Long-term changes in global socioeconomic benefits of flood defenses and residual risk based on CMIP5 climate models

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Abstract. A warmer climate is expected to accelerate the global hydrological cycle, causing more intense precipitation and floods. Despite recent

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progress in global flood risk assessment, the socioeconomic benefits of flood defenses (i.e., reduction in population/economic exposure) and the residual risk (i.e., residual population/economic exposure) are poorly understood globally and regionally. To address these knowledge gaps, we use the runoff data from a baseline and 11 CMIP5 climate models to drive the CaMa-Flood model incorporating the latest satellite-river width information. From the simulated annual maxima, we use a Gumbel distribution to estimate the river water depth - flood return period relationship. We independently evaluate flood impacts on population and economy (i.e., gross domestic product (GDP)) for a range of flood return periods. We estimate the socioeconomic benefits and the corresponding residual risk for the globe and 26 sub-continental regions. The global population (GDP) exposed to flooding is ∼8% (∼7%) per year lower when implementing existing flood protection infrastructure extracted from the FLOPROS database. If the current flood defenses were to be unchanged in the future (RCP4.5 and RCP8.5, i.e., ∼2-∼4.3°C above the pre-industrial levels), the globe and most of the regions (particularly where developing countries are concentrated) would experience an increase in residual risk. This increase is especially obvious when the gap of climate forcing between RCP8.5 and RCP4.5 widens by end of the 21st century. We finally evaluate the impact of changed flood defense levels on the socioeconomic benefits and the corresponding residual risk.

Keypoints:

- The global population (GDP) exposed to flooding is ∼8% (∼7%) per year lower when implementing current flood protection infrastructure
- Residual population (economic) exposure is ∼1% (∼0.6%) of the global population (GDP) per year
- Residual risk would magnify in the globe and most of the regions (mainly where developing countries are located) in warmer worlds

1. Introduction

Floods affect millions of people [Jonkman, 2005] and cost billions of dollars annually [Mills, 2005] due to extensive socioeconomic growth [Bouwer, 2011; Mohleji & Pielke, 2014] and perhaps large spatial variation in flood protection [Scussolini et al., 2016]. Acceleration of the global hydrological cycle in a warmer world (e.g., Oki & Kanae [2006]; Lim & Roderick [2009]; Durack et al. [2012]; Roderick et al. [2014]) is projected to intensify precipitation [Allen & Ingram, 2002; Allan & Soden, 2008; O'Gorman & Schneider, 2009; Donat et al., 2016; Fischer & Knutti, 2016], causing bigger floods [Milly et al., 2002; Hirabayashi et al., 2008] with possible risk exacerbation because of socioeconomic development, land-use change (e.g., deforestation, urbanization) and/or subsidence [Hirabayashi et al., 2013; Arnell & Gosling, 2014; Winsemius et al., 2016; Ward et al., 2017; Dixon et al., 2006; Brown & Nicholls, 2015]. However, studies of the socioeconomic benefits of flood defenses on regional and global scales are limited. Most of the global scale flood risk assessments focused on understanding of socioeconomic risks without flood defenses (e.g., Jongman et al. [2012]; Hirabayashi et al. [2013]; Arnell & Gosling [2014]; Arnell & Lloyd-Hughes [2014]; Dankers et al. [2014]); whilst a few recent assessments have begun to cover flood defenses as part of climate adaptation (e.g., European continent [Feyen et al., 2012; Rojas et al., 2013], global [Jongman et al., 2015; Winsemius et al., 2016; Alfieri et al., 2017; Ward et al., 2017]).

Nonetheless, we still do not understand how existing/potential flood defense levels would benefit the society in terms of reduction in socioeconomic exposure (e.g., population, gross domestic product (GDP); detailed definitions in Section 2.3.2). It is unclear how these numbers would evolve in different sub-continental regions [IPCC, 2012, Table 3.A-1] and the globe under long-term climate change (e.g., by middle and end of the 21st century). More specifically, a consistent analysis involving an ensemble of CMIP5 climate models to quantify the effect of climate model uncertainty is not available. To our knowledge, major global reports have not explicitly address these policy relevant knowledge gaps [IPCC, 2012, 2014a, b; Ghesquiere et al., 2014; Sadoff et al., 2015; UNISDR, 2015a]. From simulation perspective, many studies (e.g., Jongman et al. [2015]; Winsemius et al. [2016]; Ward et al. [2017]) have implemented the GLObal Flood Risk with IMAGE Scenarios (GLOFRIS) through combining a global hydrological model PCR-GLOBWB [Van Beek and Bierkens, 2009], with a subgrid parameterized dynamic flow routing scheme (using kinematic wave approximation) called DynRout and a flood extent downscaling algorithm to estimate global flood hazard (detailed description in Winsemius et al. [2013]). The Catchment-Based Macro-scale Floodplain (CaMa-Flood) model [Yamazaki et al., 2011] uses the diffusive wave approximation and has more advanced hydrodynamics than GLOFRIS should complement these studies. Addressing these knowledge gaps (above) using the CaMa-Flood model should offer greater clarity on socioeconomic benefits of flood defense levels and support decision-making about investments in flood risk management.

To contribute towards development of informed natural disaster risk reduction frameworks [Walch, 2015], we make an attempt to fill these knowledge gaps (above) using a simulation approach (see an overview of our approach in Figure 1; detailed description in Section 2). We drive a global river routing scheme using the daily runoff output for a baseline period and atmosphere-ocean global circulation models (AOGCMs) from CMIP5 archive [Taylor et al., 2012]. For a range of future climate scenarios [van Vuuren et al., 2011], we quantify the long-term change in socioeconomic benefits of flood defenses and the corresponding residual risk at ∼2-∼4.3°C global warming conditions above the pre-industrial levels. We interpret these results for the globe and 26 sub-continental regions (Figure S1 in Supporting Information).

2. Materials and methods

2.1. Global hydrological modeling

Similar to Hirabayashi et al. [2013], we obtain the daily runoff data (period: 1979-2010; spatial resolution: 1° × 1°) from the Minimal Advanced Treatment of a Land Surface Interaction Runoff (MATSIRO) [Takata et al., 2003], forced by observations and reanalysis climate data [Kim et al., 2009], to represent the 'baseline' runoff. We use the daily runoff data (historical period: 1960-2005; future period: 2006-2100 (2006-2099 for BCC-CSM1.1)) of 11 AOGCMs in this study (see Table 1). In the future period, we select RCP4.5 and RCP8.5 (period 2006-2100 (2006-2099 for BCC-CSM1.1)) which cover most of the key future climate scenarios in the IPCC AR4 (i.e., A1T, A1B, A2, A1F1 and B2 to certain extent) [IPCC, 2013, Box 1.1., their Figure 3(a)]. For each AOGCM, we rescale the daily runoff data to 1° × 1° using bilinear interpolation. In terms of global mean surface air temperature, these periods 2046-2065[RCP4.5], 2046-2065[RCP8.5], 2080-2099[RCP4.5] and 2080-2099[RCP8.5] are ∼2.0°C, ∼2.6°C, ∼2.4°C and ∼4.3°C above the pre-industrial levels, respectively [IPCC, 2013, their Table SPM.2].

We apply a distributed global river routing scheme – CaMa-Flood model [Yamazaki et al., 2011] (Figure S2 in Supporting Information). Briefly, CaMa-Flood routes the runoff input generated by a land surface model into the oceans or lakes along a prescribed river network. It calculates the storages (river channel, floodplain), river discharge, river water depth, flood depth and flooded area for each grid cell (spatial resolution: 0.25° × 0.25°). The river channel width data in the earlier versions of CaMa-Flood was estimated based on empirical functions of river discharges. To achieve a better consistency between river channel width data and the HydroSHEDS flow direction map in the CaMa-Flood model, a satellite-river width data called Global Width Database for Large Rivers (GWD-LR) [Yamazaki et al., 2014] is incorporated into the model. We use the daily runoff data (baseline, AOGCMs) to drive the CaMa-Flood model and generate river routing outputs (see Hirabayashi et al. [2013, Supplementary Information S1] for details of model validation). (Note that the calculation results for the region CGI (see Figure S1 in Supporting Information) excludes Greenland, Iceland and islands beyond 74°N.)

2.2. Extreme value statistics

Flood occurs when the flow in the river channel exceeds river channel capacity, such that excess water volume spreads across the floodplains (Figure S2 in Supporting Information). In the CaMa-Flood model (also many hydrological models), the physical profile of a river and its floodplains (channel width, channel length, floodplain elevation profile) are set constant and do not change with time. A clear relationship exists between the total water storage and the river water depth in each grid cell.

To estimate extreme value statistics in each grid cell, we use the Gumbel distribution [Gumbel, 1941] which is a member of the Generalized Extreme Value family of distribution [Coles, 2001] and is suitable for analysis of annual maxima. Its cumulative distribution function (i.e., non-exceedance probability) is

$$F(y; \mu, \lambda) = e^{-e^{-\left(\frac{y-\mu}{\lambda}\right)}} \tag{1}$$

where y [m] is the river water depth, μ is the location parameter (dimensionless) and λ is the scale parameter (dimensionless). The parameter λ is calculated as

$$\lambda = \frac{\sqrt{6}}{\pi} s_Y = 0.7797 s_Y \tag{2}$$

and parameter μ is calculated as

$$\mu = \mu_Y - \gamma\lambda \tag{3}$$

where γ (=0.5772) is the Euler's constant (dimensionless), μ_Y and s_Y are the mean and sample standard deviation for a collection of annual maxima Y(=Y_1, Y_2, ..., Y_n) for the simulated river water depth output of the baseline (period: 1979-2010) and AOGCMs (period: 1970-1999) in Section 2.1, respectively. Based on these parameters, we estimate the non-exceedance probability (Eq. (1)) of the annual maxima river water depth for the baseline; and each AOGCM over the historical period and the future period (see Section 2.3).

To estimate the specific magnitude in the non-exceedance probability of the baseline and each AOGCM, we use

$$F(y; \mu, \lambda) = 1 - \frac{1}{T} \tag{4}$$

where T [year] is the return period. We apply Eq. (4) to set the 'threshold' for a range of flood defense levels at each grid cell (see Section 2.3).

2.3. Socioeconomic benefits of flood defenses and residual risk

2.3.1. Socioeconomic data

To estimate the socioeconomic impacts of flooding, we use the World Bank data (country population, GDP based on purchasing power parity (PPP)) as baseline. For simplicity, we do not consider socioeconomic scenarios of future population and economic change.

To prepare World Bank data with sufficiently high spatial resolution, we download the population distribution map (year: 2005; spatial resolution: 2.5' $\times$ 2.5' (ca. $\sim$5 km $\times$ $\sim$5 km at the equator)) from the Gridded Population of the World version 3 (GPWv3) [CIESIN, 2005]. (We weighed the availability of computing resources to cover sufficient level of details which fit the purpose of this large scale study (Section 1).) Using country mask [Freydank & Seibert, 2008], we calculate the ratio of country population from the World Bank to the sum of distributed population of each country from the GPWv3; and multiply this ratio with the population distribution of each country in GPWv3. From there, we prepare a new global population distribution map (note: data not available for French Guiana, Taiwan and Western Sahara). We multiply the World Bank country GDP per capita (year: 2005; unit: 2005US$ PPP) with the revised population distribution map to get a global GDP distribution map (data not available for French Guiana, Greenland, Myanmar, North Korea, Somalia, Taiwan and Western Sahara). Following IPCC [2012, Table 3.A-1] (Figure S1 in Supporting Information), we aggregate the population and GDP (constant 2005) for 26 sub-continental regions and the globe in Table 2. We note that the socioeconomic data (population, GDP) prepared here is consistent in unit (2005US$ PPP) with that of the Shared-Socioeconomic Pathways (SSPs) [O'Neill et al., 2014], enabling future studies involving different SSPs to relate their estimates to current study without handling complex unit conversion for the GDP. In addition, the year 2005 is also the final year within the historical period in the CMIP5 archive (see Section 2.1), making it is a suitable baseline to represent the recent past.

2.3.2. Benefits of flood defenses and residual risk

To estimate flood inundations, we apply the extreme value statistics of the baseline (spatial resolution: 0.25° × 0.25°; see Section 2.2) and high resolution DEMs (spatial resolution: 15" × 15"). (Briefly, these DEMs include SRTM3 DEM (original spatial resolution: 3" × 3") between 60°N and 60°S; GTOPO30 (original spatial resolution: 30" × 30") above 60°N [Hirabayashi et al., 2013]. They were converted to a common spatial resolution of 15" × 15" using the Flexible Location of Waterways (FLOW) method and upscaled to 0.25° × 0.25° [Yamazaki et al., 2011].) For better accuracy, we first downscale and prepare a look-up table of flood fraction (i.e., ratio of flood inundated area to total land area per grid cell; range: 0-1; return period: 2-10000 years) using these high resolution DEMs. We multiply it with the population and GDP distribution maps (Section 2.3.1); and upscale them to produce the look-up tables of population and economic exposure (spatial resolution: 0.25° × 0.25°). The latter step allows for relating a specific flood return period (of the baseline or AOGCMs) to population/economic exposure without repeating the similar downscaling process again.

From socioeconomic perspective, we define 'benefits' as the reduction in population/economic exposure corresponding to a specific flood defense level (i.e., return period). We use the term 'residual risk' to represent the residual population/economic exposure corresponding to that flood defense level. To evaluate the potential socioeconomic benefits and residual risk of flood defenses and how they might change in the long-term, we use the recently assembled global flood defense database called FLOPROS [Scussolini et al., 2016] (gridded to a spatial resolution of 0.25° × 0.25°; we implemented the return period in this study) and a plausible range of flood defense levels (with return periods up to 1000 years). When the return period of the annual maxima is less than or equal to the 'threshold' defense level, we consider the population or economy that would have been exposed to flood inundation as the socioeconomic benefits. We quantify them by matching the return period of the annual maxima to the look-up tables of the population and economic exposure. When the return period of the annual maxima exceeds the 'threshold', we assume minimum socioeconomic benefits (i.e., maximum damage for the given water level) and count it towards the residual risk. We repeat the process at every grid cell of the baseline and AOGCMs. For each region and the globe (Table 2), we estimate the socioeconomic benefits and residual risk of flood defenses in the historical period (1986-2005; baseline and AOGCMs) and how they would change in the future periods (1986-2005 to 2046-2065 and 1986-2005 to 2080-2099; AOGCMs under RCP4.5 and RCP8.5). We present these estimates in terms of the mean annual value (e.g., % population per year or % GDP per year) (see Section 3).

3. Results

3.1. Benefits of existing flood defenses

3.1.1. Flood impacts on people

In the historical period (1986-2005), we find that the current flood defenses [Scussolini et al., 2016] reduce the population exposure from ∼9% per year (∼580 million people per year; Figure S9 (subfigure 'GLOBE', label 'None') in Supporting Information) to ∼1% per year (∼65 million people per year; Figure 3a), a reduction of ∼8% per year on a global scale (Figure 2a). Whilst the results of AOGCMs vary across regional and global scales, their ranges and ensemble means are generally consistent with that of the baseline. In the future projections (Figure 2b; Figure S3 in Supporting Information), the changes in population benefits among the AOGCMs (Δ(1986-2005 to 2046-2065) and Δ(1986-

2005 to 2080-2099)) are mixed. From their ensemble means, we find that most of these regions (excluding EAS, SAS, SEA) and the globe would experience some (often marginal) reduction in the benefits of flood protection to people under future climate conditions.

In the similar historical period, the residual population exposure ranges 0-∼6% of the regional population per year; the global mean ∼1% of the global population per year (Figure 3a), i.e., on average 65 million people per year. In terms of percentage population, the regions with low flood defense levels (median ≤10 years, e.g., CAS, EAF, SAH, WAF) would have residual population exposure above the global mean. Despite having higher flood defense levels (median ∼20 years), several regions in Africa and Asia (e.g., SAF, SEA) are still susceptible to such risk. When we examine the future changes (Δ(1986-2005 to 2046-2065) and Δ(1986-2005 to 2080-2099)), we confirm that the change in regional and global residual population exposure (AOGCMs and ensemble means) generally increase with rising greenhouse gas emissions (Figure 3b; Figure S4 in Supporting Information). These outcomes indicate that flood protection infrastructure and/or emergency response capacity would need to increase in order to adapt to climate change.

3.1.2. Flood impacts on the economy

Based on the existing flood defenses, we repeat the above analysis but this time we look at the economic perspective (we use % of the regional or global GDP as proxy) (Figure 4). Similarly, we find that high (low) defense level leads to high (low) economic benefits (but not always), and regional variation is visible (reaching ∼22% of the regional GDP per year) (Figure 4a). Globally, the current flood protection infrastructure lowered the economic exposure from ∼7.6% per year (∼US$4.8 trillion per year; Figure S13 (subfigure ‘GLOBE’, label ’None’) in Supporting Information) to ∼0.6% per year (∼US$0.38 trillion per year; Figure 5a), a reduction of ∼7% of the global GDP per year. Again, the regional and global results of AOGCMs are in general agreement with those of the baseline. Whilst the changes in economic benefits among the AOGCMs (Δ(1986-2005 to 2046-2065) and Δ(1986-2005 to 2080-2099)) are mixed under future climate conditions, the ensemble means show that most of the regions (except for a few regions in Asia, e.g., EAS, SAS, SEA) and the globe would experience reduction in economic benefits (Figure 4b; Figure S5 in Supporting Information).

In the historical period (1986-2005), our estimates show that the residual economic exposure ranges 0-∼5% of regional GDP per year; reaching about 0.6% of economy size per year (∼US$0.38 trillion per year) on a global scale (Figure 5a). In terms of percentage GDP, regions with relatively low flood defense levels (median ≤10 years, e.g., CAS, EAF, SAH, WAF) typically exceed the global mean. Several regions (e.g., SAF, SEA) are still susceptible to such risk at higher flood defense levels (median ∼20 years). From the future changes (Δ(1986-2005 to 2046-2065) and Δ(1986-2005 to 2080-2099)), we find that the regional and global residual economic exposure (AOGCMs and ensemble means) would increase with rising greenhouse gas emissions (Figure 5b; Figure S6 in Supporting Information). These provide an additional dimension on rethinking the current flood risk reduction measures.

3.2. Benefits of changing flood defense levels

3.2.1. Flood impacts on people

Next, we evaluate the impact of varied flood defense levels on population benefits. In general, the population benefits increase steeply for flood defense level ranges from the return period of 5 to 20 years; with the benefits then tailing off for the return periods of

20 to 500 years (Figure S7 in Supporting Information). The ensemble mean and range of AOGCMs are close to the baseline, giving us the confidence to explore their future projections. (The reduction in population exposure of the Sahara (SAH) is substantial because of high population density in the major rivers basins. However, in common with other global flood models, flood risk is over-estimated on the Nile because we do not include dam operation.) Comparing the results of future climate scenarios (RCP4.5 and RCP8.5), we confirm that higher greenhouse gas emissions would intensify the uncertainty of the change in population benefits by middle (Figure S8 in Supporting Information) and end of the 21st century (Figure 6). From the ensemble mean results (solid lines in Figures 6, S8), we find that the population benefits would decrease at lower flood defense levels and increase at higher flood defense levels in some regions in Asia (EAS, SAS, SEA), Africa (EAF, WAF), Latin America (AMZ, SSA, WSA) and the globe (GLOBE); consistently decline in several regions in North America (ALA, CAM, CGI, CNA, ENA, WNA), Asia (CAS, NAS, WAS), Europe/Mediterranean (NEU, CEU, MED) and Africa (SAH). Regionally and globally, the gap between the ensemble means (of RCP4.5 and RCP8.5) might offer a general sense of the potential range of population benefits.

Typically, the residual population exposure (ensemble mean and AOGCMs) declines significantly as flood defense level rises from a return period of 5 to 20 years; the decline is mild at higher flood defense levels (opposite to the population benefits in Section 3.1.1) (Figure S9 in Supporting Information). The pattern of the ensemble mean and range of AOGCMs are consistent with that of the baseline, hence it is reasonable to evaluate their future projections. An examination of the future scenarios (RCP4.5 and RCP8.5) shows that elevated greenhouse gas emissions increase the uncertainty of the change in residual population exposure by middle (Figure S10 in Supporting Information) and end of the 21st century (Figure 7). From the ensemble mean results without flood defenses (labeled 'None' in Figures 7, S10), the population exposure would increase in some regions (Asia (SAS, SEA), Africa (EAF, WAF) and Latin America (AMZ, SSA, WSA)), decrease in several regions (e.g., Europe/Mediterranean (CEU, NEU, MED), North America (ALA, CNA, WNA), Asia (NAS, WAS)) but relatively uncertain elsewhere. The global aggregates range ∼0.5%-∼1% and ∼1%-∼2% of the global population by middle and end of the 21st century, respectively. From the ensemble mean results with flood defenses, we find that the residual population exposure would increase in some parts of America (AMZ, CAM, NEB, SSA, WNA, WSA, ENA), Asia (EAS, SAS, SEA, TIB), Africa (EAF, WAF, SAF, SAH) and the globe (GLOBE). The generalized range of residual population exposure is formed in-between these ensemble means (i.e., RCP4.5 and RCP8.5).

3.2.2. Flood impacts on the economy

The economic benefits accelerate as the flood defense level increase from the return period of 5 to 20 years; from return period of 20 to 500 years (Figure S11 in Supporting Information). (The increase in economic benefits in the Sahara (SAH) is significant because concentration of economic activities follow the population distribution near the major river basins. Nonetheless, dam operation should have minimized the economic impacts of flooding in the Nile.) Again, the results of the future climate scenarios (RCP4.5 and RCP8.5) confirm that higher greenhouse gas emissions lead to higher uncertainty of the population benefits by middle (Figure S12 in Supporting Information) and end of the 21st century (Figure 8). From the ensemble means (solid lines in Figures 8 and S12), we find that the economic benefits fall at lower flood defense levels and rise at higher flood defense levels in some parts of Asia (EAS, SAS, SEA), Africa (EAF, WAF), Latin America (AMZ, SSA, WSA) and the globe (GLOBE); consistently fall across North America (ALA, CAM, CGI, CNA, ENA, WNA), Asia (CAS, NAS, WAS), Europe/Mediterranean (NEU, CEU, MED) and Africa (SAH). Regionally and globally, the gap between the ensemble means (of RCP4.5 and RCP8.5) might resemble the range of potential economic benefit.

The pattern of declining economic exposure (including ensemble mean and range of AOGCMs) with increasing flood defense levels is consistent with our general expectations (Figure S13 in Supporting Information). Similar to above, the residual economic exposure declines substantially from the flood defenses with return period of 5 to 20 years and gets milder thereafter. Again, we confirm that these results are close to the baseline. The tendency of rising greenhouse gas emissions (RCP4.5 and RCP8.5) in introducing a higher uncertainty is evident with widening range of change in residual economic exposure by middle (Figure S14 in Supporting Information) and end of the 21st century (Figure 9). The ensemble mean results without flood defenses (labeled 'None' in Figures 9, S14) show that the economic exposure would increase in some regions (e.g., Asia (SAS, SEA), Africa (EAF, WAF) and Latin America (AMZ, NEB, SSA, WSA)), decrease in several regions (e.g., Europe/Mediterranean (CEU, NEU, MED), North America (ALA, CNA, WNA), Asia (NAS, WAS)) and inconclusive elsewhere. The global aggregates range 0-$\sim$0.3% and $\sim$0.2%-$\sim$0.7% of the global economic size by middle and end of the 21st century, respectively. From the ensemble mean results with flood defenses, the residual economic exposure would increase in some parts of America (AMZ, CAM, ENA, NEB, SSA, WNA, WSA, ENA), Asia (EAS, SAS, SEA, TIB), Africa (EAF, WAF, SAF, SAH) and the globe

(GLOBE). The gap between the ensemble means (of RCP4.5 and RCP8.5) of these results might provide insights about the potential range of residual economic exposure.

4. Discussion

4.1. Comparison with previous studies

With the FLOPROS database [Scussolini et al., 2016], the global aggregate of residual population exposure in the historical period (∼65 million per year; see Section 3.1.1) is much closer to the observed record on freshwater flooding of the OFDA/CRED International Disaster Database (EM-DAT) [Jonkman, 2005, ∼81 million per year for the period 1975-2001 in Table VI (Freshwater floods)] than a recent estimate [Alfieri et al., 2017, 54 million per year], suggesting that the calculations here are more reliable. From both population and economic perspectives, our future projections concur with recent reports on concentration and elevation of (residual) risk in Africa and Asia (e.g., Hirabayashi et al. [2013]; Alfieri et al. [2017]), followed by some Latin American regions. These regions are home to vast majority of the less wealthy developing countries (in terms of GDP per capita) where existing flood defense levels lag behind those of the wealthier developed countries (refer to Table 2), probably constrained by the financial capacity to invest on disaster risk reduction measures [Jongman et al., 2015]. This study consistently explored the protection benefits (population and economy) and corresponding residual risk for a spectrum of flood defense levels without additional assumptions (e.g., loss function, asset valuation, discount rate), this complements the cost-benefit analysis of Ward and colleagues [Ward et al., 2017].

4.2. Limitations and recommendations for future research

The outcomes of this study are broadly suitable for understanding the potential flood defense benefits and residual risk on regional and global scales. For local adaptations, details at finer spatial resolutions would be achievable through downscaling (set the boundary conditions using AOGCMs outputs) using regional climate modeling tools or statistical approaches. Considering the energy balance perspective of the climate system, advances in regional climate simulation tools (see recent review [Xie et al., 2015]) might offer more insights on hydrological extremes on local scale. Depending on the local conditions, a specific flood defense infrastructure (e.g., floodgates, flood water control through dam operation, embankments, water pumping, reservoir storage) might alter the hydrodynamics of river discharges. When such information becomes available, incorporation of this infrastructure into a hydrological model would improve the calculations. When analyzing local scale impacts (e.g., country, small region), a combination of these hydrologic calculations with socioeconomic data at a much higher spatial resolution (e.g., GPWv4) should offer useful quantitative insights for decision-making.

We assumed that GDP distribution within each country follows the population distribution because actual spatial GDP information is scarce. Despite its simplicity, such generalization could serve as a proxy for large scale analysis (e.g., Jongman et al. [2012], current study). Since country-based GDP per capita varies in each region, the flood impacts (e.g, benefits, residual risk) on the population and economy are also different in terms of percentage (%) and absolute value. To this end, the international organizations (e.g., United Nations, World Bank) should find both population and economic residual risk projections (see Section 3) relevant for developing better targeted risk reduction goals and measures for flood-prone regions. When validated relationship between land-use (e.g., rural, urban) and GDP within each country becomes available, a combination of such relationship with population distribution map might improve the assessment of flood impacts on the economy.

The FLOPROS database contains uncertainty because it consists of several layers (i.e., policy, design and model), and local measures with high protection level (e.g., dams, reservoirs) were not included [Scussolini et al., 2016, their Section 4]. To a good approximation, relating the median global/regional flood defense level in the FLOPROS database (see Table 2) to the estimates in Section 3.2 (e.g., Figures S7, S9, S11, S13) would produce outcomes close to the results in Section 3.1 (e.g., Figures 2a, 3a, 4a, 5a). In a sense, the estimates in Section 3.2 resemble a sensitivity analysis for the FLOPROS database. Since a logarithmic profile exists between estimated flood magnitude and return period (in Section 2.2, a rearrangement of Eqs. (1) and (4) gives y = -λ ln[-ln(1 - $\frac{1}{T}$)] + μ), these estimates are more (less) sensitive at lower (higher) flood defense levels.

The current study investigated the flood impacts of climate change and set the socioeconomic parameters constant. The data of several countries are not available and that might have affected the regional aggregation but are small for the global aggregation. Future studies could incorporate socioeconomic scenarios [O'Neill et al., 2014] and asset classes (e.g., Suwathep et al. [2015]). In addition to examination of flood defense infrastructure, it would be helpful to explore the resources needed for emergency response, resilience capacity building and/or transboundary cooperation arrangements.

5. Conclusions

Based on the most recent global river width database and CaMa-Flood model [Yamazaki et al., 2011, 2014], we independently performed a consistent analysis (overview in Figure 1) of socieconomic benefits of various flood defense levels and corresponding residual risk across the 26 sub-continental regions and the globe (Figures 2-9, S3-S14). This comprehensive analysis addressed several knowledge gaps (see Section 1) that are apparent in the IPCC AR5 [IPCC, 2014a, b] and the World Bank reports [Ghesquiere et al., 2014; Sadoff et al., 2015] and should complement recent studies (e.g., Feyen et al. [2012]; Rojas et al. [2013]; Arnell & Gosling [2014]; Jongman et al. [2015]; Winsemius et al. [2016]; Alfieri et al. [2017]; Ward et al. [2017]). In terms of CO_2 equivalent concentrations, the RCP scenarios considered here (i.e., RCP4.5 and RCP8.5) include the major SRES scenarios [IPCC, 2013, see Box 1.1., Figure 3(a)]. Hence these findings should supplement the lack of such evaluation in the earlier IPCC SREX report [IPCC, 2012]. Notably, the estimates Δ(1986-2005 to 2046-2065[RCP4.5]) here are directly relevant to climate change adaptations in-line with the Paris Agreement's ultimate target on stabilising global warming within 2°C. We found stronger lift in residual risk for the globe and most of the regions under higher greenhouse gas emissions scenario (RCP8.5), particularly in sub-continental regions where most developing countries are located. The insights into regional variation should support decision-making on climate change adaptations (priorities in UNISDR [2015b], e.g., water infrastructure investment, flood warning system, emergency and resilience capacity building). Moreover, expectation of reduced global residual risk under lower greenhouse gas emission scenario (such as RCP4.5 or lower) should assist climate change mitigation efforts at international level [UN, 2015].

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Table 1. Basic information of AOGCMs sourced from the CMIP5 archive (http://cmip-pcmdi.llnl.gov/cmip5/index.html).

Model	Modeling center/group	Country	Spatial resolution†
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration	China	$\sim$2.8° × $\sim$2.8° (128 × 64)
CCCma-CanESM2	Canadian Centre for Climate Modelling and Analysis	Canada	$\sim$2.8° × $\sim$2.8° (128 × 64)
CMCC-CM	Centro Euro-Mediterraneo sui Cambiamenti Climatici	Italy	0.75° × 0.75° (480 × 240)
CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Advancees en Calcul Scientifique	France	$\sim$1.4° × $\sim$1.4° (256 × 128)
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	Australia	$\sim$1.9° × $\sim$1.9° (192 × 96)
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	USA	2.5° × 2° (144 × 90)
INM-CM4	Institute for Numerical Mathematics	Russia	2° × 1.5° (180 × 120)
MIROC5	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan	$\sim$1.4° × $\sim$1.4° (256 × 128)
MPI-ESM-LR	Max Planck Institute for Meteorology	Germany	$\sim$1.9° × $\sim$1.9° (192 × 96)
MRI-CGCM3	Meteorological Research Institute	Japan	$\sim$1.1° × $\sim$1.1° (320 × 160)
NCC-NorESM1-M	Norwegian Climate Centre	Norway	2.5° × $\sim$1.9° (144 × 96)

† We include the grids in the bracket '()' as reference.

Table 2. Basic information of land area, socioeconomic data (constant 2005) and existing flood defense levels for each region defined in Figure S1.

Label	Regional representation	Land area [million km^2]	Population [million]	GDP [billion 2005US$ PPP]	Flood defense levels* Range ; median ; mean [Years]
ALA	Alaska / Northwest Canada	3.36	0.6	25.5	45.7 - 500 ; 45.8 ; 223.8
AMZ	Amazon	8.28	65.6	651.5	0 (6.5) - 33.3 ; 16.5 ; 15.2 (15.3)
CAM	Central America and Mexico	3.25	184.4	1903.1	0 (6.5) - 500 ; 17.6 ; 29.4 (29.8)
CAS	Central Asia	2.82	183.9	607.1	2 - 100 ; 10 ; 11.3
CEU	Central Europe	3.45	368.5	7706.2	0 (6.5) - 4000 ; 49.2 (49.3) ; 82.1 (82.8)
CGI	East Canada, Greenland, Iceland	7.86	1.2	40.1	0 (45.7) - 200 ; 45.7 ; 48.8 (48.9)
CNA	Central North America	3.98	102.7	4527.7	17.9 - 500 ; 500 ; 371.5
EAF	East Africa	6.37	260.6	314.4	0 (2) - 20 ; 2 ; 2.7
EAS	East Asia	8.28	1498.8	11455.5	0 (2) - 937.8 ; 20 ; 31.2
ENA	East North America	2.66	148.7	6400.2	0 (46.5) - 500 ; 500 ; 306.2 (307.1)
MED	Southern Europe and Mediterranean	4.99	366.2	5442.4	0 (6.5) - 606.2 ; 16.7 (16.8) ; 29.2 (30.2)
NAS	North Asia	14.60	82.4	981.3	0 (6.5) - 500 ; 45.7 ; 44.4
NAU	North Australia	6.31	5.2	149.9	0 (6.5) - 100 ; 100 ; 99.8 (99.9)
NEB	Northeastern Brazil	2.82	75.9	802.0	16.8 - 38.7 ; 18.1 ; 20.1
NEU	Northern Europe	2.57	114.5	3725.0	0 (10) - 10000 ; 46.4 ; 102.7 (103.4)
SAF	Southern Africa	6.36	139.0	611.5	0 (2) - 100 ; 16.4 ; 31.4
SAH	Sahara	9.29	57.3	444.0	0 (2) - 101.9 ; 2 (6.5) ; 6.4 (8.2)
SAS	South Asia	5.08	1356.6	3802.5	0 (2) - 100 ; 100 ; 64.7
SAU	South Australia / New Zealand	2.61	20.0	623.5	100 ; 100 ; 100
SEA	Southeast Asia	5.99	510.6	3207.0	0 (2) - 163.7 ; 21.5 (26.5) ; 50.8 (52.9)
SSA	Southeastern South America	4.59	144.5	1503.4	0 (6.5) - 356.9 ; 17.7 ; 18.8
TIB	Tibetan Plateau	4.71	72.3	305.8	0 (2) - 100 ; 20 ; 20.9
WAF	West Africa	7.72	338.3	871.6	0 (2) - 47.1 ; 2.1 ; 5.3
WAS	West Asia	6.26	182.5	3005.9	0 (6.5) - 160.5 ; 17.2 (17.3) ; 27.5 (27.7)
WNA	West North America	5.20	79.1	3212.9	17.6 - 500 ; 500 ; 304.5
WSA	West Coast South America	2.23	49.9	441.6	0 (6.5) - 257.2 ; 17.0 ; 28.2 (29.1)
GLOBE	Globe (excluding Antarctica)	146.21	6450.9	63206.5	0 (2) - 10000 ; 17.1 (45.7) ; 51 (72.4)

* Source: Scussolini et al. [2016] (gridded to a spatial resolution of 0.25° × 0.25°). We note that '0' here means 'no value'; and we assume no flood defenses in such case throughout this manuscript. To understand the significance of excluding '0', we display the results in the bracket '()' if they differ from the former version as reference.

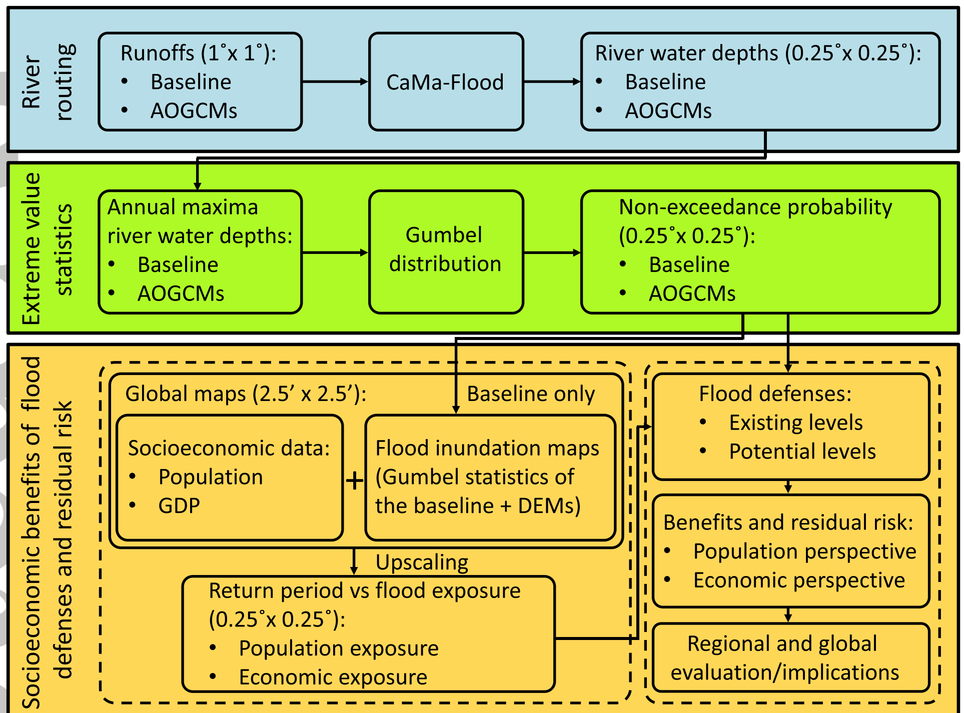


Figure 1. An overview of materials, methods and workflow of this study (details in Section 2).

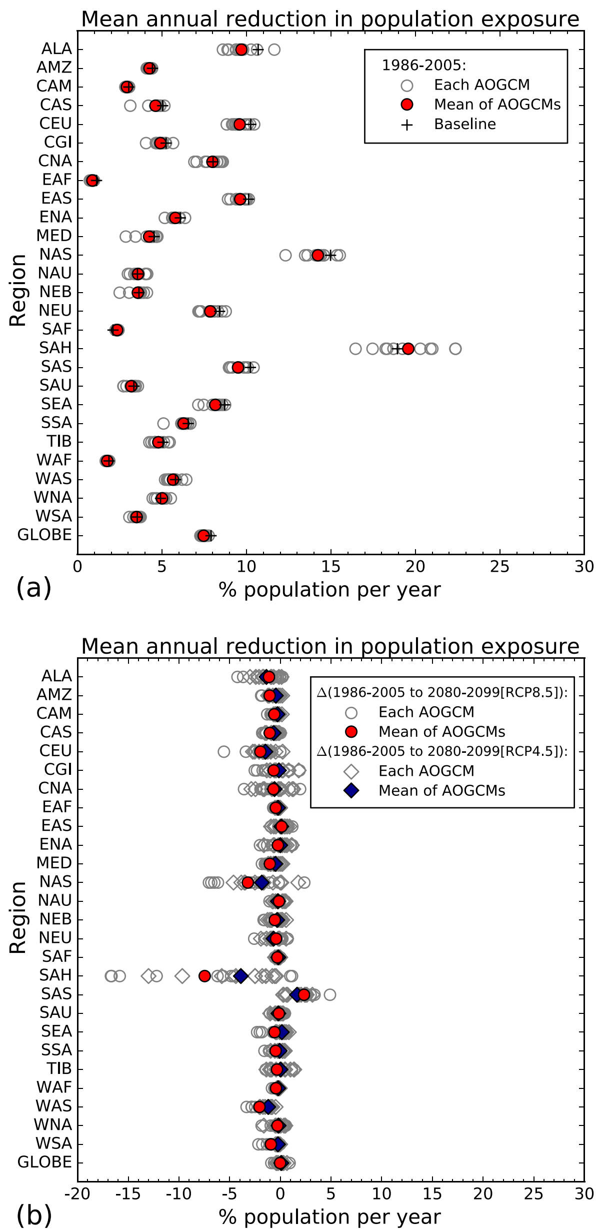
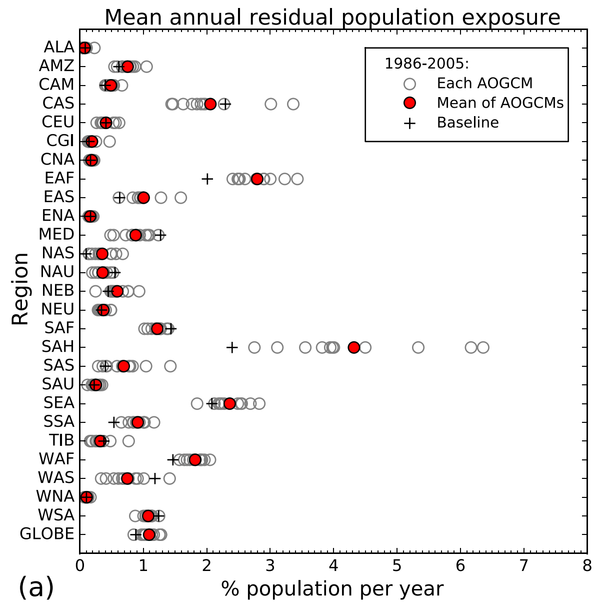


Figure 2. Reduction in population exposure at existing flood defense levels as a percentage of population per year in each region (Table 2) for: (a) 1986-2005 and (b) Δ(1986-2005 to 2080-2099).



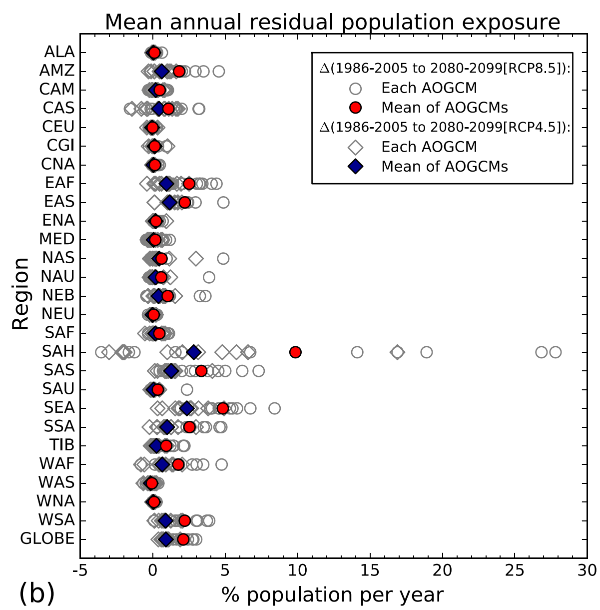


Figure 3. Residual population exposure at existing flood defense levels as a percentage of population per year in each region (Table 2) for: (a) 1986-2005 and (b) Δ(1986-2005 to 2080-2099).

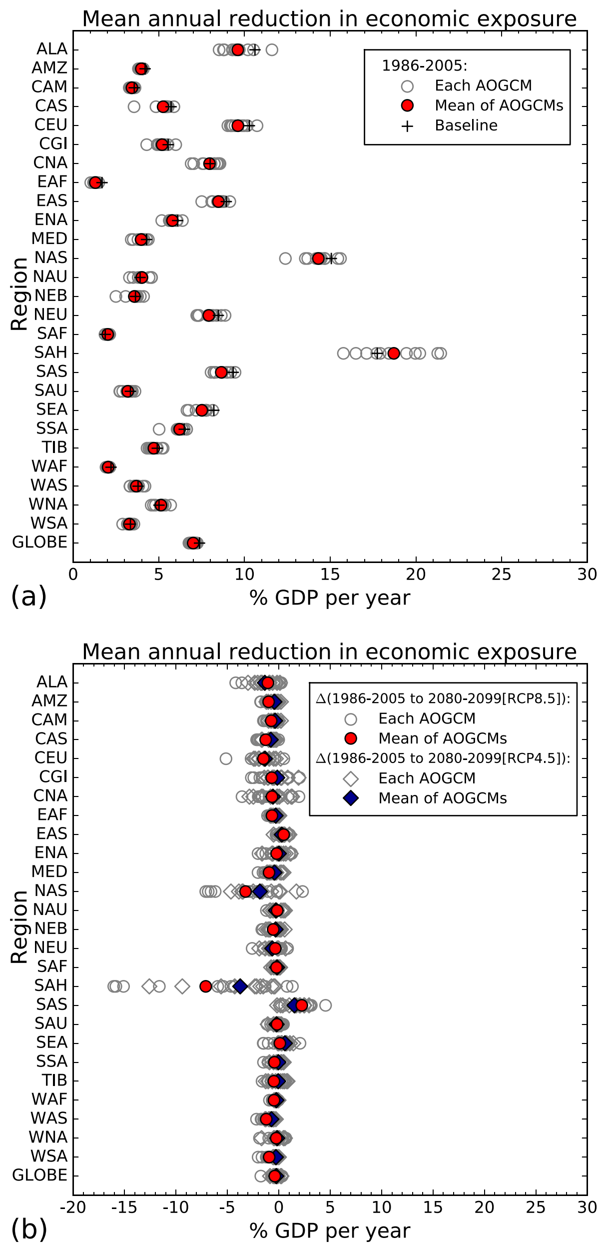


Figure 4. Reduction in economic exposure at existing flood defense levels as a percentage of GDP per year in each region (Table 2) for: (a) 1986-2005 and (b) Δ(1986-2005 to 2080-2099).

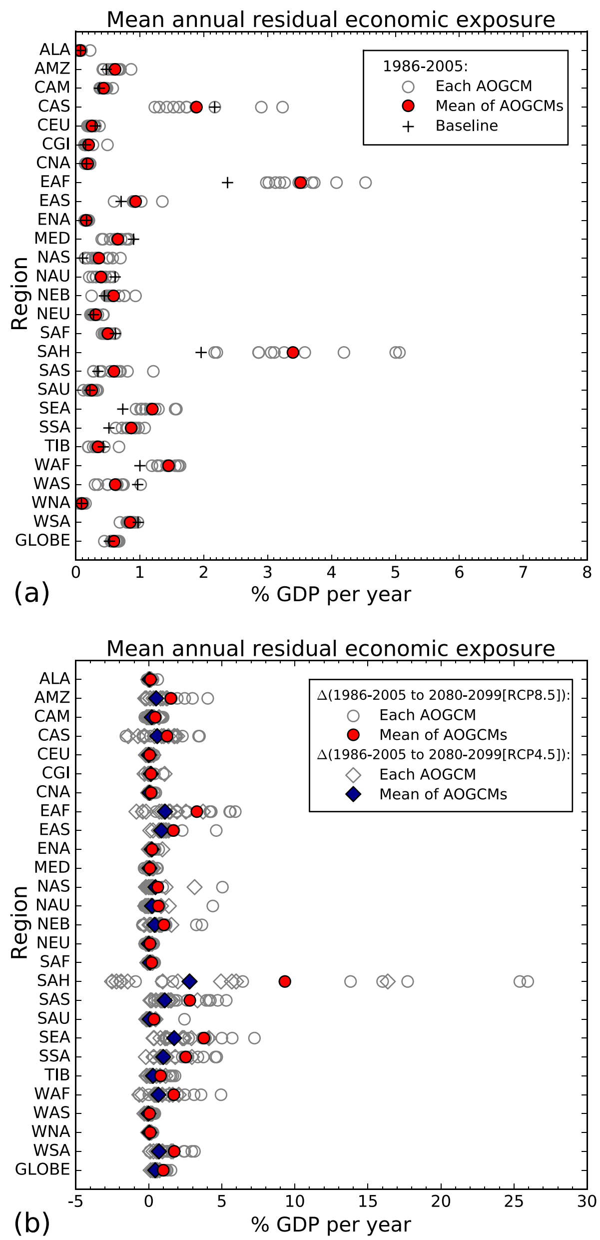


Figure 5. Residual economic exposure at existing flood defense levels as a percentage of GDP per year in each region (Table 2) for: (a) 1986-2005 and (b) Δ(1986-2005 to 2080-2099).

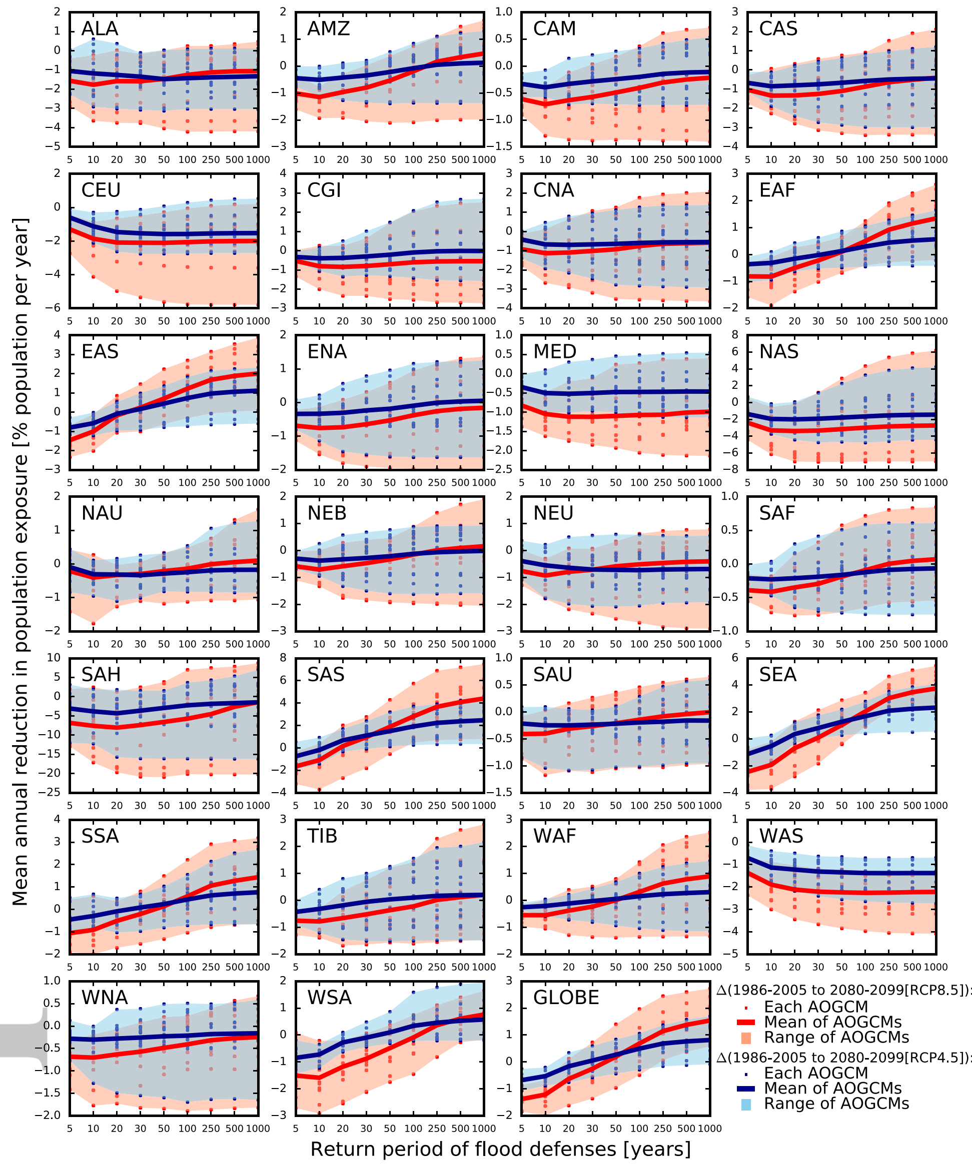


Figure 6. Reduction in population exposure versus flood defense level (expressed in return period) as a percentage of population per year in each region (Table 2) for Δ(1986-2005 to 2080-2099).

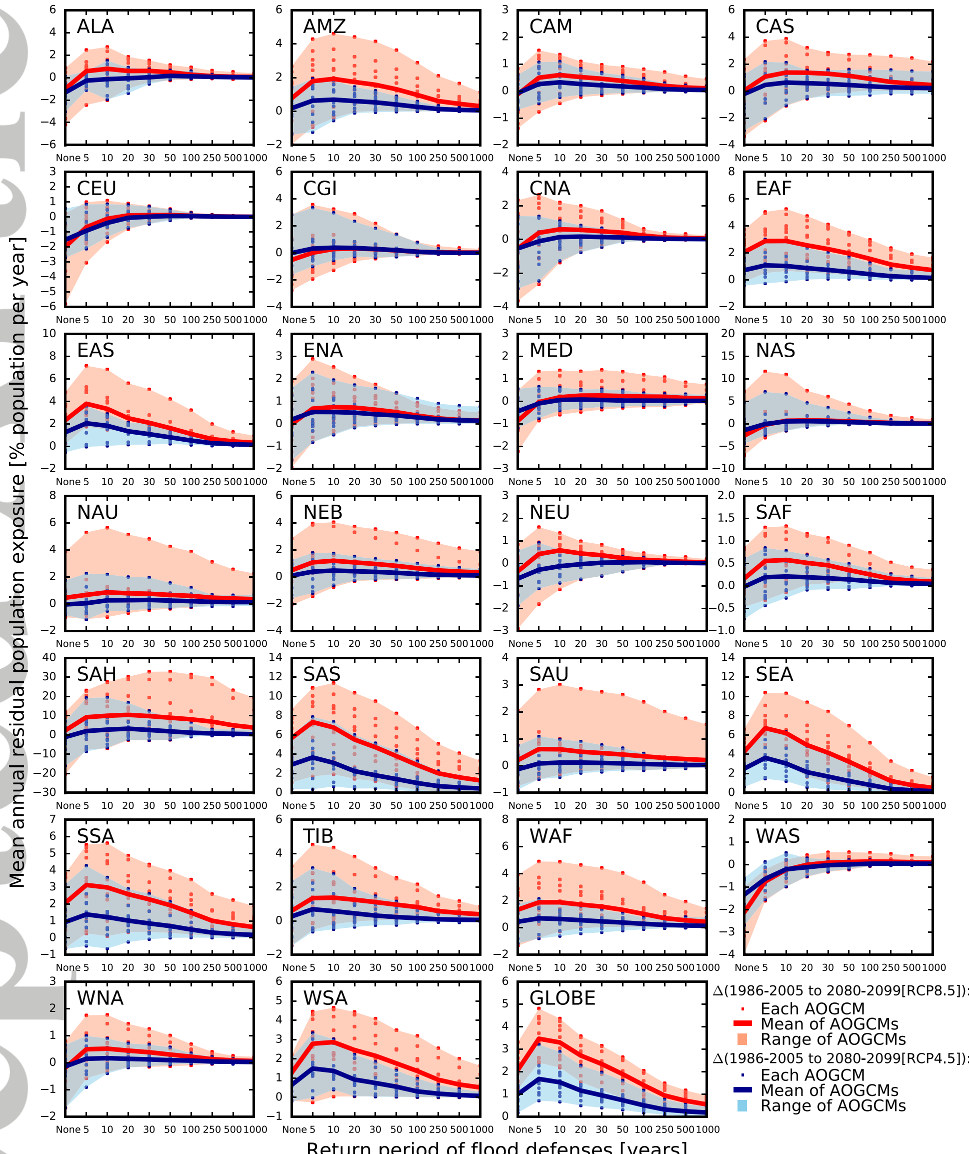


Figure 7. Residual population exposure versus flood defense level (expressed in return period) as a percentage of population per year in each region (Table 2) for Δ(1986-2005 to 2080-2099).

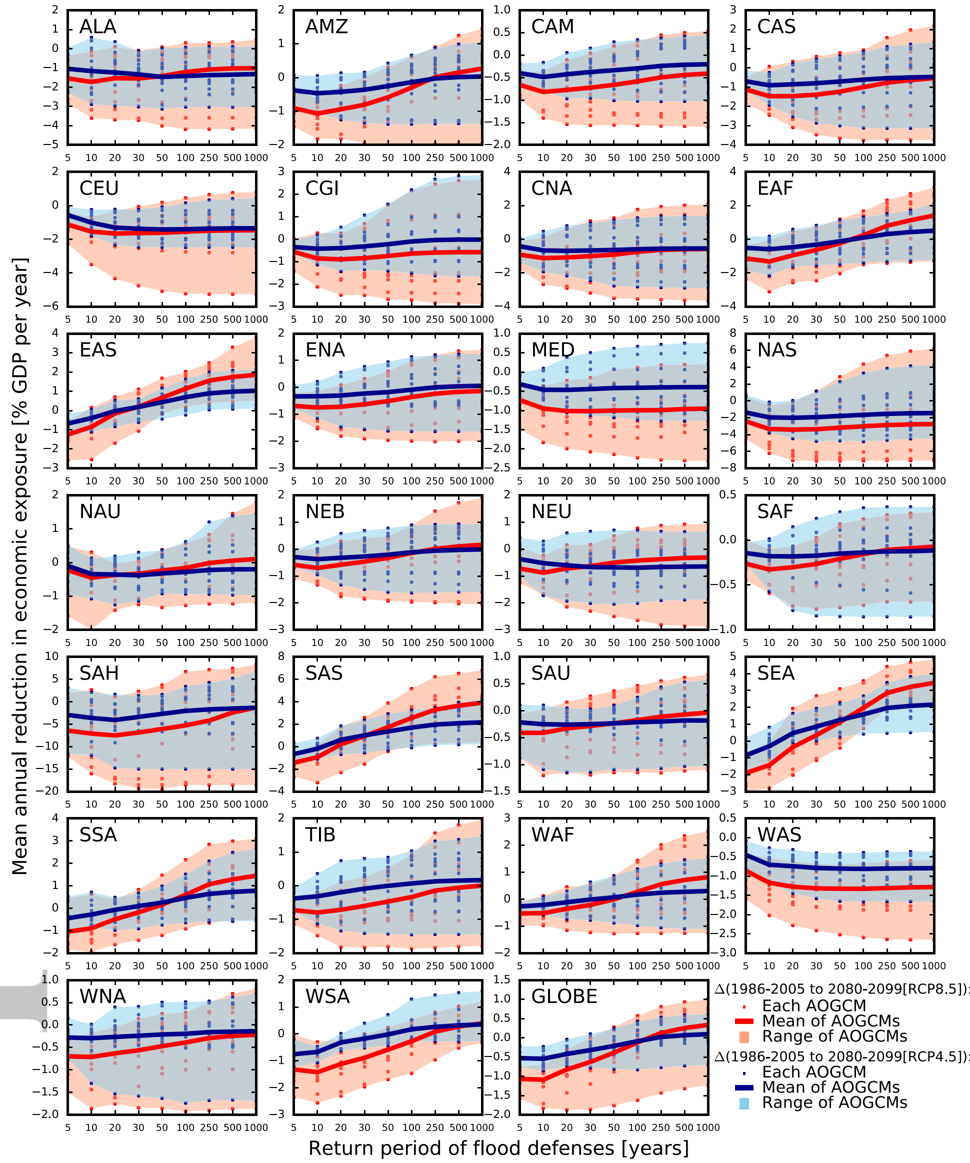


Figure 8. Reduction in economic exposure versus flood defense level (expressed in return period) as a percentage of GDP per year in each region (Table 2) for Δ(1986-2005 to 2080-2099).

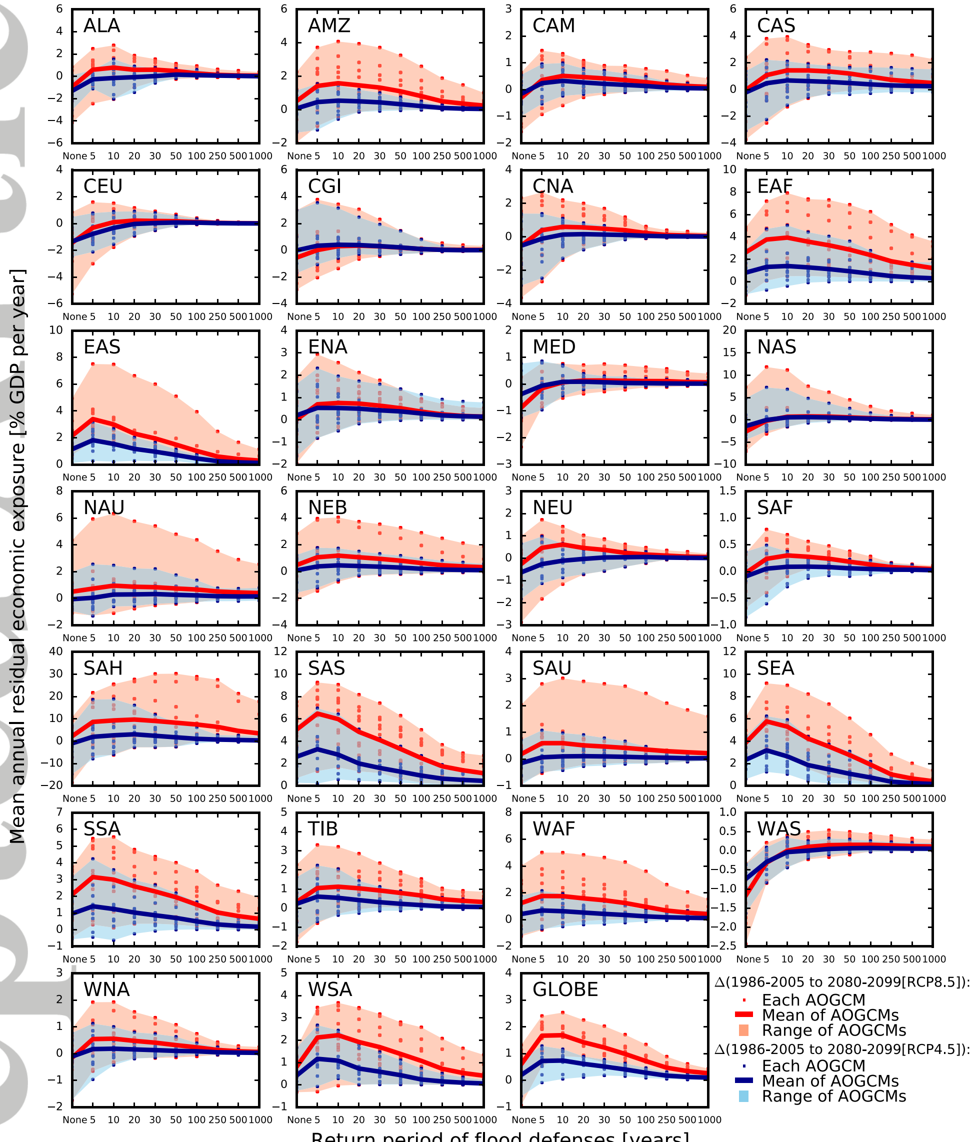


Figure 9. Residual economic exposure versus flood defense level (expressed in return period) as a percentage of GDP per year in each region (Table 2) for Δ(1986-2005 to 2080-2099).