People's Republic of China
[2] Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai, Japan
[3] Center for Climate Systems Research, Columbia University, New York, NY, United States of America
[4] NASA Goddard Institute for Space Studies, New York, NY, United States of America
[5] Graduate School of Engineering and Science, Shibaura Institute of Technology, Tokyo, Japan
[6] Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan
[7] School of Environment and Society, Tokyo institute of Technology, Tokyo, Japan

E-mail: kkakinuma@shu.edu.cn

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Abstract

Strengthening the resilience of societies to extreme weather events is an urgent and critical priority around the world. Extreme weather often causes population displacement that compromises human security. Environment-induced displacement is multifaceted because climate extremes, population, and socio-economic conditions, among other factors, converge to influence individuals' decisions to move. When large-scale, catastrophic floods occur, people tend to move both suddenly and rapidly for survival. Quantifying the patterns and mechanisms of such displacement at global scale is essential to support areas at high risk for climate-induced displacement. Here we present the global distribution of vulnerability to floods by mapping potential flood exposure and observed flood-induced displacement. We found that countries in Africa might be highly vulnerable to floods because they have high flood-induced displacement even at low- to mid-level flood exposure. Our results show that income levels (Gross National Income) substantial impact flood-induced displacement. Moreover, the relationship between income levels and displacement is nonlinear, and this nonlinearity indicates large gaps in flood-induced displacement between high- and low-income countries. We suggest that low-income countries, particularly in Africa, face a high likelihood of flood-induced displacement and need to develop adaptation measures to mitigate the potential for displacement and the associated risks.

1. Introduction

Assessments of climate change impacts on human security are urgently needed in the world today (Smith *et al* 2014, United Nation General Assembly 2015). Extreme weather events, such as floods, often cause population displacements, which force people to change their residences temporarily or permanently (Black *et al* 2011, Lu *et al* 2016, Mora *et al* 2018). According to the Internal Displacement Monitoring Center (IDMC, 2019), around 16.1 million people in the world were displaced in 2018 because of weather-related events; among them, 33% (5.4 million people) were displaced by floods. Moreover, the magnitude and frequency of floods are projected to increase (Hirabayashi *et al* 2013), and future climate change may amplify the risk of population displacement (Smith *et al* 2014, Mora *et al* 2018).

Complex and multiple social and environmental factors drive population displacement (Black *et al* 2011, Hauer *et al* 2020). Individual decisions to move are affected by socio-economic conditions in addition to climate extremes. On the other hand, the effects of climate extremes are highly dependent on economic, political, social, and demographic contexts (Black *et al* 2011). For example, the effects of climate variables, such as extremely high temperature, on population internal migration in South Africa vary greatly with the socio-economic conditions of affected individuals; low-income people are strongly influenced by climate variables (Mastrorillo *et al* 2016). Bakar and Jin (2018) also showed that

both climate variables and socio-economic variables are significantly associated with population flow in the Murray–Darling Basin in Australia, where the economy largely depends on agriculture, which is sensitive to climate variability. Thus, climate factors alone (e.g. flooding) cannot explain the occurrence of disaster-related displacements. It is important to understand the environmental and socio-economic drivers of climate-induced displacements

Although regional studies have examined patterns and mechanisms of flood-induced displacements, such as in Bangladesh (Gray and Mueller 2012, Lu *et al* 2016) and the Murray–Darling Basin in Australia (Bakar and Jin 2018), few studies have focused on displacement at a global scale. A global perspective is essential to identify and support regions or countries at high risk of flood-induced displacements. Moreover, the United Nations presented Sustainable Development Goals (SDGs), which are urgent calls for action by the global community (United Nations General Assembly 2015), and global assessment of flood-induced displacements is a cross cutting issue that is relevant to several SDGs (Goals 1, 10, 11, 13) and targets. For example, Target 1.5 mentions building the resilience of the poor and those in vulnerable situations and reducing their exposure and vulnerability to climate-related extreme events. Quantifying flood-induced displacement patterns and mechanisms by which socio-economic and climate factors drive them at global scale would facilitate achievement of these goals and targets.

In this study, we assessed the global distribution of areas vulnerable to flood-induced displacements from 2008 to 2013 by mapping modelled flood-exposed populations and observed flood-induced displacements. Then we examined effects of country income levels and flood exposure on these flood-induced displacements. Note that the modelled flood exposures include only river flooding and not coastal flooding. We combined hydrological, demographic, and economic data to discuss areas at high risk for flood-induced displacements at a global scale.

2. Methods

2.1. Modelled flood exposure

We use modelled flood exposure (i.e. the number of people potentially affected by flooding) derived from Tanoue *et al* (2020). The modelled flood exposure was calculated by overlaying global population data with the modelled flooded area fraction, derived from a global river and inundation model simulation (Cama-Flood; Yamazaki *et al* 2011). The modelled flood exposure covered from 1960 to 2013 with horizontal resolution of 30" × 30". We extracted the modelled flood exposure for the period 2008–2013, in order to correspond with flood-induced displacement datasets from IDMC (see section 2.2). We aggregated the gridded data by country, and divided it by total population in each country. The total population data were derived from the World Bank (https://data.worldbank.org/indicator/SP.POP.TOTL).

Note that the modelled flood exposures include only river flooding and not coastal flooding. We accounted for flooding with a return period of longer than 2 years in the modeled exposure calculation because Ward *et al* (2013) suggested that exceeding a 2-year return-period has the potential to cause flooding. As our model estimates inundation extent along high-resolution topography, the inundation area and hence flood exposure reflects the magnitude of flooding. Moreover, note that the calculation of flooded areas does not consider the effect of flood protection infrastructure; hence, flooded areas may be overestimated. For this reason, we assumed that the modelled flood exposure is the potential flood exposure in the absence of flood protection infrastructure. The effect of current flood protection standards is discussed in section 3.4.

2.2. Flood-induced displacement

Flood-induced displacement was derived from IDMC datasets. The IDMC Global Report on Internal Displacement 2017 (IDMC 2017) has the number of internal displacements caused by weather disasters by country. We extracted the number of displacements caused by 'Flood'. The report does not distinguish between river floods and coastal floods; so, we cannot extract from the dataset only river flood-induced displacements. Moreover, the dataset focuses on internal displacements and we were unable to get information related to international displacements. Although IDMC includes data for 2008–2018, we used only the data from 2008 to 2013 to correspond with the time scale of potential flood exposure used in this study.

2.3. Bivariate maps

We introduce an adapted bivariate choropleth map (Grossenbacher and Zehr 2019, Baptista *et al* 2020) in R to evaluate the degree of relation between flood-induced displacement and potential flood exposure at the country level. We normalized the flood-exposed population and flood-induced displacement by total population in each country. We used average values of flood-induced displacement and potential flood exposure during 2008–2013 for each country. To map the appropriate classes with nine different colors, we calculated 1/3-quantiles for both variables. Then, the countries were put into the appropriate class corresponding to their average flood-induced displacement and flood exposure.

2.4. Statistical analysis

We used a generalized linear model (GLM) to examine effects of flood exposure and economic condition (income level) on flood-induced displacements as follows:

Flood-induced displacement $= \beta 0 + \beta 1 \times$ economic income levels $+ \beta 2 \times$ flood exposure

where βi is the coefficient of the explanatory variables. We used the average value of each variable during 2008–2013 for each of 174 countries. We standardized all variables before performing GLM and assumed a Gaussian distribution.

To measure economic income level, we used the Gross National Income (GNI) per capita (current US$) for 2008–2013 as provided by the World Bank (https://data.worldbank.org/indicator/ny.gnp.pcap.pp.cd). The World Bank uses GNI per capita to classify countries by income level. According to the World Bank, GNI per capita is a useful indicator that closely reflects quality of life in each country (https://datahelpdesk.worldbank.org/knowledgebase/articles/378831-why-use-gni-per-capita-to-classify-economies-into).

We used a piecewise regression model (Muggeo 2003) to detect the breakpoint of the relationship between GNI per capita and flood-induced displacement. We used the average value of GNI per capita and flood-induced displacement during 2008–2013 for each country. All statistical analyses were performed using R software (R 3.3.2).

3. Results and discussion

3.1. Mapping global flood exposures and displacements

We evaluated the relation between flood-exposed population and flood-induced displacement at the country level (figure 1). In accordance with the definition of displacement by IDMC, we used displacement to mean 'involuntary or forced movements, evacuation, or relocation of individuals or groups of people from their habitual places of residence' (Internal Displacement Monitoring Center (IDMC) 2017). From 2008 to 2013, flood-induced displacement was high in Africa, South/Southeast Asia, and Central/South America, and they were low in Europe (figure 1). There were different levels of exposure among countries that have high flood-induced displacement. In the countries most vulnerable to floods (red in figure 1), such as Burkina Faso, Ghana, Kenya, Mauritania, and Zimbabwe, flood-induced displacement was high even though exposure was low. For example, in Burkina Faso mean flood exposure was 4.6 per 1000 people and mean flood-induced displacement was 2.2 per 1000 people. Both exposure and displacement were high (dark purple countries in figure 1) in countries such as India, China, and the Philippines. The Philippines had 61.2 mean flood exposures (per 1000 people) and 7.0 mean flood-induced displacements (per 1000 people). In contrast, less vulnerability (blue in figure 1) was found in Europe in countries such as the Netherlands and Finland. The Netherlands had the highest mean flood exposure (239.4 per 1000 people), but no flood-induced displacement; in other words, there was no flood-induced displacement despite high exposure. Overall, high-displacement and low-exposure (red) were found in many African countries while high-displacement and high-exposure (dark purple) were found in most Asian countries. The results show that vulnerable countries in Africa might need to pay attention to even small flood exposures, while most Asian countries (dark purple colored areas) may need to adapt to large flood exposures.

3.2. Nonlinear relationship between income level and flood-induced displacement

As a first estimate, we used a GLM to examine effects of flood exposure and income level on flood-induced displacement. We observed that the effect of income level is significantly negative, whereas the effect of flood exposure is not significant (table 1); thus, low-income level may amplify flood-induced displacement. In addition to the fact that the relationship between displacement and income level (GNI per capita) is nonlinear, the result of piecewise regression suggests that there is a breakpoint at GNI per capita = US$13 387, such that countries with a higher GNI per capita than the breakpoint have much lower flood-induced displacement (figure 2). We also categorized countries into four income levels and found that high-income countries had less flood-induced displacement than did middle- and low-income countries (figure S.2). These results indicate that there are large gaps in flood-induced displacement between high- and low-income countries. Previous research has also shown that flood damage, such as a mortalities, are higher in poorer countries (Jongman *et al* 2015, Tanoue *et al* 2016, Formetta and Feyen 2019). Economic development may mitigate the impact of floods on societies through encouraging high levels of protective infrastructure and residential management (Scussolini *et al* 2016, Lim *et al* 2018). For example, flood protection levels in Europe, which includes high-income countries, are higher than those in Africa (Scussolini *et al* 2016, Lim *et al* 2018). Moreover, higher flood protection levels mitigate the expected economic damage of floods, particularly in high-income countries (Winsemius *et al* 2016, Ward *et al* 2017). Our results also confirm that Europe has relatively few flood-induced displacements (blue areas in figure 1). In particular, the Netherlands has a very small number of flood-induced displacements, even though exposure there is high (figures 1 and 3). In other words, lower-GNI countries may be more vulnerable to floods and have a higher potential for flood-induced displacement. Development of measures to adapt to floods is an especially critical and urgent issue for lower income countries.

This study focuses only on income levels and flood exposure to examine flood-induced displacement, but various other variables may

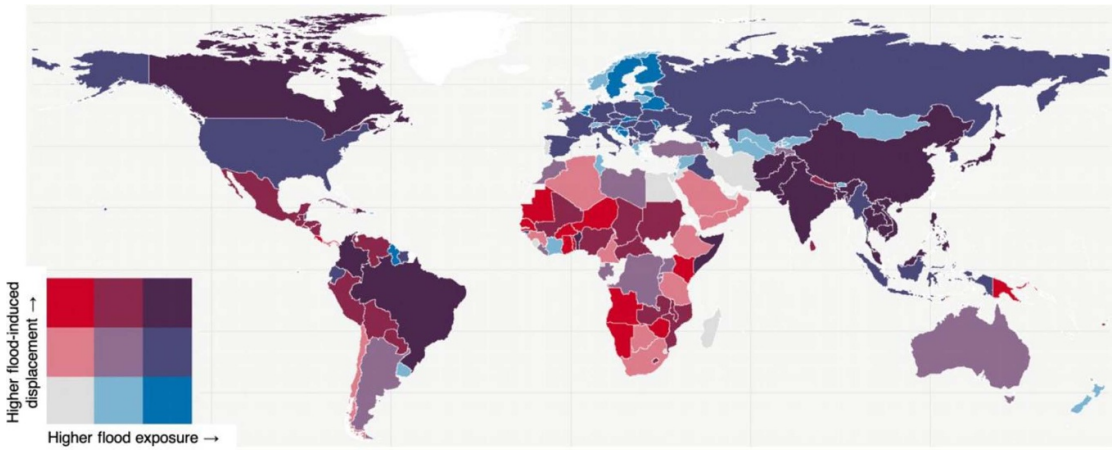

Figure 1. Global flood-induced displacement vs flood exposure during 2008–2013. We used average of flood-induced displacement and flood-exposure in each country during 2008–2013. Flood-induced displacement and flood exposure are normalized by total population in each country. The relation between flood-induced displacement and flood exposure was mapped onto color based on 1/3 quantiles of each variable. White areas have no available data. Ranges of values for each category are shown in table S.1 and figure S.1 (stacks.iop.org/ERL/15/124029/mmedia). Here we assume no flood protection.

Table 1. Parameter estimates for the Generalized Linear Model.

	Estimates	95% Credible Interval	p
Income level[a]	–0.25	[–0.39, –0.080]	< 0.01
Flood exposure	0.064	[–0.089, 0.22]	0.41

[a]Gross National Income per capita

affect flood-induced displacement, such as political institutions, infrastructure, and land use. These variables should be considered in future studies to examine the factors that affect flood-induced displacement.

3.3. Flood-induced displacement in low- and middle-income countries

Our results suggest that African countries may be at high risk of flood-induced displacement at even low or medium flood exposures (figure 1). One of the possible reasons is the effects of low income (table 1, figure 2). Previous studies pointed out that poverty may accelerate flood-induced displacement in African countries (Douglas *et al* 2008, Dube *et al* 2018). People often moved from rural to urban areas because of poverty or unstable social conditions, and some of them were forced to live in unsafe zones around a city (Douglas *et al* 2008). In addition, infrastructure and drainage management were often not improved at a pace commensurate with rapid and massive urbanization (Agbola *et al* 2012). For instance, in Nigeria, which had middle exposure and high displacement (figure 1), floods hit metropolitan areas in 2011 and a lack of effective drainage management amplified the impacts of the floods (Agbola *et al* 2012). In Zimbabwe, where low flood exposure produced high displacement (figure 1), a feedback loop between poverty and flood exposure was observed, as poor people usually live in flood-exposed areas and suffer more severe economic damage as a result of floods (Dube *et al* 2018). The feedback loop is also observed in Southeast Asia; for example, poor people in Myanmar tend to live in flood-prone areas, where a rise of water over 1 m causes flooding, and floods can cause and exacerbate poverty (Kawasaki *et al* 2020). Poor people are often trapped in environmentally vulnerable zones, even after flooding, because their economic conditions make it difficult for them to move to other areas (Black *et al* 2013). In addition, to economic conditions, unstable social conditions, such as conflicts and rapid urban growth, may interact with extreme weather events and cause large displacements. For example, in Colombia, with high exposure and high displacement (figures 1 and 3), around 3 million people were displaced by floods in 2010 (Internal Displacement Monitoring Center (IDMC) 2017); most of these flood-displaced people in 2010 experienced conflict-induced displacement as well (Shultz *et al* 2014). Combination of flood- and conflict-induced displacements were also reported in East African countries, where conflicts often force people to settle in environmentally vulnerable places (Tafere 2018). Poverty, unstable social conditions, and rapid population growth may contribute to flood-induced displacements, and this may be one of the most important reasons that many African countries are very vulnerable (figure 1).

While income levels may affect flood-induced displacement (figure 2), we also find that some middle- or low-income countries, such as Vietnam and Bangladesh, have relatively little flood-induced displacement, despite extremely large flood exposure (figure 3). This result suggests that there are adaptation measures unrelated to high income that mitigate impacts of extremely large floods. People in Vietnam have been living with floods for a long time, and their society may have developed adaptive capacities

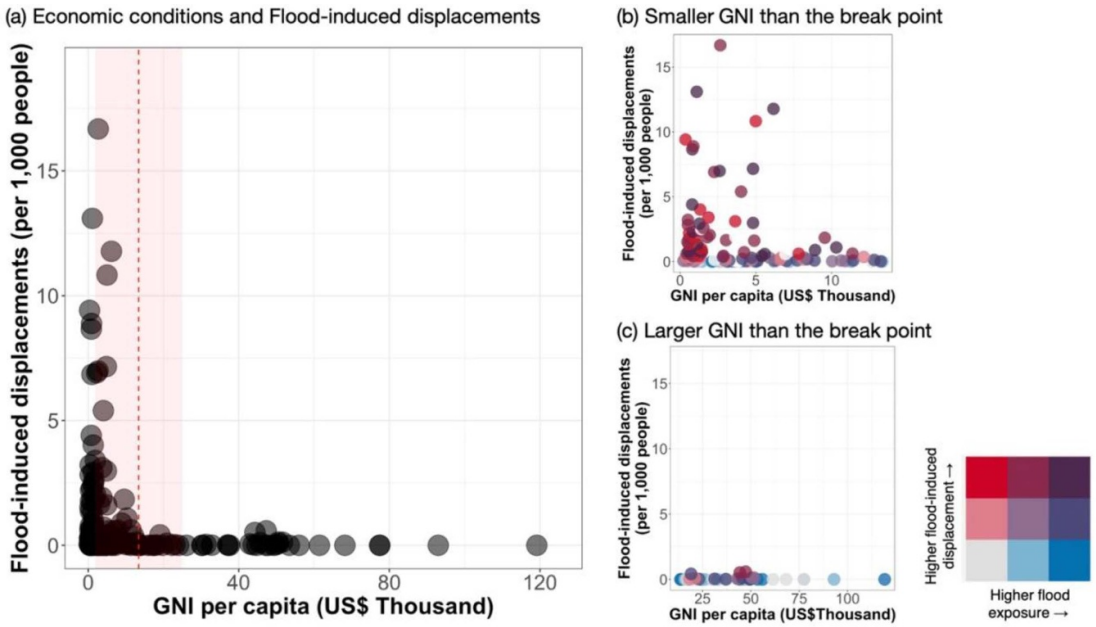

Figure 2. Flood-induced displacement versus Gross National Income (GNI) per capita (a) A nonlinear relationship between GNI per capita and flood-induced displacement. Each point represents a country's average value during 2008–2013. The red dashed line is the breakpoint (GNI per capita = US$13 387) derived by piecewise regression, and the red shading is the 95% confidence interval of the breakpoint [US$1828, US$24 945]. Flood-induced displacement in countries with (b) smaller and (c) larger GNI per capita than the breakpoint of US$13 387 normalized by the total population in each country. Colors in (b) and (c) show the relationship between flood-induced displacement and flood exposure as in .figure 1

(Nguyen and James 2013). Vietnam also has a long history of government-managed resettlement, and people in unsafe conditions were relocated after severe floods in 2010 (United Nations in Viet Nam 2014). There were some difficulties after relocation; for example, people needed more time to access their agricultural lands or fishing areas (United Nations in Viet Nam 2014). Generally, planned relocations involved high costs and affected political legitimacy (Hino *et al* 2017, Mortreux *et al* 2018). Despite these difficulties, planned relocations may strongly reduce exposure to floods in Vietnam (United Nations in Viet Nam 2014), and they are a potentially effective measure to prevent local people from suffering flood damage in other countries (Arnall 2019, Barnett and O'Neill 2012, Hino *et al* 2017, Mortreux *et al* 2018). Moreover, some households adapt well to floods in Vietnam and are able to secure food and income during disaster periods. For example, many farmers grow rice and crops whereas they collect fish, crab, and snails during flood seasons (Nguyen and James 2013). Although Bangladesh also is one of the countries with the largest flood exposure (figure 3), flood-induced displacement there is not extremely high (figure 3). Around 4000 km of embankments was constructed in Bangladesh in the 1960s, and local people work together to repair and maintain the embankments when floods hit them (Dewan *et al* 2015). This community-based flood protection management could enhance long-term resilience to floods in Bangladesh (Yu *et al* 2017). Even though income levels in Vietnam and Bangladesh are not high, these societies have developed adaptive capacities based on long experience with floods (Yu *et al* 2017). Economic development may not be the only solution to mitigate flood exposure, and such adaptation measures would be useful for other low-income countries to reduce the impacts of floods.

3.4. Sensitivity to flood protection

Although our results suggest that high-income countries might successfully mitigate the impact of floods on displacement (figures 1 and 2), some high-income countries may have high potential of flood-induced displacement. We calculated flood exposure with flood protection standards that are estimated from Gross Domestic Product of each country (Scussolini *et al* 2016) (figure S.3). Some high-income countries, such as Japan, Australia, and France have middle to high flood-induced displacement despite low to middle flood exposure with their flood protection standards (figure S.3). Severe flood damage has been reported in these countries. For example, in Australia in 2010, severe economic damages were reported in the amount of US$5.1 billion as the result of one flood (Guha-Sapir *et al* 2011), and in Japan in 2018, a flood caused US$9.5 billion worth of economic loss and around 230 deaths (EM-DAT 2019). High-income countries may still be affected by large flood events that overwhelm their flood protection capacities. Moreover, where there is strong infrastructure and a high level of flood protection, people are likely to live close to rivers (Mård *et al* 2018). In that case, in the future large numbers of people

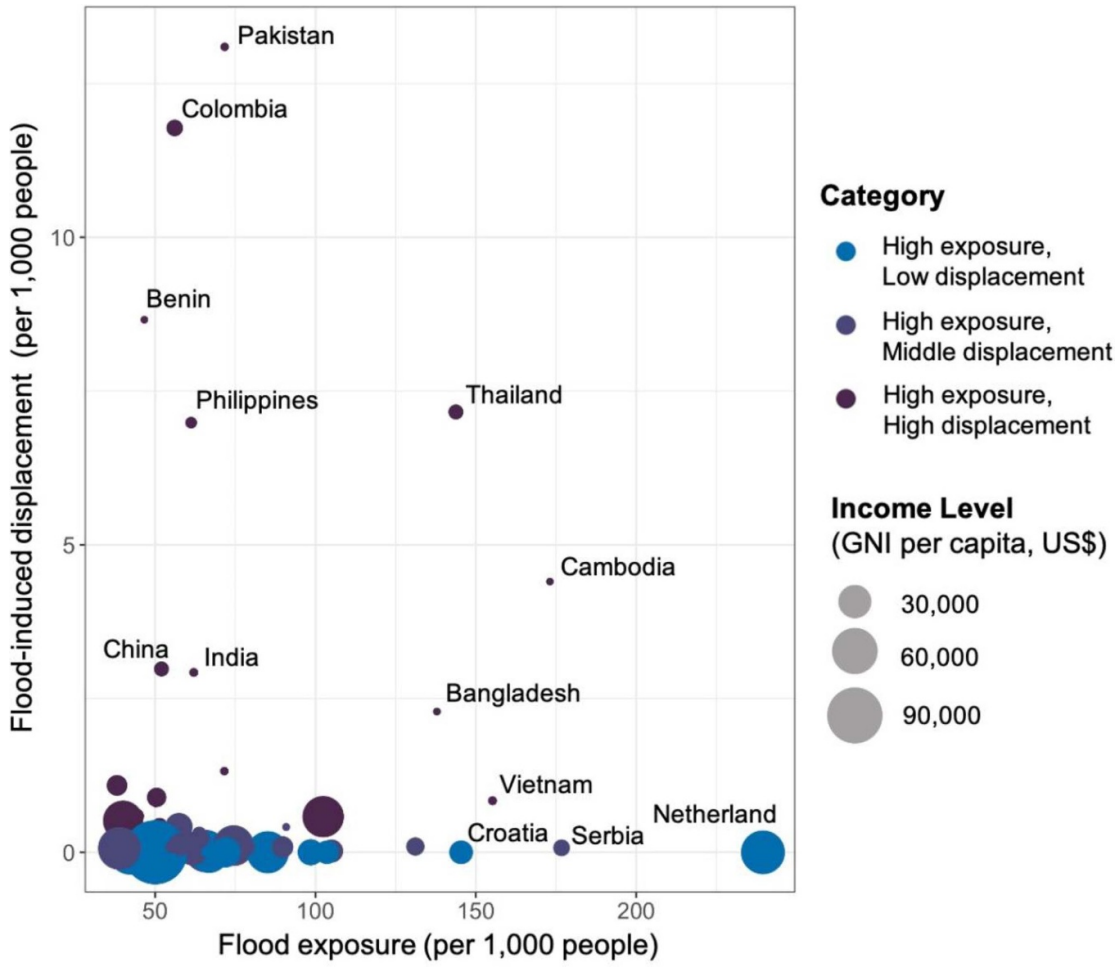

Figure 3. Flood-induced displacement in high flood exposure countries. Average of values during 2008–2013 for each country. Colors show the relationship between flood-induced displacement and flood exposure (both normalized by total population in each country) as in figure 1; circle size represents Gross National Income (GNI) per capita.

will be exposed to catastrophic flood events (Di Baldassarre *et al* 2015, Mård *et al* 2018). Thus, high-income countries also need to develop adaptation measures for large flood events, such as early warning systems and community engagement programs to raise awareness of flood risk (Di Baldassarre *et al* 2015). While results of some high-income countries may be sensitive to an assumption of flood protection, this does not affect results of low-income countries in Africa (figures 1 and S3) because of their low flood protection standards (Scussolini *et al* 2016). Thus, our result in figure 1, that low income countries in Africa have high displacement at small flood exposures, is robust regardless of flood protection standards.

4. Conclusions

Extreme weather events are projected to increase, which will have substantial impact on population displacement, thereby degrading human security (Smith *et al* 2014). Assessments of potential flood-induced displacement from a global perspective are critical to developing measures for adaptation to future climate change. We assessed the global distribution of flood-induced displacement relative to flood exposure, and suggest that certain countries, especially in Africa, are very vulnerable to flooding. In addition, we show that the relationship between income level and displacement is nonlinear, and that there are large gaps between displacement in low- and high-income countries (figures 2 and S.2). Countries with high flood-induced displacement, such as those in eastern Africa, Southeast Asia, and Peninsular India, are projected to experience floods with increased intensities and magnitudes (Hirabayashi *et al* 2013). The need to develop adaptation measures to floods is urgent. We suggest that African countries may need to improve adaptation to even small flood exposures, while in Asian countries, adaptation to large flood exposures may suffice. Note that we assumed fluvial floods are the dominant mechanism while calculating flood exposures, although we cannot distinguish between fluvial and coastal floods in flood-induced displacement. Thus in this study, for countries where coastal flood exposures are high, such as Asian counties

(Kulp and Strauss 2019) and other coastal regions, flood exposures are underestimated. Recent studies of the compound impacts of river and coastal floods (Ikeuchi *et al* 2015, Eilander *et al* 2020) suggest that it is important to integrate river and coastal flood exposures in future studies to examine flood-induced displacement. Moreover, data availability restricted our study period to 2008–2013. The research periods in future studies should be expanded if more recent flood exposure datasets become available. We also note that the study focused only on income level and flood exposures to explain flood-induced displacement, but displacements are complex phenomenon and thus, multiple factors, such as policy, demography, land use, and agriculture need to be considered to clarify patterns and mechanisms of displacement in future studies (Black *et al* 2011). Particularly, societies' adaptive capacities to floods that are based on long experience with floods may also have an important role in social resilience to floods (e.g. Nguyen and James 2013, Yu *et al* 2017). Not only income levels, but also local adaptation measures, such as community-based flood protection management (Yu *et al* 2017), secure food and income during disaster periods (Nguyen and James 2013), and planned relocation (Arnall 2019, Barnett and O'Neill 2012, Hino *et al* 2017, Mortreux *et al* 2018) will be important factors to examine flood impacts on displacements in future studies. In addition, population migration and displacement occur and are interrelated across multiple scales, so it is important to conduct research at local as well as global scales. Despite these limitations, this study has taken an important step to showing the areas of high potential for flood-induced displacement in the world.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Kaoru Kakinuma https://orcid.org/0000-0003-4647-9582
Michael J Puma https://orcid.org/0000-0002-4255-8454
Yukiko Hirabayashi https://orcid.org/0000-0001-5693-197X
Masahiro Tanoue https://orcid.org/0000-0003-1365-0187
Emerson A Baptista https://orcid.org/0000-0001-7582-2736
Shinjiro Kanae https://orcid.org/0000-0002-3176-4957

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