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Each 0.5°C of Warming Increases Annual Flood Losses in China by More than US$60 Billion

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ABSTRACT: In the warming climate, flood risk is likely to increase over much of the globe. We present projections of changes of flood losses in China for a range of global warming scenarios, from 1.5° to 4.0°C above the preindustrial temperature, with a 0.5°C step. Projections of flood losses in China are based on river runoff simulations by a distributed hydrological model driven by multiple downscaled general circulation models, the national GDP projected at shared socioeconomic pathways, and the "intensity–loss rate" function. When interpreting changes caused by the combined effect of economic and climatic conditions, flood losses in China are projected to soar in the future, particularly in lowland regions subject to rapid economic growth. Under global warming of 1.5° and 4.0°C, in an average year, flood losses are projected to be, respectively, 4 and 17 times that at present. Pursuing the international climate policy target of limiting global warming is projected to reduce exposure to floods in China. In this way, flood losses in China can be reduced by tens of billions of U.S. dollars (on average, US$67 billion and up to 0.04% of GDP) for each 0.5°C that warming is reduced. Our study improves understanding of the impact of climatic and nonclimatic changes on flood risk. Our scientific contribution is the first study to quantify flood impacts across China under different development pathways (shared socioeconomic pathways) for a broad range of global warming levels.

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Large floods break continuity of development, at the local to regional to national levels. In fact, if flood damage reaches several percent of GDP, the affected area can be set back by years in its development. Sustainable development interpreted by nondecreasing quality of life is in jeopardy (Kundzewicz et al. 2018a). On average, floods cause annual material damage on the order of tens of billions of U.S. dollars worldwide and kill thousands of people (Hirabayashi et al. 2013; Jiménez Cisneros et al. 2014; Döll et al. 2015). Globally, an increase in the severity of flood impacts has been observed in recent years and flood risk is projected to increase in the future under increases in the frequency and intensity of extreme precipitation and changes in socioeconomic systems (Field et al. 2012; Kundzewicz et al. 2014; Wasko and Sharma 2015; Donat et al. 2016; Zhang et al. 2018; Willner et al. 2018). The number of large floods was found to have increased in Europe (Kundzewicz et al. 2017a). In addition to regional studies in the United States, the United Kingdom, and the European region (Choi and Fisher 2003; Mokrech et al. 2014), flood risk caused by climate change, socioeconomic development, or their combined effects has been recently estimated across the global domain (Ward et al. 2013; Winsemius et al. 2015; Arnell and Gosling 2016; Alfieri et al. 2017; Döll et al. 2018). These studies demonstrate that projections of flood hazard and flood risk are highly uncertain. Kundzewicz et al. (2017b, 2018b, 2019) studied propagation of uncertainty through a multistage process of developing projections of climate change impact on flood hazard and adaptation to climate change. Uncertain are socioeconomic scenarios, as well as all the transfer functions: from socioeconomic scenarios to atmospheric greenhouse gas concentrations, further to climate change (global to regional to local), and then to impacts on flood hazard and flood risk. Hence, there can be large differences between results obtained by using different scenarios and different climate and impact models. Uncertainties may depend on the future time horizon of concern, usually increasing for a more remote horizon; that is, in a near-future climate model, uncertainties may dominate, while in a more remote future, uncertainties are due to the selection of a scenario (RCP). Since climate models generate differing projections, ensembles of general circulation models (GCMs) are used. Their selection as well as the process of downscaling (empirical–statistical or dynamic) can explain a major portion of differences in impact projections. Since climate models do not satisfactorily simulate the historical climate, a bias correction is often necessary and this is again a source of uncertainty. Finally, hydrological models—their structures, parameters, initial conditions, flood threshold estimation, and calibration methods—are also a source of further uncertainty.

Floods have been one of the key national concerns in China throughout its history, hence projections of increases in extreme precipitation (Qin et al. 2015) are bad news. A warmer climate is likely to lead to an expansion of area affected by severe floods (Hoegh-Guldberg et al. 2018). Limiting global warming to no more than 2.0°C above the preindustrial level has been recognized as an important global climate policy target, and meeting this target may reduce disastrous consequences in comparison to continuing business as usual (Vautard et al. 2014). The Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) goes even further, proposing to hold the increase in global mean temperature to well below 2.0°C above preindustrial levels and to pursue efforts to limit the warming to 1.5°C (UNFCCC 2015).

To date, studies have not quantified the range of flood impacts across China under different development pathways at global warming levels from 1.5° to 4.0°C. In this study, downscaled outputs by 21 GCM simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5) are used to drive a distributed hydrological model to project changes in flood amplitude in China for six global warming scenarios (1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C higher than the preindustrial), and for three representative concentration pathways (RCPs): RCP2.6, RCP4.5, and RCP8.5. Different shared socioeconomic pathways (SSPs; O'Neill et al. 2014; Leimbach et al. 2017) are combined with the RCPs (van Vuuren et al. 2011a), according to mitigation scenarios (van Vuuren et al. 2014), and future flood losses in China are estimated by applying the scenario-comparison approach.

The broad range of global warming scenarios covered in this paper include both the aspirational levels of the Paris Agreement (1.5° and 2.0°C; see UNFCCC 2015), the values 3.0° and 3.5°C spanning the interval where the Voluntarily Determined Contributions (VDCs) of the global climate policy are likely to reside (estimated at 3.2.0°C; see Peters et al. 2017), and the value of 4.0°C corresponding to business as usual (van Vuuren et al. 2011b).

Historical flood losses in China

Being influenced by the seasonal monsoon and complex topography, much of China is flood-prone and indeed destructive floods frequently affect the country (Kundzewicz et al. 2019). Annual average flood losses recorded in the period 1984–2018 in China reached $19.2 billion (normalized to 2015 values), which accounted for 0.5% of the national GDP in China and 54% of the total national direct economic losses due to climate and weather. Yet, in the period 2006–18, flood losses increased to $25.3 billion annually. The most costly floods in a single year were recorded in 1998, 2010, and 2016, resulting in absolute losses of $49.7 billion, $64.6 billion, and $49.3 billion, respectively, that is, much more than double (in case of 2010, more than triple) the average of the 1984–2018 period (Fig. 1a). The destructive floods in 1998 alone, which affected vast areas of China, including drainage basins of the Yangtze River, the Songhua River in northeast China, and the Pearl River in south China, consumed nearly 3.0% of the national GDP (China Meteorological Administration 2019). In spatial terms, the bulk of high flood losses are in the lowland plain areas with high damage potential. Areas at elevation below 200 m MSL (Fig. 1b) constitute 15% of China, but flood losses in these areas make up half of the national total, on average, and may even reach at 70% in some particular years, such as 1991 and 1998 (Fig. ES5).

Projected changes in flood hazard

Changes in flood hazard in a warming world can be illustrated by changes in the return period of what used to be 30-, 50-, and 100-yr events in the reference period 1981–2010. It

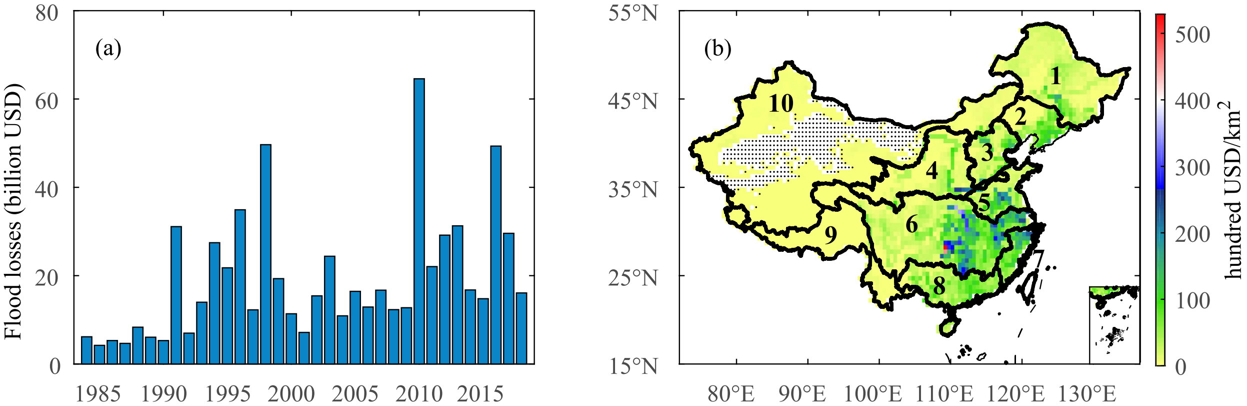

Fig. 1. (a) Temporal and (b) spatial distribution of annual flood losses (in 2015 U.S. dollars) in China in the period 1984–2018. Borders marked in (b) indicate 10 river basin areas (1 = Songhua River basin; 2 = Liaohe River basin; 3 = Haihe River basin; 4 = Yellow River basin; 5 = Huaihe River basin; 6 = Yangtze River basin; 7 = Southeast River basins; 8 = Pearl River basin; 9 = Southwest River basins; 10 = Northwest River basins). White regions with dots denote bare land (desert and sandy land, with very low damage potential).

is projected that historical reference 100-yr floods in China under 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C global warming scenarios will occur much more frequently, becoming 71- (interquartile range, IQR: 58–81), 68- (50–78), 59- (44–72), 50- (39–60), 42- (37–58) , and 42-yr (32–47) events (medians of GCM results), respectively. The average rate of decrease of the return period is 7 yr $(0.5°C)^{-1}$ from 1.5° to 4.0°C (Fig. 2g). In space, the return periods for reference 100-yr floods (determined for 1981–2010) are projected to become shorter over 80%, 78%, 80%, 82%, 81%, and 82% of China at the 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C global warming levels, respectively (Figs. 2a–f). Reference 100-yr events might become at least 5 times more frequent, that is, <20-yr floods under the 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C warming scenarios in 0.8%, 1.4%, 3.0%, 6.4%, 9.7%, and 15.5% of the area of China, respectively, mainly along a southwest-to-northeast belt crossing the Southwest, Upper and Middle Yangtze, Middle Yellow, Upper Haihe, western Liaohe, and eastern Songhua River basins. In most areas projected to encounter increasing floods, reference 100-yr events are projected to become 50–100-yr events under the 1.5° and 2.0°C warming scenarios and 20–50-yr events under the 2.5°, 3.0°, 3.5°, and 4.0°C warming scenarios. In contrast, floods are projected to become less severe in the Upper Songhua, Lower Liaohe, Upper Yellow, and northern Huaihe River basins.

For the reference 30- and 50-yr floods, shortening of the return period is also projected over almost all of China at different global warming levels. Each additional 0.5°C in global warming, from 1.5° to 4.0°C, represents a scenario of more frequent and more intense flooding in China (see supplemental material, Figs. ES6–ES10).

The GDP in the area exposed to floods

With an increase in warming, GDP exposed to floods in China significantly increases, due to both the growth of economy and the increase of affected area (Fig. 3). Floods in China affected an area of 1.2 million $km^2\ yr^{-1}$ in the reference period 1981–2010, and approximately $0.32 trillion of annual GDP was present in the affected area, accounting for 14% of national GDP. From the reference period (~0.7°C warmer than preindustrial conditions) to 4.0°C warming, the increase of flood-affected area is projected at the rate of 0.2 (IQR: 0.1–0.3) million km^2 per 0.5°C of warming, while national GDP is projected to increase by $9.0 (9.0–10.2) trillion per 0.5°C of warming. Under the 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C warming levels, the flood-affected area is projected to be 1.7 (1.5–2.1), 1.7 (1.5–2.2), 2.0 (1.6–2.5), 2.2 (1.8–2.6), 2.3 (2.0–2.8), and 2.4 (1.9–3.1) million km^2, that

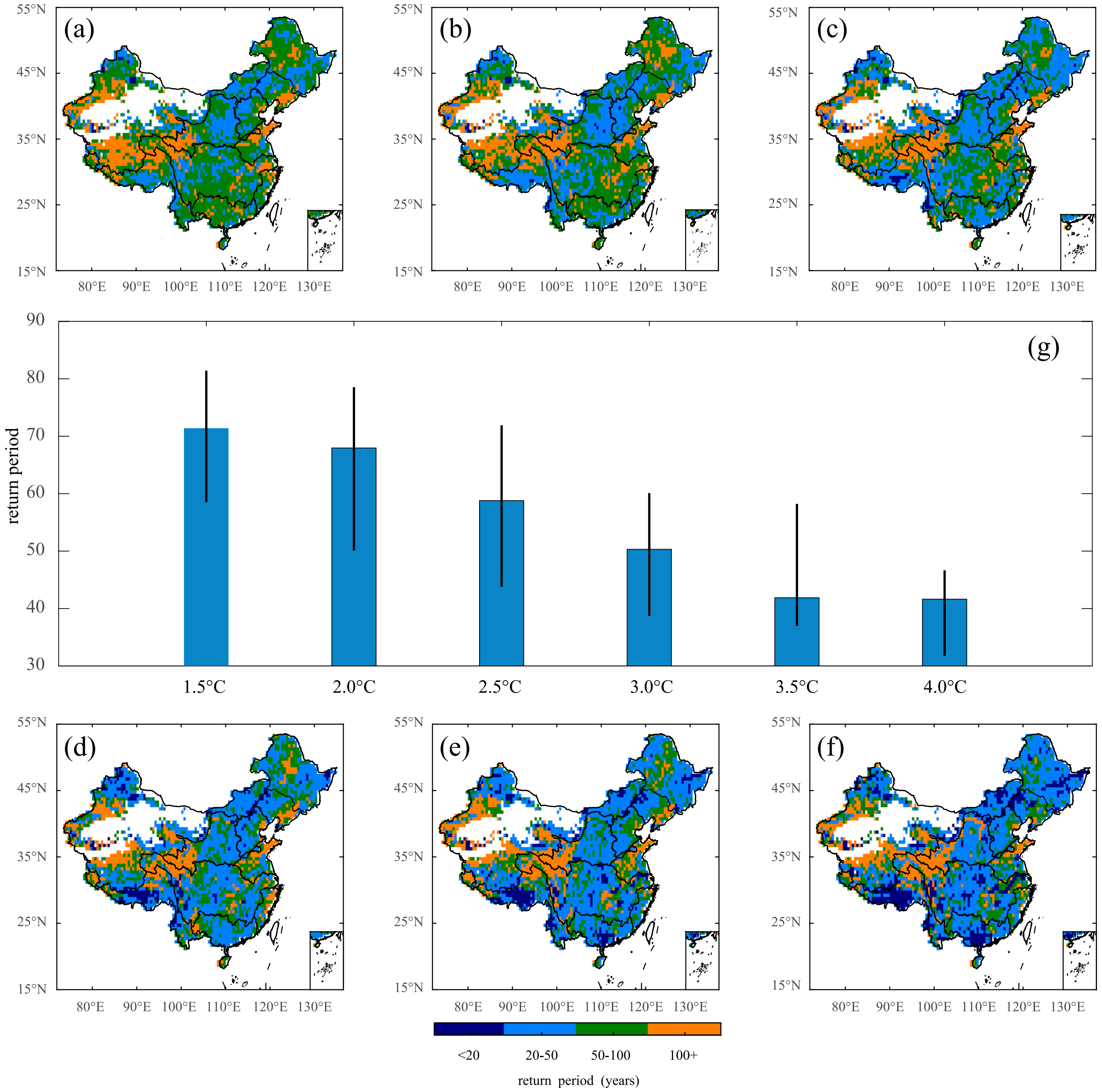

Fig. 2. Projected return period of 100-yr floods (corresponding to the reference period, 1981–2010) under the (a) 1.5°, (b) 2.0°, (c) 2.5°, (d) 3.0°, (e) 3.5°, and (f) 4.0°C global warming scenarios for China using the median of multi-GCM-driven results. (g) Histograms and error bars are the medians and interquartile ranges of GCM results. White regions in (a)–(f) denote bare land (desert and sandy land, with very low damage potential).

is, 42%–100% higher than that in the reference period. The national GDP is projected to be $19.8 ($18.4–$24.6), $31.1 ($24.6–$38.0), $41.6 ($35.3–$48.8), $46.5 ($42.9–$55.7), $52.6 ($49.7–$60.6), and $64.3 ($57.3–$72.2) trillion, that is, 8.6–28.0 times higher than that in the reference period (Figs. 3a,b).

With the increase in affected area to 2.4 (IQR: 1.9–3.1) million km^2 (Fig. 3b) and the growth of the economy to $64.3 ($57.3–$72.2) trillion (Fig. 3a) at the 4.0°C warming level, increasing wealth is projected to be accumulated in the flood-exposed area (Fig. 3c). From reference period to 4.0°C, the increase of flood exposure is $2.2 ($2.0–$2.5) trillion per 0.5°C of warming. The GDP in the exposed area is projected to increase to $4.4 ($3.8–$5.1), $5.9 ($4.9–$6.8), $7.9 ($7.0–$10.0), $10.3 ($8.7–$11.8), $12.8 ($11.5–$14.3), and $14.8 ($13.7–$16.9) trillion for the 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C global warming scenarios, respectively, which are 14 (12–16), 18 (15–21), 25 (22–31), 32 (27–37), 40 (36–45), and 46 (43–53) times that in the reference period. Relative to the previous scenario with 0.5°C less warming, each additional 0.5°C of warming is projected to result in increased exposure by 34%, 34%, 30%, 24%, and 16% from the 1.5° to 4.0°C global warming levels. Flood exposure share of GDP is projected to increase from the 14% in reference to 22%, 19%, 19%, 22%, 24%, and 23% under the 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C global warming scenarios (Table ES4).

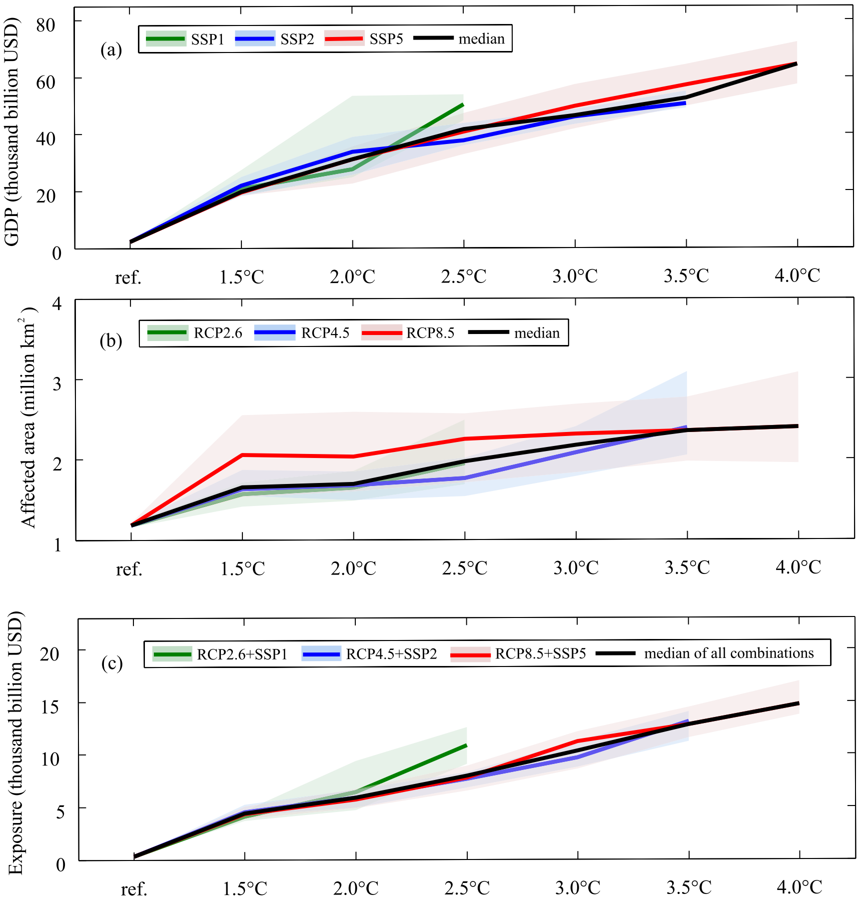

Fig. 3. (a) GDP, (b) annual flood-affected area, and (c) GDP of the flood-affected area in China in the reference period (1981–2010) and under global warming of 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C. Thick lines denote the median of 21 GCM-driven results. Shadows show the interquartile ranges of multi-GCM-driven results.

Flood losses under different warming scenarios

Assuming socioeconomic futures after SSPs, one can project flood losses to increase significantly at the 1.5°C warming level, with average annual losses of $112 billion (IQR: $91–$136 billion), that is, more than 4 times higher than the losses in the recent period of 2006–18, amounting to $25.3 billion (Table ES5). Increasing changes are projected for further warming, with the average rate reaching $67 ($62–$82) billion per 0.5°C increment. The lowest increase, $44 billion, is projected between 1.5° and 2.0°C of warming and the highest, $106 billion, between 3.0° and 3.5°C of warmning. Further warming is projected to lead to flood losses of $156 ($123–$193), $221 ($178–$278), $274 ($238–$365), $380 ($342–$456), and $435 ($385–$534) billion under the 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C global warming scenarios, respectively (Fig. 4a).

Annual flood losses in relation to GDP reached, on average, 0.92% in 1984–2005, while the value of this index decreased to 0.28% for the more recent period of 2006–18, due to dynamic economic development (China Meteorological Administration 2019). However, the declining trend of relative GDP loss may reverse in the future with persistent warming. Flood-induced losses are likely to consume approximately 0.53% (IQR: 0.46%–0.65%) of GDP at the 1.5°C warming level, while the 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C warming levels are 0.48% (0.40%–0.61%), 0.52% (0.42%–0.66%), 0.61% (0.48%–0.77%), 0.66% (0.57%–0.91%), and 0.71% (0.58%–0.91%) of GDP, respectively (Fig. 4b). For each 0.5°C warming increment, up to 0.04% (0.03%–0.07%) of the growing GDP is projected to be consumed, additionally, by floods.

Annual flood losses attributable to climate warming can be also explored by combining floods simulated under different warming levels with the GDP fixed at the 2010 level ($7.6 trillion; see Fig. ES11 and Table ES5). Flood losses are estimated to be about

$33.5–$56.8 billion for 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C of warming, that is, between a 1.3- and ~2.2-fold increase of losses in 2006–18 is anticipated (Fig. ES12). In relative terms, warming is projected to lead to a higher flood loss, and up to 0.06% (IQR: 0.05%–0.09%) GDP per 0.5°C of avoided warming might be saved by pursuing the more stringent climate change mitigation policy aimed at a lower warming target, within the warming scenarios from 1.5° to 4.0°C (Table ES5).

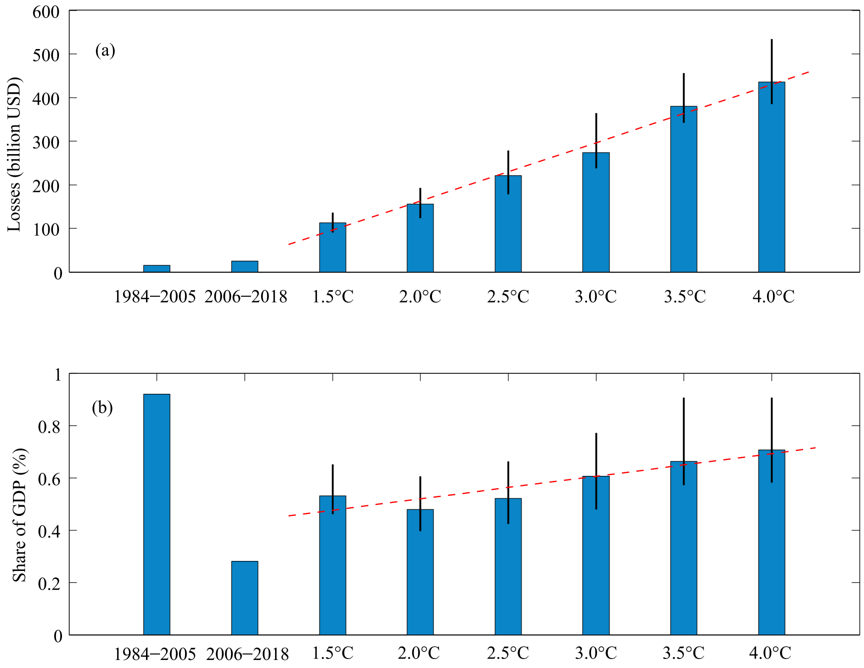

Fig. 4. (a) Flood losses and (b) their share of GDP in China for the period 1984–2018 and for global warming of 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C. Histograms for the periods 1984–2005 and 2006–18 are the recorded values. Histograms and error bars are the medians and interquartile ranges of GCM results. Red dashed lines are the linear trends of flood losses or their share of GDP under the warming climate.

The spatial distribution of flood losses and their share of GDP in the warming world is projected to be almost same as at the 1.5°C warming (Fig. 5, Figs. ES13 and ES14). Relatively higher losses occur mainly in lowland regions and increase with the warming climate. Under the 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C warming scenarios, medians of gridded flood losses over China are $615.5; $815.6; $1,129.5; $1,521.9; $1,746.9; and $2,207.5 km^{-2}, respectively (Fig. 5a and Fig. ES13). From the perspective of loss share of GDP, the regions in highest danger are likely to be those located in the Yangtze and parts of the Songhua River basins.

Insights into flood mitigation and risk reduction in China in a changing climate

Projections obtained in this study illustrate increase of flood hazard in China. We gave substantiation to the general statement that "stationarity is dead" (Milly et al. 2008, 2015). We demonstrated that exceedance probability of reference 100-yr flood is projected to be much higher than 1% in any one year in future decades. That is, an event that was considered rare in the past is likely to become more frequent. Almost all regions of China were projected to encounter higher flood risk. Also, we projected flood losses (absolute and relative) that are substantially higher than those during the historical period, and our national-scale results for China can be seen as a valuable counterpart to results of global studies by Alfieri et al. (2017) and Willner et al. (2018).

Our findings are policy relevant, illustrating that massive adaptation to changing conditions will be required to reduce future river flood risk in China. This is of considerable potential relevance and interest to policy- and decision-makers, both in the field of climate change adaptation and natural disaster reduction. Indeed, China has embarked upon an ambitious, high-budget task to upgrade flood-risk reduction measures and strengthen flood preparedness, by both structural and nonstructural measures that alleviate the burden of river flooding, but also flash and urban flooding. Flood-risk reduction is one of the principal climate change adaptation activities in China, as discussed in more detail in Kundzewicz et al. (2019).

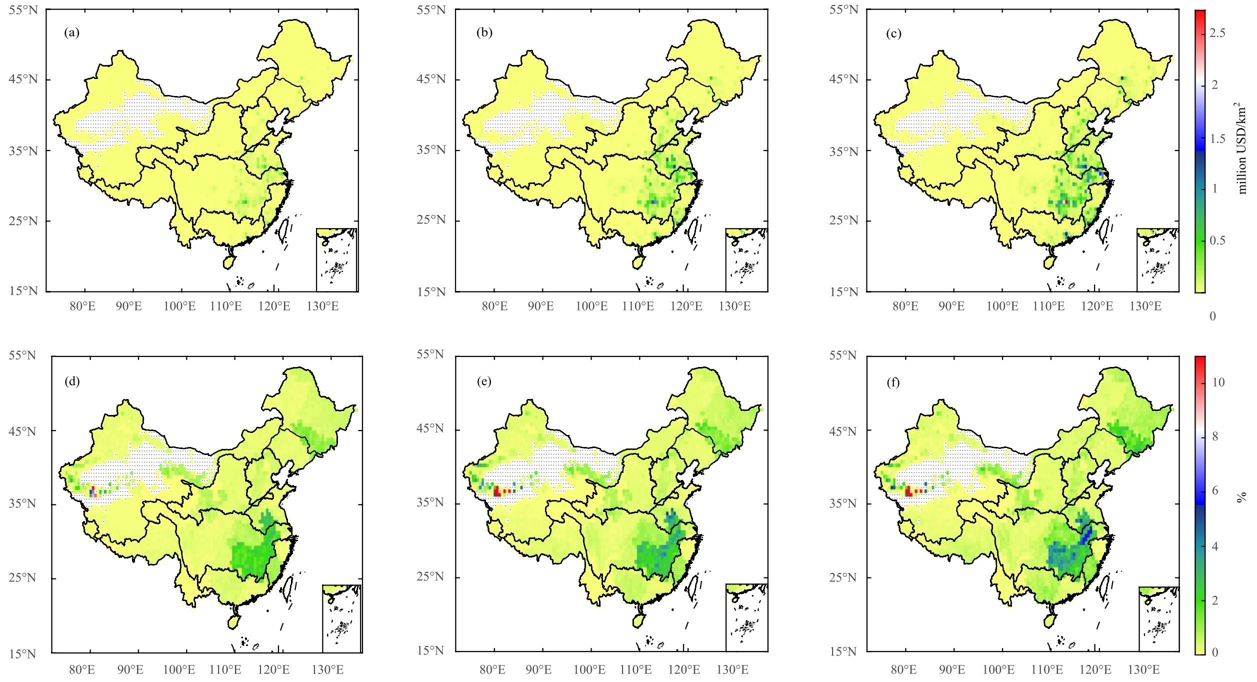

Fig. 5. (a)–(c) Spatial distribution of flood losses (in millions of U.S. dollars per square kilometer) and (d)–(f) their share of GDP (%) in China at the 1.5°, 3.0°, and 4.0°C global warming levels. The results are based on the median of 21 GCM-driven results. White areas with dots denote bare land (desert and sandy land, with very low damage potential).

Conclusions

Along with the increasing flood hazard, also exposure to floods is projected to increase with global warming. As a result, the severity of flood impacts is likely to increase throughout China under warming climate. The GDP that is exposed to floods is projected to increase by a factor of almost 14 (IQR: 12–16) and 46 (43–53) relative to 1981–2010 levels, respectively, at the 1.5° and 4.0°C warming scenarios. When interpreting changes caused by the combined effect of economic and climatic conditions, flood losses are projected to be higher than those during the historical period by 4–17 times under 1.5°–4.0°C of global warming, with greater impacts in lowland regions.

Projections of floods based on multi-GCM-driven simulations have moderately high consistency. More areas are expected to be under the risk of frequent and intense floods in a warmer climate. Approximately 0.2 (IQR: 0.1–0.3) million km^2 of exposed area and $2.2 ($2.0–$2.5) trillion of economic exposure to floods could be reduced for each 0.5°C of less warming. Thus, pursuing the target of limiting global warming is projected to reduce flood losses in China by tens of billions of U.S. dollars for each 0.5°C of less warming, especially for the flood-prone Yangtze River basin. We examined the policy-relevant range of warming, from 1.5° to 4.0°C above preindustrial levels, and found that each additional warming by 0.5°C is projected to increase the flood loss by $67 ($62–$82) billion, on average. Huge increase of flood losses under the warming climate is largely from the socioeconomic conditions, but still can be also attributed to the increase of flood frequency and intensity. Under the assumption of fixed economic condition at the year 2010, flood losses would still increase by 32%–125% under 1.5°–4.0°C of global warming.

Pursuing a more stringent warming target allows us to reduce the index of relative loss as the share of GDP. Up to 0.06% (IQR: 0.05%–0.09%) of GDP could be saved by pursuing the 0.5°C of reduced warming under the assumption of a frozen economy at the level of year 2010. When considering the rapid growth of the economy in China, this figure goes down to 0.04% (0.03%–0.07%).

Data and methods

Data. Observed climate records from more than 2400 stations for the period 1961–2018 were collected from the National Meteorological Information Center of the China Meteorological Administration and hydrological records from 61 stations for the period 1961–2012 come from Hydrological Yearbooks compiled by the Hydrological Bureau of Ministry of Water Resources, China.

The 21 climate simulations used to drive the hydrological model in this study are outputs from 12 GCMs, namely, CNRM-CM5, CanESM2, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM, MIROC-ESM-CHEM, NorESM1-M, MPI-ESM-MR, and MPI-ESM-LR with different runs (see Table ES1). The climate variables include precipitation, temperature (mean, maximum, minimum), relative humidity, wind speed, and surface downwelling shortwave radiation. Referring to the observational data, GCM outputs were downscaled and bias-corrected to 0.5° resolution (see "Selected climate models" section in the supplemental material).

Direct economic losses from floods are recorded in the *Yearbook of Meteorological Disasters in China* (China Meteorological Administration 2019). County-level socioeconomic data for the period 1984–2018 were collected from the *China Statistical Yearbook (County-Level)* (e.g., National Bureau of Statistics of China 2019) and interpolated to 0.5° resolution by the area-weighted interpolation method. To maintain the homogeneity of the data series, losses and GDP records for 1984–2018 were normalized to 2015 prices.

Five SSPs were designed to represent different strategies of socioeconomic development and challenges of mitigation and adaptation (O'Neill et al. 2014). Considering the socioeconomic challenges to mitigation and economic development under different SSPs (O'Neill et al. 2017; Huang et al. 2019), the "Sustainability" pathway SSP1 with a low challenge to mitigation, "Middle of the road" SSP2 with a medium challenge to mitigation, and "Fossil-fueled development" pathway SSP5 with a high challenge to mitigation are separately combined with the RCP2.6, RCP4.5, and RCP8.5 scenarios to assess flood impacts at global warming levels of 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C. The provincial-scale socioeconomy for 2010–2100 is projected under the SSPs parameter scheme (Leimbach et al. 2017) by considering the regional information on total factor productivity, capital stock, and labor force from the latest census and the current universal two-child policy in China for labor force projection (Jiang et al. 2018; Huang et al. 2019). Gridded GDP is derived by scaling the SSP projections to 0.5° resolution, based on the weights of individual grid cells to total provincial GDP, which is from recorded data. The projected GDP was normalized to 2015 prices.

Definitions of 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C warmer world. Timings of the warming by 1.5°, 2.0°, 2.5°, 3.0°, 3.5°, and 4.0°C above the preindustrial level are obtained using 29-yr running-average global mean surface temperature for each model (12 GCMs with 21 runs) and RCP scenario (three RCPs: RCP2.6, RCP4.5, and RCP8.5). The warming periods are defined as the 29-yr windows centered on the years when global warming levels are exceeded (Tables ES6–ES8). All results under different warming levels are first calculated by the average of changes in the corresponding warming periods for each climate model and RCP scenario, and then obtained from the median of multimodel ensemble with different RCP scenarios. Uncertainties from different data sources are shown by the multimodel interquartile range.

Runoff simulation. Runoff at the 0.5° gridcell scale is simulated using a distributed hydrological model, Variable Infiltration Capacity (VIC), at 214 tertiary watersheds in China (see Fig. ES1b). The parameters of the hydrological model were calibrated using the observed daily discharge data from 61 selected gauging stations (Tables ES2 and ES3). The parameters were transferred to neighboring catchments, based on the similarity of climate conditions, land cover, soil properties, digital elevation models, etc. Streamflow was projected until 2099, and the results for 1981–2010 and 2011–99 were used to represent the model reference period and future conditions, respectively.

For the convenience of analysis, flood events at each tertiary watershed are identified according to flood thresholds, which are defined at grid scale as the mean plus one standard deviation (SD) of annual maximum runoff for 1981–2010. Acceptance of this particular definition of flood threshold clearly affects the quantitative results of analysis. The thresholds of 30-, 50-, or 100-yr floods at each grid were estimated for the reference period (1981–2010) using the generalized extreme value (GEV) distribution function (Kotz and Nadarajah 2000).

Intensity-loss rate function. Flood losses can be quantified by combining the flood regime, the socioeconomic status, and the intensity–loss rate function representing the socioeconomic vulnerability to floods. To quantify socioeconomic vulnerability to floods in China, the "intensity–loss rate" curves were established for each tertiary watershed, based on the historical river runoff and direct economic losses for 1984–2018. Here, intensity of a flood event is quantified as to what extent maximum daily runoff fluctuated from its historical norm (1981–2010) by means of standard deviation over flooded grids in a tertiary watershed. The loss rate is the ratio between watershed flood losses and GDP in flood-exposed areas (see "Intensity–loss rate curve" section in the supplemental material). Then, the intensity–loss rate combined with future flood exposure and projected flood intensity was used to estimate the future flood losses.

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B. D. Su, Z. W. Kundzewicz, and J. Xia conceived the study; T. Jiang, B. D. Su, and J. L. Huang contributed equally to this paper by performing analysis and drafting the paper; H. M. Sun, L. P. Zhang, and C. S. Zhan simulated runoffs with hydrological modeling VIC; J. Q. Zhai and G. J. Wang downscaled the climatic projections; Y. J. Wang and Y. Luo set up regionalized SSP scenarios; and H. Tao and M. Xiong set up the intensity-loss rate curve. All authors discussed the results and edited the manuscript. The authors declare that no competing financial interests exist.

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