Environmental Research Letters

LETTER

Flood-induced population displacements in the world

Kaoru Kakinuma, Michael J Puma, Yukiko Hirabayashi, Masahiro Tanoue, Emerson A Baptista and Shinjiro Kanae

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

Keywords: climate change, climate-induced migration, exposure, extreme weather events, migration, vulnerability

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

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:

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.
Flood-induced displacement = \( \beta_0 + \beta_1 \times \text{economic income levels} + \beta_2 \times \text{flood exposure} \)

where \( \beta_1 \) 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.ccd). 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.

| Parameter          | Estimate | 95% Credible Interval | p   |
|--------------------|----------|-----------------------|-----|
| Income level*     | -0.25    | [-0.39, -0.080]       | < 0.01 |
| Flood exposure     | 0.064    | [-0.089, 0.22]        | 0.41 |

*aGross 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...
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.

Acknowledgments

Kaoru Kakinuma gratefully acknowledges fellowship support from a Grant-in-Aid for JPSS Fellows Grant Number 15J12081 and financial support from JPSS KAKENHI Grant Number 19K20487 and the Shanghai Municipal Education Commission Grant Number TP2019035. Yukiko Hirabayashi acknowledges financial support from the Environment Research and Technology Development Fund (JPMEEF202020005) of the Environmental Restoration and Conservation Agency of Japan. Michael J Puma was supported in part by the Army Research Office/Army Research Laboratory under the World Modelers Program (grant W911NF1810267 (Multidisciplinary University Research Initiative) and the Defense Advanced Research Project Agency under the World Modelers program (grant W911NF1910013). The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies either expressed or implied of the Army Research Office or the US Government.

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

References

Agbola B S, Ajayi O, Taiwo O J and Wahab B W 2012 The August 2011 flood in Ibadan, Nigeria: anthropogenic causes and consequences Int. J. Disaster Risk Sci. 3 207–17
Arnall A 2019 Resettlement as climate change adaptation: what can be learned from state-led relocation in rural Africa and Asia? Clim. Dev. 11 253–63
Bakar K S and Jin H 2018 Spatio-temporal quantitative links between climatic extremes and population flows: a case study in the Murray-Darling Basin, Australia Clim. Change 148 139–53
Baptista E A, Kakinuma K and Queiroz B L 2020 Association between cardiovascular mortality and economic development: a spatio-temporal study for prefectures in Japan Int. J. Environ. Res. Public Health 17 1311
Barnett J and O’Neill S J 2012 Islands, resettlement and adaptation Nat. Clim. Change 2 8–10
Black R, Adger W N, Arnell N W, Decon S, Geddes A and Thomas D 2011 The effect of environmental change on human migration Globale Environ. Change 21 53–11
Black R, Arnell N W, Adger W N, Thomas D and Geddes A 2013 Migration, immobility and displacement outcomes following extreme events Environ. Sci. Policy 27 S32–43
Dewan C, Mukherji A and Buisson M-C 2015 Evolution of water management in coastal Bangladesh: from temporary earthen embankments to depoliticized community-managed polders Water Int. 40 401–16
Di Baldassarre G, Viglione A, Carr G, Kuij L, Yan K, Brandimarte L and Bloschl G 2015 Debates-Perspectives on socio-hydrology: carturging feedbacks between physical and social processes Water Resour. Res. 51 4770–81
Douglas I, Alam K, Maghenda M, Mcdonnell Y, Mclean L and Campbell J 2008 Unjust waters: climate change, flooding and the urban poor in Africa Environ. Urban 20 185–205
Dube E, Mtapuri O and Matunhu J 2018 Flooding and poverty: two interrelated social problems impacting rural development in Tsholotsho district of Matabeleland North province in Zimbabwe Jambh: Journal of Disaster Risk Studies 10 4555
Eilander D, Cousoanon A, Ikeuchi H, Muis S, Yamazaki D, Winsenius H and Ward P J 2020 The effect of surge on riverine flood hazard and impact in deltas globally Environ. Res. Lett. 15 104007
EM-DAT(International Disaster Database), 2019. Natural Disaster 2018 (available from: www.emdat.be/publications)
Formetta G and Feyen L 2019 Empirical evidence of declining global vulnerability to climate-related hazards Glob Environ. Change 57 101920
Gray C L and Mueller V 2012 Natural disasters and population mobility in Bangladesh Proc. Natl Acad. Sci. USA 109 6000–5
Grossenbacher T and Zehr A 2019 Bivariate maps with ggplot2 and sf (available from: https://github.com/grossnbchr/bivariate-maps-ggplot2-sf)
Guha-Sapir D, Bos P, Below R and Ponsseur S 2011 Annual disaster statistical review 2010: the numbers ad trends (Brussels: CRED) (available from: www.cred.be/sites/default/files/ADSR_2010.pdf)
Hauer M E, Fussell E, Mueller V, Burkett M, Call M, Abel K, Mcleman R and Wrathall D 2020 Sea-level rise and human migration Nat. Rev. Earth Environ. 1 28–39
Hino M, Field C B and Mach K J 2017 Managed retreat as a response to natural hazard risk Nat. Clim. Change 7 364–70
Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H and Kanase S 2013 Global flood risk under climate change Nat. Clim. Change 3 816–21
Ikeuchi H, Hirabayashi Y, Yamazaki D, Kiguchi M, Koirala S, Nagano T, Kotera A and Kanase S 2015 Modeling complex flow dynamics of fluvial floods exacerbated by sea level rise in the Ganges–Brahmaputra–Meghna Delta Environ. Res. Lett. 10 94012
Internal Displacement Monitoring Center (IDMC) 2017 Global report of internal displacement available from: (https://reliefweb.int/sites/reliefweb.int/files/resources/2017-GRID.pdf)
Internal Displacement Monitoring Center (IDMC), 2019. Global report on internal displacement available from: (www.internal-displacement.org/sites/default/files/publications/documents/2019-IDMC-GRID.pdf)
Jongman B, Winsemius H C, Aerts J C J H, Coughlan de Perez E, Internal Displacement Monitoring Center (IDMC) 2017 A global framework for future costs and vulnerability to river floods and the global benefits of adaptation Proc. Natl Acad. Sci. USA 112 E2271–80
Kawasaki A, Kawamura G and Zin W W 2020 A local level relationship between floods and poverty: a case in Myanmar Int. J. Disaster Risk Reduct. 42 101348
Kulp S A and Strauss B H 2019 New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding Nat. Commun. 10 4844
Lim W H, Yamazaki D, Koirala S, Hirabayashi Y, Kanase S, Dadsom J S, Hall W J and Sun F 2018 Long-term changes in global socioeconomic benefits of flood defences and residual risk based on CMIP5 climate models Earth’s Future 6 938–54
Lu X et al 2016 Unveiling hidden migration and mobility patterns in climate stressed regions: a longitudinal study of six million anonymous mobile phone users in Bangladesh Glob Environ. Change 38 1–7
Márd J, Di Baldassarre G and Mazzoleni M 2018 Nighttime light data reveal how flood protection shapes human proximity to rivers Sci. Adv. 4 eaar5779
Mastrorillo M, Licker R, Bohra-Mishra P, Fagiolo G, Estes D L and Oppenheimer M 2016 The influence of climate variability on internal migration flows in South Africa Glob Environ. Change 39 155–69
Mora C et al 2018 Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions Nat. Clim. Change 8 1062–71
Mortreux C, Safrá de Campos R, Adger W N, Ghosh T, Das S, Adams H and Hazra S 2018 Political economy of planned relocation: a model of action and inaction in government responses Glob Environ. Change 50 123–32
Muggeo V M R 2003 Estimating regression models with unknown break-points Stat. Med. 22 3055–71
Nguyen K V and James H 2013 Measuring household resilience to floods: a case study in the Vietnamese Mekong River Delta Ecol. Soc. 3 13
Scussolini P, Aerts J C J H, Jongman B, Bouwer L M, Winsemius H C, de Moel H and Ward P J 2016 FLOPROS: an evolving global database of flood protection standards Nat. Hazards Earth Syst. Sci. 16 1049–61
Shultz J M, Ceballos Â M G, Espinel Z, Oliveros S R, Fonseca M F and Florez I. J H 2014 Internal displacement in Colombia: fifteen distinguishing features Disaster Health 2 13–24
Smith K R et al 2014 Climate change 2014: impacts, adaptation, and vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Cambridge: Cambridge University Press) Ch. 11
Tafer M 2018 Forced displacements and the environment: its place in national and international climate agenda J. Environ. Manage. 224 191–201
Tanoue M, Hirabayashi Y and Ikeuchi H 2016 Global-scale river flood vulnerability in the last 50 years Sci. Rep. 6 36021
Tanoue M, Taguchi R, Nakata S, Watanabe S, Fujimori S and Hirabayashi Y 2020 Estimation of direct and indirect economic losses caused by a flood with long-lasting inundation: application to the 2011 Thailand flood Water Resour. Res. 36 91
United Nations General Assembly 2015 Transforming our world: the 2030 agenda for sustainable development (available from: www.un.org/ga/search/view_doc.asp?symbol=E/RES/2015/L.1)
United Nations in Viet Nam 2014 Migration Resettlement and Climate Change in Viet Nam (Vietnam: Phu Sy Printing Company) pp 1–32
Ward P J et al 2017 A global framework for future costs and benefits of river-flood protection in urban areas Nat. Clim. Change 7 642–6
Ward P J, Jongman B, Weiland F S, Bouwman A, van Beek R, Bierkens M F P, Ligtenvoet W and Winsemius H C 2013 Assessing flood risk at the global scale: model setup, results, and sensitivity Environ. Res. Lett. 8 044019
Winsemius H C et al 2016 Global drivers of future river flood risk Nat. Clim. Change 6 381–5
Yamazaki D, Kanase S, Kim H and Oki T 2011 A physically based model of flood vulnerability in the last 50 years Nat. Clim. Change 1 84–90
Yamazaki D, Kim H, Oki T and Hanasaki N 2007 A physically based model of flood vulnerability in the last 50 years Nat. Clim. Change 1 84–90
Zekri A, Seneviratne S I, Nicholls R J and Ciais P 2015 Assessing global and regional impacts of sea level rise in a CMIP5 ensemble Earth’s Future 3 324–35