Dynamic Geography of the Population and Economic Response to Sea Level Rise

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Sea-level rise and ensuing permanent coastal inundation will cause spatial shifts in population and economic activity over the next 200 years. Using a highly spatially disaggregated, dynamic model of the world economy that accounts for the dynamics of migration, trade, and innovation, this paper estimates the consequences of probabilistic projections of local sea-level changes under different emissions scenarios. Under an intermediate greenhouse gas concentration trajectory (Representative Concentration Pathway [RCP] 4.5), permanent flooding is projected to reduce global real GDP by an average of 0.22% in present value terms, with welfare declining by as much as 0.76% as people move to places with less attractive amenities. By the year 2200 a projected 0.79% of world population will be displaced (with a 95% credible interval 0.20%-1.51%). Losses in many coastal localities are more than an order of magnitude larger, e.g., 10% of $1^\circ \times 1^\circ$ coastal cells lose more than 8% of real GDP in present discounted value terms.

sea-level rise | climate economics | migration

The world will face major challenges from a historically rapid rise in sea level already occurring and likely to accelerate during this century and beyond. Ocean thermal expansion, mountain glacier melt, and ice-sheet retreat in Greenland and Antarctica contribute about equally to the current rate of rise, ~ 3 mm/yr (1). Under intermediate scenarios of greenhouse gas emissions, the International Panel on Climate Change (IPCC) projects that, by 2100, global mean sea level (GMSL) is likely to rise by 0.3 to 0.6 meters compared to 1986-2005 (2). Recent ice-sheet modeling suggests that substantially larger increases are plausible in high-emissions scenarios (3). Given the concentration of the world's population in coastal areas, these predictions bode ill for many megacities, such as Mumbai, Miami, Amsterdam and Ho Chi Minh City (4). More than 50% of the U.S. population lives in coastal watershed counties, with an additional 1.2 million people moving there annually (5).

Sea-level rise (SLR) will profoundly impact the spatial distribution of population, economic activity, and innovation, thus affecting the future evolution of local and global GDP. Given the scope of the problem, quantitatively assessing the economic and demographic impacts of permanent flooding of coastal areas generated by SLR is both necessary and urgent.* This paper provides a novel evaluation, based on a high-resolution, global spatial dynamic model. By analyzing the entire globe at a spatially disaggregated level over the next 200 years, and by taking into account trade and migration linkages across space, the model is able to make predictions about the economic cost of coastal flooding at the local, city, country and global level. This approach addresses many of the shortcoming in existing assessments.

Existing studies often quantify future flood damages based on current data. For example, ref. 6 uses detailed GIS data on current population and GDP to estimate the impact of future sea-level rises of 1–5 meters. Their analysis ignores that the share of the population residing in low-lying coastal areas, and the share of world GDP produced in those locations, will change over the coming centuries. Additionally, flood damages depend on how the economy responds to SLR. These studies fail to take into account that people will move when their land becomes permanently inundated, and that their migration will affect existing and future clusters of population and economic activity.

Some researchers incorporate the changing future distribution of population and economic activity into their analysis (e.g., 7–9). They do so by using different socio-economic scenarios, such as those of the IPCC's Special Report on Emissions Scenarios (SRES; 10). As an example, one SRES scenario assumes rapid future convergence in GDP per capita and fertility across the different regions of the globe. This alters estimates of future damages, as it takes into account how the world economy might evolve over the next century. However, these scenarios only make projections for large regions. In most cases, they simply assume that all locations in a given region experience identical growth patterns (11). In addition, these studies still do not account for the adjustment of the economy once coastal flooding occurs.

Attempts at exploring the economy's adjustment to the rise in sea level have so far been limited to analyzing SLR impacts on capital accumulation and savings in an otherwise standard aggregate growth model (12, 13). However, such analyses do not incorporate the important links between the spatial distribution of population, economic activity, innovation and growth. For example, if SLR obliges people to leave Miami, it is not only the local capital stock that is lost, but also the local agglomeration economies that come with urban density. Depending on whether the abandonment of Miami leads to the emergence of new clusters or to the spatial dispersion of economic activity, productivity and innovation will be affected one way or the other. To assess the growth effects of coastal flooding, one therefore needs to account for the entire economic geography, as some clusters may disappear while others come into being. In fact, since flooding happens progressively over many years, capital depreciation implies that the loss of physical structures may not be the most important concern. Intuitively, flooding Manhattan is costly because of the technology and agglomeration economies lost. Manhattan's buildings are valuable primarily because of where they are, not because of the cost of rebuilding them.

A final issue relates to the appropriate geographic level of analysis when evaluating the impact of permanent flooding. Damages from a rise in sea level have been assessed at the local level

*Throughout the paper, we use the term flooding to indicate permanent inundation and not episodic, temporary, flooding.

(14, 15), the regional level (16, 17), and the global level (18, 19). Local studies ignore the economic linkages to the rest of the world, such as the possibility of people moving to other areas, while regional or global studies often are not conducted at a spatially disaggregated level and thus ignore that many of the effects of flooding are local in nature.

A high-resolution global dynamic framework is therefore needed to analyze the effects of local flooding on both the places that suffer directly from a rising sea level and the rest of the world economy. In such a model, dynamics are crucial if we want to evaluate how different localities are likely to evolve. Assessing how the economy reacts to flooding also requires realistically modeling the economic links between locations, in particular the trade of goods and the migration of people. We employ the model of ref. 20, which incorporates dynamics and a spatially disaggregated analysis of the entire world economy.

This paper uses the benchmark economic scenario in ref. 20 to evaluate the dynamic economic effects of flooding on the world economy at a $1^\circ \times 1^\circ$ spatial resolution. We assess the spatial economic and demographic impact of probabilistic SLR projections for different greenhouse gas emissions scenarios constructed by ref. 21 for the period 2000 to 2200. Using many realizations of sea-level paths, we analyze which areas become permanently submerged over time and compute economic scenarios in which people cannot live or produce in flooded areas. This exercise yields average predicted costs of flooding in all areas of the world over time, as well as confidence bands for these costs, that depend on the severity of the realized flooding paths. We measure these costs in terms of an individual's real income and in terms of his welfare; the latter measure also takes into account locational amenities and an individual's idiosyncratic preferences for a location.

We take SLR projections to be exogenous to the evolution of the economy and ignore adaptation efforts aimed directly at reducing flooding.[†] However, we do introduce endogenous economic adaptation to flooding through migration and trade. Our assessment quantifies the costs of flooding relative to eliminating flooding completely; these costs can then be combined with cost estimates of flood mitigation and other forms of adaptation to properly evaluate different policy options.

A dynamic spatial model

Consider a gridded world map. Each grid cell is a location with four characteristics — technology, amenities, land and geography — that evolve over time. (Figure S1 presents a flowchart of the model in ref. 20). A location's technology refers to the ability of the local firms to transform labor and land into a variety of consumption goods. At the beginning of each time period t, a location's technology depends on the last period's technology and current investments by firms to improve it, as well as on local agglomeration economies and the diffusion of technology from other locations. The technological improvements that result from this process are the main driver of the economy's evolution over time and space.

A location's amenities are partly exogenous (e.g., a nice beach or a beautiful mountain) and partly endogenous, as they suffer from congestion due to population density. A location's land refers to the share of its area that can be used for productive purposes and is not flooded, and its geography refers to where it is located relative to other markets. A well-connected place, either because of nearby markets or low transport costs, gives local consumers cheaper access to goods and gives local firms easier access to other markets. The geography of a location also affects the cost of moving to other locations.

These four characteristics determine a location's attractiveness as a place to live and produce. For example, a technologically advanced location, with good amenities and lots of land, will tend to attract people and firms. Of course, how easy it is for people to move to such places depends on mobility and migration costs, and how likely it is for firms to set up shop there depends on trade costs and a location's connectivity to other markets. The reshuffling of people and economic activity across space causes further feedback loops to both technology and amenities. Locations that become denser benefit from increased agglomeration economies, as the geographic clustering of economic activity improves productivity. Importantly, greater spatial concentration also expands local market size, particularly in a well-connected location, making it more profitable for local firms to invest in innovation. Both effects feed back into the local technology, and hence further impact where people and firms prefer to locate. The process by which a location with good characteristics attracts residents, thus expanding the local market size and in turn increasing the incentives to innovate and improve the location's future characteristics, is at the core of the evolution of economic activity over time. Increased population density is not all beneficial, though. It leads to greater congestion, implying higher land costs and less attractive amenities. Here as well, this feedback loop further affects where people choose to live and where firms choose to produce.

Starting with the four characteristics of each location at the beginning of period t, these different forces and feedback loops determine the spatial distribution of people and economic activity, as well as each location's technology and amenities, at the end of period t. This then gives rise to each location's technology and amenities at the beginning of period $t + 1$. As for land and geography, any SLR between periods t and $t + 1$ affects the share of land in each grid cell, as well as a location's connectivity to the rest of the world. Once we have the four characteristics of each location at the beginning of period $t + 1$, the economy evolves as described above. Throughout, we maintain total world population fixed over time. The reason is that we interpret the different economic forces in the model as depending on population shares, rather than population levels. Our model is isomorphic to one with population growth where all economic decisions depend on population shares.

An individual's decision on where to locate depends not only on the real income levels in the different localities, but also on the amenities of the different places and on the individual's idiosyncratic preferences. That is, an individual cares about his overall utility, which includes not just his real income, but also the amenities he can enjoy where he resides and his personal idiosyncratic evaluation of the location. Hence, when assessing the impact of flooding, we will focus not just on real income, but also on welfare.

Although agents take into account the future when deciding where to move and how much to invest, in order to make the dynamic spatial model computationally solvable we assume an economic environment where decisions only depend on the economy's current state. In the case of migration, the cost of entering a location is only paid while the individual resides in that location. In the case of innovation, the local market for land is perfectly competitive, and the technology is embedded in a location so that

[†] Impact-specific optimization models have been used to look in greater detail at the tradeoff between adaptation costs and residual damages (19, 22, 23). An alternative approach forgoes optimization, focusing instead on comparing costs under different adaptation scenarios (24–26).

anyone producing there has access to past local innovations. The implication is that future rents from innovation are completely capitalized in land rents. As such, expectations about any future events, whether related to migration, productivity or flooding, will affect the price of land, but not current land rents or agents' decisions.

Materials and Methods explain how this spatial dynamic model is quantified and how it can be combined with sea-level rise projections to assess the economic impact of coastal flooding.

Global effects

Figure 1(a) shows 40 stratified, random paths of GMSL rise over the next 200 years under the moderate-emissions Representative Concentration Pathway (RCP) 4.5. It also depicts the mean, the median and the 20-80% band of the RCP 4.5 probability distribution of ref. 21. The median shows GMSL rise of ~ 1.3 meter between 2000 and 2200, with a 20-80% band going from 0.8 to 2.0 meters. Figure 1(b) displays the percentage of real GDP per capita that is lost due to flooding. The mean loss peaks at 0.37% of real GDP in the year 2069, and then declines, turning to a slight gain of $\sim 0.2\%$ by 2200. This non-monotonicity is due to the dynamics of how the world adjusts to coastal flooding. As people are forced to move out of flooded areas, some economic clusters get destroyed, but others are reinforced and new ones emerge. Over time the greater geographic concentration of people increases the dynamic incentives to innovate, thus compensating the direct negative impact of flooding. Uncertainty in SLR implies uncertainty in its economic effects. Taking a 95% credible interval,[‡] the effect on real GDP/capita ranges from $\sim -0.6\%$ to $\sim +0.5\%$. Figure 1(c) depicts the share of the world population displaced by flooding. The mean share displaced increases monotonically over time, from 0.41% in 2100 to 0.79% in 2200 under RCP 4.5 (Table 1). In the more extreme emissions scenario RCP 8.5, the mean share displaced rises to 1.10% in 2200.

Figure 1(d) displays average welfare losses across individuals in the world over the next 200 years for the different sea-level paths. Losses are increasing over most of the time period, reaching a mean level of $\sim 1.5\%$ in 2200, with a 95% credible interval between -0.1% and 3.1%. The welfare losses are several times larger than the real GDP losses. Coastal flooding makes people move to areas with less attractive amenities, either because they relocate to inland places with worse inherent amenities or because they relocate to more crowded places where amenities suffer from greater congestion. This latter possibility helps explain another difference between the effect on real GDP and the effect on welfare: if relocation enhances the spatial concentration of people, innovation increases, mitigating the real GDP losses, whereas congestion worsens, thus further exacerbating the welfare losses. This explains why in Figure 1(d) we see increasing welfare losses over most of the 200 years, whereas in Figure 1(b) initial real GDP losses are reduced in later years.

In addition to examining the time series of losses, we also compute the expected present discounted value of future losses. All present-value calculations reflect the period 2000 to 2200 for the three different emissions pathways. Using a 4% annual discount rate, Table 2 reports how much higher the present discounted value of real GDP is under no flooding relative to the mean under flooding. (See Supplementary Information for alternative discount rates.) For the moderate-emissions RCP 4.5, the expected present-value loss of world real GDP per capita due to flooding is 0.22% (95% credible interval of 0.12%–0.31%). Across scenarios, the expected present-value losses range from 0.20% (95% credible interval of 0.10%-0.30%) under RCP 2.6 to 0.27% (0.19%–0.37%) under RCP 8.5. Turning to welfare, the present discounted mean loss in the moderate-emissions pathway RCP 4.5 amounts to 0.76% (95% credible interval of 0.42%–1.05%) over the period 2000 to 2200, more than three times the loss in real GDP. Under the more extreme RCP 8.5, mean losses increase to 0.95% (0.65% – 1.27%).

[‡]Given that we use 40 paths, we take the interval between the second largest and the second smallest outcome. We refer to this as a credible interval, since the procedure used to generate the SLR probability distribution in ref. 21 is Bayesian.

Table 1. Share of world population displaced by flooding

Scenario	2050	2100	2200
RCP 8.5	0.31%	0.57%	1.10%
	(0.23–0.42%)	(0.35–0.87%)	(0.59–1.70%)
RCP 4.5	0.27%	0.41%	0.79%
	(0.15–0.35%)	(0.25–0.70%)	(0.20–1.51%)
RCP 2.6	0.27%	0.35%	0.58%
	(0.16–0.35%)	(0.15–0.68%)	(0.12–1.31%)

Primary numbers are mean values; parenthetical numbers are 95% credible intervals. Percentage of population displaced refers to the sum of differences in absolute value of cell population under no flooding scenario and cell population under the mean flooding scenario divided by twice the total population.

Table 2. Present discounted value aggregate world losses in real GDP and welfare.

Scenario	Real GDP PDV	Welfare PDV	Real GDP Maximum	Year
RCP 8.5	0.27%	0.95%	0.47%	2075
	(0.19–0.37%)	(0.65–1.27%)	(0.33–0.64%)	
RCP 4.5	0.22%	0.76%	0.37%	2069
	(0.12–0.31%)	(0.42–1.05%)	(0.25–0.51%)	
RCP 2.6	0.20%	0.71%	0.36%	2058
	(0.10–0.30%)	(0.36–1.02%)	(0.22–0.49%)	

Primary numbers are mean values; parenthetical numbers are 95% credible intervals. Calculations based on 4% annual discount rate. Percentage change in PDV refers to (PDV of nonflooding scenario / mean of PDV of flooding scenarios) -1, using a simulation over 200 years. Maximum refers to maximum effect of flooding for mean, 97.5th percentile and 2.5th percentile paths. Year denotes the year of the maximum effect of flooding for mean path.

To further analyze the impact of flooding, Figure 2(a) plots the relationship between GMSL rise in 2100 and the present discounted value of world real GDP per capita for each of the 40 stratified random paths and three RCPs. The slope is around 0.3: the present-value of real world GDP per capita between 2000 and 2200 drops by about 0.3% per 1 m GMSL rise in 2100. This relation appears to be similar under RCP 2.6, 4.5 and 8.5. Figure 2(b) plots a similar graph for the share of the world population in 2100 that is displaced by flooding. The slope is around 0.6, indicating that a 1 m GMSL rise in 2100 implies a displacement of around 0.6% of the world population in 2100. However, GMSL rise in 2100 is not a full description of the entire dynamics of an SLR path, nor of its local variation. Thus, outcomes with a similar GMSL rise in 2100 can generate different losses. This variation can be quite large: for example, for a GMSL rise of ~ 0.6 meters, Figure 2(a) shows that the cost of inundation measured in terms of the present-value of aggregate real GDP ranges from around 0.1% to 0.3%. This variation highlights the importance of using an economic model that incorporates dynamics and local disaggregation.

Fig. 1. (a) Flooding realizations, (b) World losses in real GDP, (c) Share of world population displaced, and (d) World average welfare losses. All results shown for RCP 4.5.

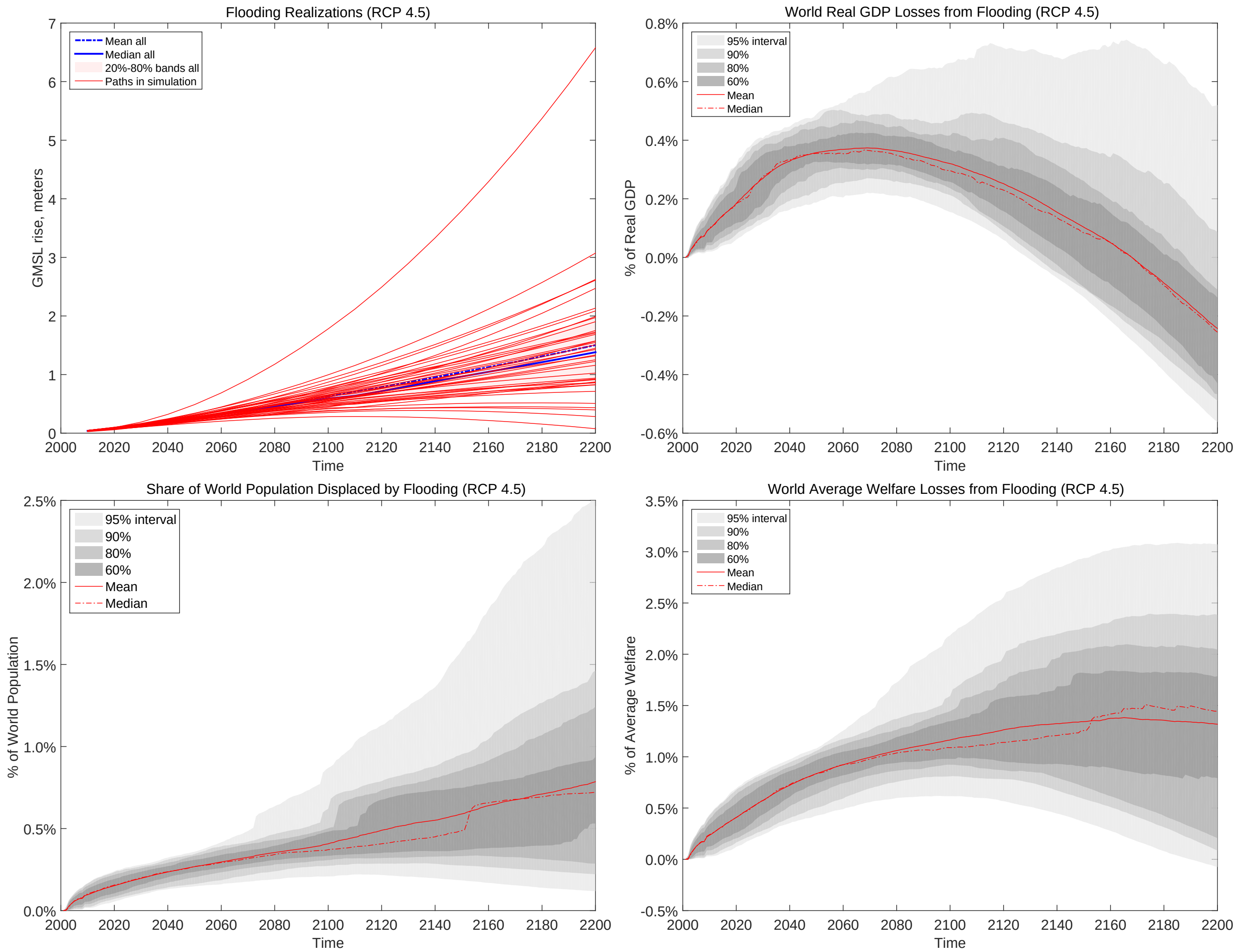
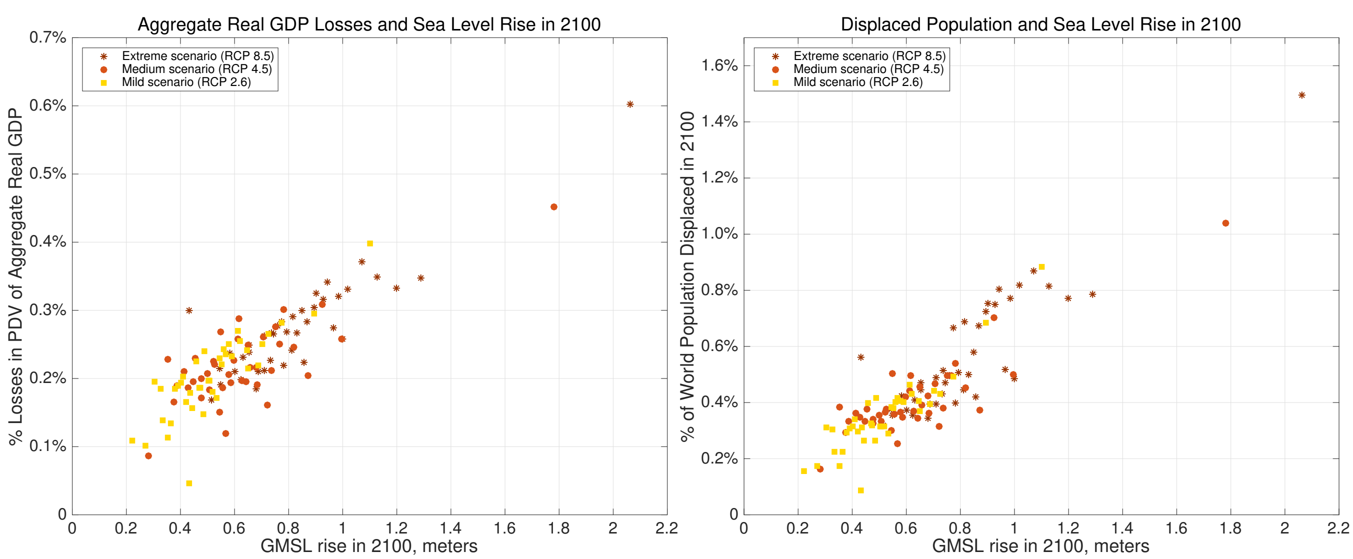


Fig. 2. (a) Present discounted value of world losses in real GDP, and (b) Displaced world population in 2100, both as a function of GMSL rise in 2100.



Local and country effects

The global economic effects of SLR mask extremely heterogeneous local effects. Some regions suffer dramatically from inundation, while others experience economic gains. When presenting real output and welfare outcomes at the local level, we face the decision whether to focus on total local real GDP and welfare, which are directly affected by the number of people in a given region, or on per capita outcomes, which are not. The former is helpful to illustrate that some areas not only experience a decline in the average well-being of their residents, but also become relatively empty by losing population. We start by discussing total outcomes, and then proceed to analyze outcomes in per capita terms.

Figure 3(a) displays a world map of the mean loss in total real GDP across realizations in the year 2200. The effects for 95% of $1^\circ \times 1^\circ$ cells range from losses of 18% to gains of 2%. As expected, coastal areas suffer significant losses across the globe, but the effects are unevenly distributed. The negative effects tend to be larger in Southeast Asia, Northwest Europe and the Atlantic coast of the Americas, while they are more contained in Africa and the Pacific coast of the Americas. Flooding also affects areas that are not directly impacted by the sea-level rise. In particular, in the year 2200, inland regions tend to gain between 1% and 2% of GDP. These results underscore the importance of our spatially disaggregated general equilibrium analysis: focusing only on flooded areas would ignore this redistribution. In present discounted value terms, almost 80% of coastal cells lose, with 10% of them incurring a loss of more than 8%. In contrast, almost all inland cells gain, although none gain more than 1% (Figure 4(a)).

Figure 3(b) depicts for each grid cell the flooding-induced percentage loss in population in the year 2200. The effects for 95% of $1^\circ \times 1^\circ$ cells go from losses of 21% to gains of 1%. Not surprisingly, the areas with the greatest share of displaced population are the same as those that lose most in terms of real GDP. In the year 2200 about 80% of all coastal cells lose population, with 10% of them losing more than 20% of their population (Figure 4(b)).

We further illustrate our findings by looking at the fate of some particular countries. The Supplementary Information presents, as examples, the evolution of real GDP and welfare for China, Germany and the U.S. We also present losses in real GDP, welfare and population for most countries in the world (Table S1). For example, China's loss in real GDP per capita due to permanent inundation peaks in 2062 at 0.19%. For the U.S. the PDV of real GDP losses amount to 0.15% with a population loss that peaks in 2200 at 0.56%. Another interesting case is the Netherlands.[§] It loses heavily from flooding, with total real GDP declining 3.3% and the welfare in the country dropping 5.2%. This is natural: given its low altitude, the Netherlands is flooded disproportionately. The country loses 14.5% of its population in 2200, and as a result economic activity declines.

Coastal flooding is bound to have an important effect on many of the world's largest cities. Table 3 reports the estimated effect of flooding on population and real GDP in a sample of 25 large coastal metropolitan areas in the year 2200. We use the built-up area in 2016 and assign the proportion of the cells covered by this area to the metropolitan area for the entire 200-year period. Compared to a world without flooding, Ho Chin Minh City is predicted to lose 30.5% of its population and 32.8% of its real GDP. Other metropolitan areas that stand to lose an important share of their population are Amsterdam (20.5%), Miami (13.9%) and Bangkok (10.9%). Population losses are significant, although more modest, in New York (1.8%), Shanghai (3.2%), and Sydney (4.0%). The corresponding real GDP losses are commensurate. The uncertainty of the effects is often substantial. Using a 95% credible interval, Miami, for example, is projected to lose between 4.5% and 49.5% of its population.

[§] In our simulations the Netherlands inundates immediately since we do not consider existing dikes or other forms of protection against inundation. As mentioned before, the numbers we find should be compared with cost estimates of mitigation and other forms of adaptation.

Table 3. Population and real GDP loss in a sample of 25 megacities in 2200

Metropolitan Area	Real GDP Loss		Population Loss	
Amsterdam	19.5%	(6.5–27.3%)	20.5%	(7.8–28.1%)
Bangkok	11.1%	(1.2–104.6%)	10.9%	(2.2–88.4%)
Barcelona	0.8%	(-0.9–1.7%)	1.4%	(-0.4–2.2%)
Buenos Aires	-0.4%	(-1.8–1.6%)	0.1%	(-1.1–2.0%)
Ho Chi Minh City	32.8%	(0.4–83.3%)	30.5%	(1.0–76.5%)
Hong Kong	-0.6%	(-1.3—0.1%)	-0.1%	(-0.5–0.3%)
Houston	0.7%	(-0.5–2.2%)	1.2%	(0.0–2.4%)
Karachi	4.3%	(1.4–10.4%)	4.6%	(1.8–10.3%)
Kolkota	0.0%	(-1.2–3.3%)	0.3%	(-0.8–3.0%)
Kuala Lumpur	1.5%	(0.7–2.6%)	1.9%	(1.5–2.5%)
Lagos	-1.6%	(-2.7—0.7%)	-1.0%	(-1.9—0.2%)
Lima	3.0%	(1.0–4.7%)	2.5%	(1.0–3.4%)
Los Angeles	0.3%	(-1.3–1.6%)	0.4%	(-0.6–1.2%)
Manila	1.5%	(-0.2–2.9%)	2.1%	(0.6–3.4%)
Miami	13.8%	(3.8–53.3%)	13.9%	(4.5–49.5%)
Mumbai	2.9%	(-0.1–7.2%)	3.2%	(0.6–7.3%)
New York	1.6%	(-0.7–5.6%)	1.8%	(-0.1–4.9%)
Rio de Janeiro	-0.4%	(-1.3–0.1%)	0.2%	(-0.6–0.6%)
San Francisco	0.9%	(-0.2–2.6%)	1.5%	(0.5–2.7%)
Seoul	3.3%	(2.2–6.1%)	3.7%	(2.9–6.0%)
Shanghai	2.8%	(-1.1–7.7%)	3.2%	(-0.4–7.9%)
Singapore	2.5%	(0.2–5.4%)	3.2%	(1.2–5.7%)
Sydney	3.7%	(-0.5–8.4%)	4.0%	(0.0–7.6%)
Tianjin	-0.7%	(-1.8–0.1%)	-0.2%	(-1.0–0.5%)
Tokyo	0.5%	(-0.5–1.9%)	1.1%	(0.1–2.5%)

Primary numbers are mean values; parenthetical numbers are 95% credible intervals. The geographic extent of metropolitan areas is defined as their built-up areas in 2016 and come from the Atlas of Urban Expansion (http://www.atlasofurbanexpansion.org/). Percentage loss refers to (nonflooding scenario / mean of flooding scenarios) -1.

Conclusion

Permanent coastal inundation is an important consequence of anthropogenic climate change. Evaluating the economic consequences of any climate-related phenomenon raises the challenge of accurately accounting for its variation in space, its dynamic evolution, and the uncertainty inherent in environmental projections. To address this challenge, this paper combines recently developed economic modeling with probabilistic flooding projections, conditional upon emissions pathways. The results indicate that coastal flooding has a large economic impact that is significantly shaped by spatial dynamics. Under RCP 4.5, we estimate that coastal flooding will induce an average decline in real GDP of 0.22% (with 95% credible interval 0.12-0.31%) and an average drop in welfare of 0.76% (with 95% credible interval 0.42 to 1.05%). In some countries, the effects are an order of magnitude bigger, with an estimated decline in real GDP of 5.15% in Belize, 3.22% in Vietnam and 2.30% in Denmark. In terms of population, in the year 2200 flooding is predicted to displace an average of 0.79% of world population (with a credible interval 0.20 to 1.51%). At a national level, population displacement is 7.09% in Belize, 12.25% in Vietnam and 6.62% in Denmark.

Fig. 3. (a) Percentage mean loss in total cell real GDP in 2200 under RCP 4.5. (b) Percentage mean population change by cell in 2200 under RCP 4.5.

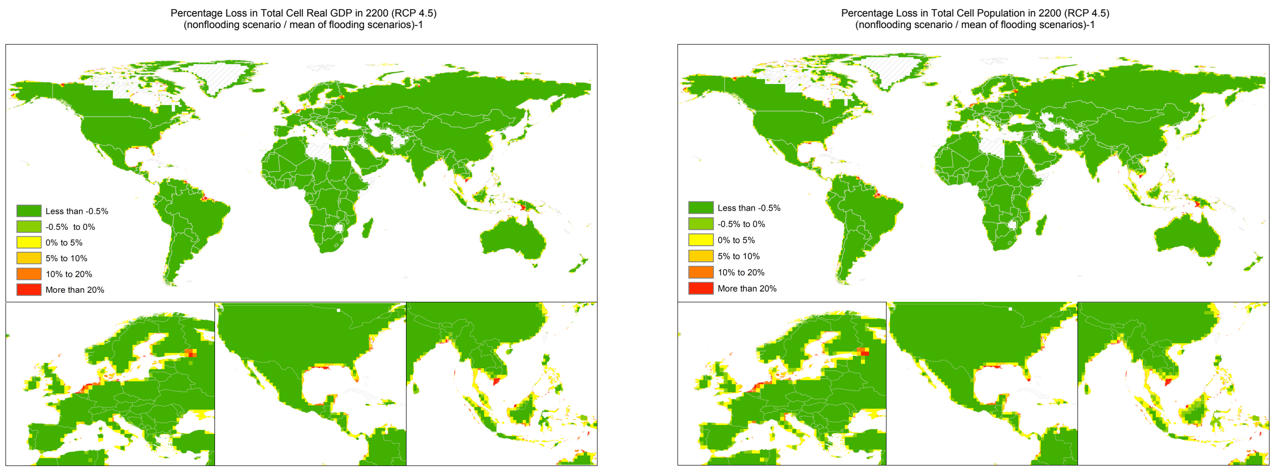
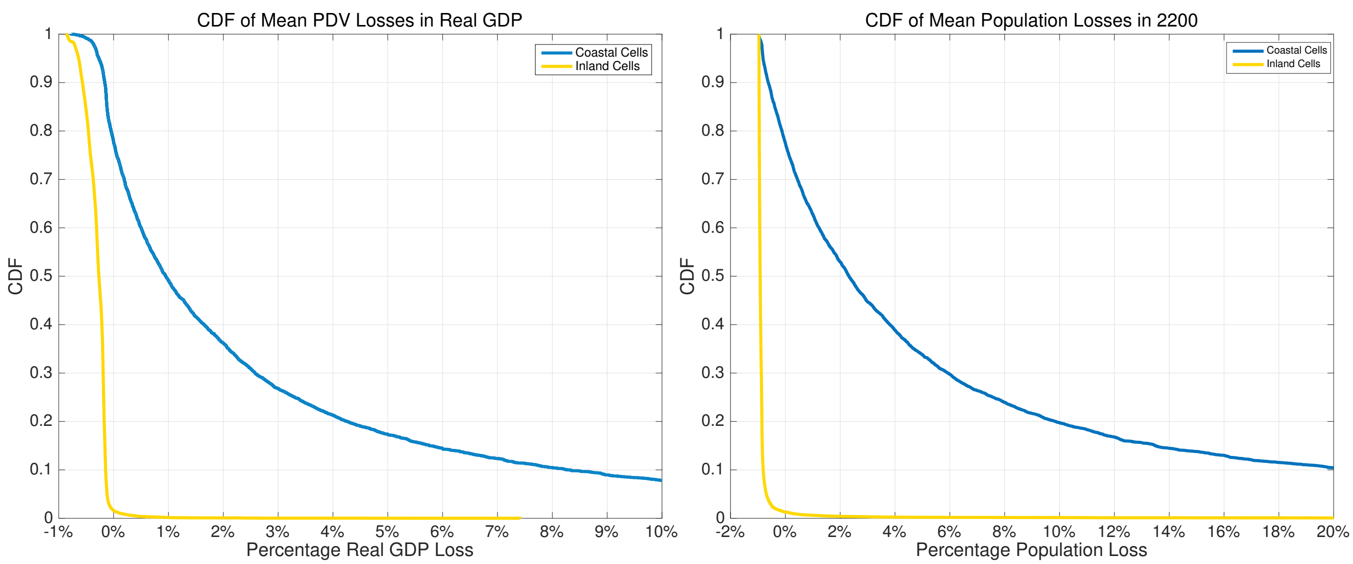


Fig. 4. Cumulative density functions of (a) the PDV of total percentage losses in real GDP, and (b) the population losses for coastal and inland cells in 2200 (RCP 4.5).



Given the complexity of the issue at hand, our model necessarily leaves out some important aspects. First, although we account for the uncertainty in flooding scenarios, and we demonstrate the robustness of our evaluation to a variety of economic parameters, our evaluation does not include potential measurement error in economic variables or model misspecification. Second, we do not account for feedback loops between economic outcomes and flooding through changed emissions pathways. Third, we only analyze the impact of permanent, albeit gradual, inundation and not temporary flooding caused by extreme weather events. Finally, we do not model efforts to mitigate flooding using a variety of methods such as barriers and dikes. Future work should focus on extending this research in these directions, to improve further our estimates of the economic consequences of coastal flooding.

Materials and Methods

Quantification and simulation. We discretize the world into 64,800 $1^\circ \times 1^\circ$ cells. Structural parameter values are partly taken from the literature and partly estimated from data. Throughout, we use the parameters of the baseline simulation in ref. 20. For the year 2000, we use data on the geographic distribution of population and output per worker from G-Econ 4.0 (27) to invert the model and recover local productivity measures. We also need estimates of amenities for all grid cells. In a world with perfect mobility, it is enough to have information on population and productivity to get such estimates: locations with low productivity but large populations must have good amenities. However, when mobility is limited, those same low-productivity, high-density locations might also be low-utility places that are hard to leave. In a world with restricted mobility, we therefore need data on utility, as well as population and productivity, to estimate local amenities. To that end, we use country-level survey data on subjective well-being from the Gallup World Poll (28).[¶] Subjective well-being, measured on a scale

[¶]Because the data are at the country level, there are no utility differences across locations within countries in the initial period. Such utility differences do arise in future periods.

from 0 to 10, where 0 represents the worst possible life and 10 the best possible life, has been shown to be an adequate measure of welfare (29). To simulate the model, we also need information on mobility and transport costs. We use Gabriel Peyre's Fast Marching Toolbox for Matlab (30) to calculate optimal routes between locations given the costs of crossing each grid cell. These costs are determined by a variety of attributes, including whether the cell is covered by water and whether it has a river, a railroad or a highway.[‖]. We estimate the cost of moving in and out of each location so that the model matches the evolution of population between 2000 and 2005 exactly. The intuition is simple: if a location experiences a large relative increase in productivity but its relative population level does not change much, it must have high migratory barriers.

Once we have estimates for all the parameters, the migration and trade costs, and the initial distributions of technology, amenities and land, we can simulate the model forward. Every period we update the spatial distribution of technology given local investments, we account for the amount of land lost to flooding, and then solve for the distribution of population and welfare (see ref. 20 for details) To gauge the performance of the model, that paper runs backcasting exercises and shows that the benchmark calibration has significant predictive power for population levels and changes going back many decades in time.

Flooding scenarios. The flooding scenarios we analyze are based on ref. 21's probabilistic SLR projections of for the global mean and for local relative SLR at 1,091 tide-gauge sites around the world from 2000 to 2200. These projections are conditional upon three alternative pathways of future greenhouse gas concentrations, known as Representative Concentration Pathways (RCPs) 8.5, 4.5, and 2.6 (31). RCP 8.5 is a high-emissions pathway, consistent with fossil-fuel-intensive economic growth, leading to CO_2 concentrations of 540 ppm in 2050, 936 ppm in 2100 and 1830 ppm in 2200 (compared to 278 ppm in 1750 and 400 ppm in 2015). RCP 4.5 is a moderate-emissions pathway, leading to CO_2 concentrations of 487 ppm in 2050, rising to 538 ppm in 2100 and then stabilizing at 543 ppm. RCP 2.6 is a low-emissions pathway, consistent with the aspirational goals laid out in the Paris Agreement, in which atmospheric CO_2 concentrations peak at 443 ppm in 2050 and decline to 421 ppm in 2100 and 384 ppm in 2200.

For each RCP, ref. 21 generate 10,000 Monte Carlo samples for each RCP to calculate a joint probability distribution of global and local relative SLR. For our analysis, we take the 10,000 paths in the year 2100, divide them into 40 equally-sized 2.5 percentile bins based on the GSL, and then take a random path from each one of the 40 bins.

For these 40 random stratified samples from the ref. 21 probability distribution for each RCP, we compute an estimated SLR for all grid cells of the world by taking a distance-weighted average of the 1,091 tide-gauge sites. If d_{ij} denotes the distance of location i to tide-gauge j, we use weights given by $e^{-\delta d_{ij}}$. We set $\delta = 20$ in order to obtain a smooth surface for the sea level, while at the same time ensuring that the local sea level is mainly driven by the closest tide-gauges. To compute how much land gets flooded, for each grid cell we combine the estimated SLR with 6'-resolution land-elevation data from the Global Land One-km Base Elevation (GLOBE) digital elevation model (DEM) (32). Because the DEM resolution is 100x higher than that of our 1° economic data, when estimating the economic impact of flooding, we estimate the share of each grid cell that gets flooded.

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[‖]These data come from http://www.naturalearthdata.com

Supporting Information (SI).

Country Effects. Figure S2, Panels a and b, displays the losses in real GDP per capita and welfare in China. These effects are in per capita terms, and hence measure the impact on an individual resident. The mean loss in real GDP per capita due to flooding peaks at 0.19% in the year 2062, and declines thereafter, with the loss turning to a gain in the first half of the 22nd century. Figure S2, Panels c and d, shows the case of Germany. With a relatively short coastline, the direct effects of flooding are limited. However, as the country receives flooding refugees from other countries, the spatial concentration of economic activity increases, leading to more innovation and higher GDP per capita in the long run. The welfare effects are negative though, because of the crowding out of amenities. Figure S2, Panels e and f, displays the behavior of real GDP per capita and welfare in the U.S. over the next 200 years. Although the country experiences important coastal flooding in Florida and the East Coast, the overall losses are limited. Given the size of the country and the high internal mobility, there is enough scope for adaptation.

Table S1 presents the total real GDP, total welfare, and total population changes that result from flooding, as well as the peak losses in real GDP per capita and total population for all countries in our analysis. In PDV terms, calculated over the period 2000 to 2200, China's total GDP increases by 0.16% because of flooding. This positive effect is due not only to the gains in real GDP per capita after 2120, but also to China's gains in total population relative to other countries. Furthermore, China's fast growth compensates the discount rate when calculating the PDV, hence increasing the weight of the later gains in GDP. In terms of the average resident's welfare, China experiences losses due to flooding over the period 2000 to 2200. However, the total utility of the sum of all Chinese residents remains virtually unchanged, because population in the area increases. In the year 2200, population in China is 0.65% higher, compared to a world without flooding. Hence, even though China loses from flooding in per capita terms, flooding increases the share of the world population that locates in China, thereby increasing the size of its economy and keeping total utility unchanged.

A contrasting and noteworthy case is Congo. There the peak per capita income losses are negligible given that the country is not directly affected by flooding. However, it attracts migration from flooded areas, leading to an increase in population by around 1% in 2200. These gains in population imply that both total output and the total utility generated in the country increase.

Robustness. Model results depend on the parameter values governing the forces of the economic model. These parameters were chosen as in the benchmark scenario in ref. 20. That paper estimates the parameters of the model using a variety of data and finds that the resulting economic model is successful in matching other, non-targeted, empirical moments. Still, there is uncertainty about the true value of these parameters. Hence, we conduct a number of robustness checks, related to the strength of production externalities, the importance of congestion costs, the intensity of technological diffusion across space, and the degree at which the future is discounted. In all of them we keep the same selection of the 40 sea level paths for RCP 4.5. The results, reported in Table S2, demonstrate that our evaluation of the cost of permanent inundation is quite robust to changes in these parameters.

No production externalities. In a first robustness check, we eliminate static production externalities. That is, we no longer assume that local density has a direct positive effect on local productivity. This of course leads to less concentration of economic activity, but how does this affect the economic impact of flooding? A sea-level rise reduces the amount of land available, implying more spatial concentration of economic activity. In a world with production externalities, this greater concentration partly compensates the direct negative impact of flooding on real income. However, if there is no longer a direct productivity benefit from agglomeration, this mitigating effect disappears. As a result, the negative impact of a sea-level rise on the present discounted value of real GDP slightly increases, from 0.22% in the benchmark to 0.23%. The effect on welfare is similar in magnitude: the losses from flooding slightly increase, from 0.76% in the benchmark to 0.77% when there are no production externalities.

Larger congestion costs. In a second robustness check, we increase the congestion parameter by 50%. That is, we increase the elasticity of amenities to population density by one-half, implying that local amenities suffer more from congestion than before. This reduces the incentives for people to geographically concentrate. As in the previous robustness check, the mitigating effect of the increased spatial concentration that comes with a rise in sea level weakens. As a result, the negative effect from flooding on the present discounted value of real GDP per capita slightly increases, from 0.22% in the benchmark to 0.25%. Because the increase in congestion costs has a direct impact on the utility that people derive from amenities, the greater geographic concentration that comes from land loss implies a larger negative welfare effect from flooding: in present discounted value terms, it increases from 0.76% in the benchmark to 0.93% when the congestion parameter is 50% larger.

Stronger spatial diffusion of technology. In a third robustness check, we increase the parameter that determines the strength of spatial technology diffusion by 20%. This has two effects: on the one hand, it gives places better access to best-practice technology, and on the other hand, it reduces the incentive to agglomerate. How does this affect the losses from flooding? The rise in the sea level forces economic activity to move out of some previously highly productive places. However, if other locations have easier access to best-practice technology through spatial diffusion, that loss is less pronounced. As a result, in present discounted value terms, the loss in real GDP drops from 0.22% in the benchmark to 0.20% when spatial diffusion of technology is stronger. The welfare effects of flooding remain unchanged at 0.76%.

Lower discount rate. In a fourth robustness check, we lower the discount rate from 4% to 3%. This is the central discount rate used by the U.S. government when calculating the social cost of carbon. This parameter change increases the relative importance of future years in our present discounted value calculations. Since the losses in real GDP are concentrated in the first century and a half, with some gains in the last half a century, giving more weight to later years slightly lowers the losses, from 0.22% to 0.19%. The opposite happens with welfare, where the losses are increasing over most of the time period. As a result, welfare losses increase from 0.76% to 0.96%.

Ramsey discounting. In a fifth robustness check, we use time-varying Ramsey discounting. The Ramsey equation is often used in cost-benefit analysis, and relates the discount rate to the growth rate of the economy. For example, a future benefit is discounted more in a fast-growing economy than in a slow-growing economy, because of diminishing marginal utility, and a future benefit is discounted less if there is more uncertainty about future growth if agents are risk averse. As a result, in a world where future growth rates may be changing over time, the discount rate will be time-varying. To generate Ramsey discount rates for the next 200 years, we take the predicted growth path of real GDP in the no-flooding scenario, and plug this into equation (30) in ref. 33, together with a coefficient of relative risk aversion of 2 and a rate of pure time preference of zero (so as not to favor any particular generation in the calculation of PDVs). In the baseline quantification, our model predicts that growth rates first increase and then decline slowly to their balanced growth level, so discount rates exhibit a similar pattern. With Ramsey discounting, the predicted loss in real GDP remains unchanged at 0.22%, whereas the welfare loss decreases from 0.76% to 0.55%.

Fig. S1. The model in a flowchart

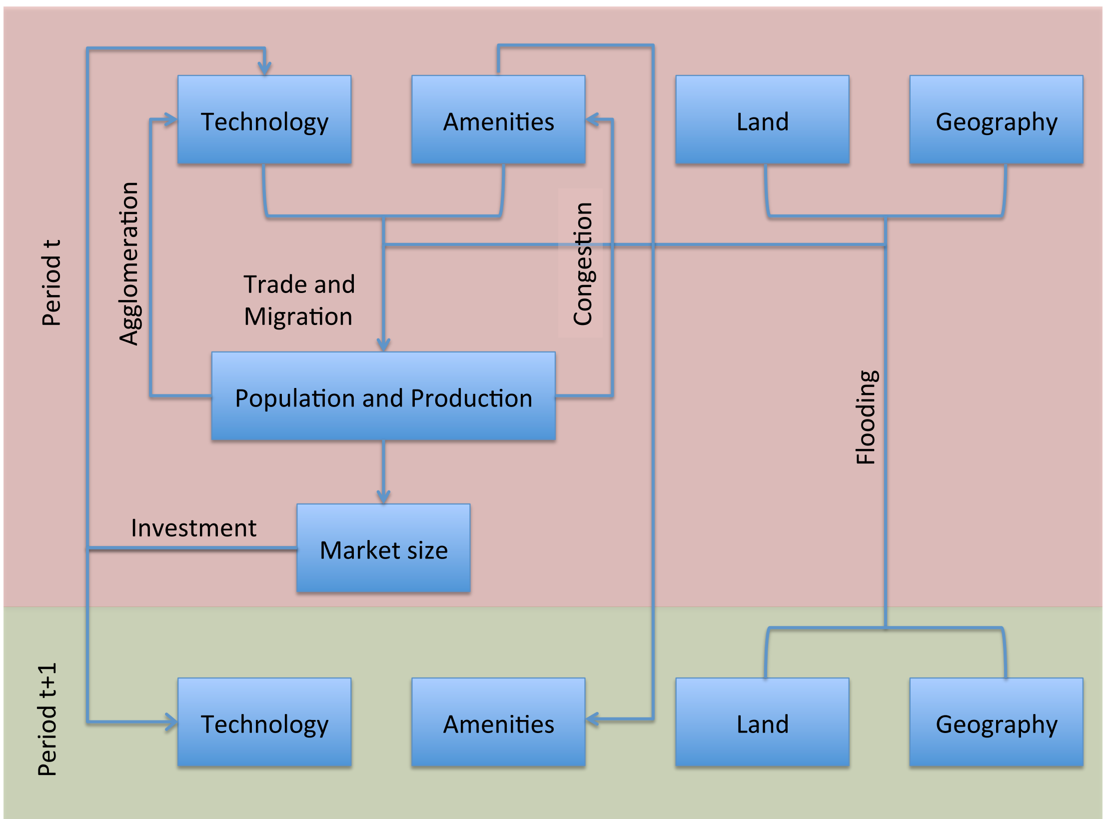

Fig. S2. (a) Real GDP per capita and (b) welfare losses in China, (c) Real GDP per capita losses in Germany, (d) welfare losses in Germany, (e) real GDP per capita losses in the U.S., (f) welfare losses in the U.S.

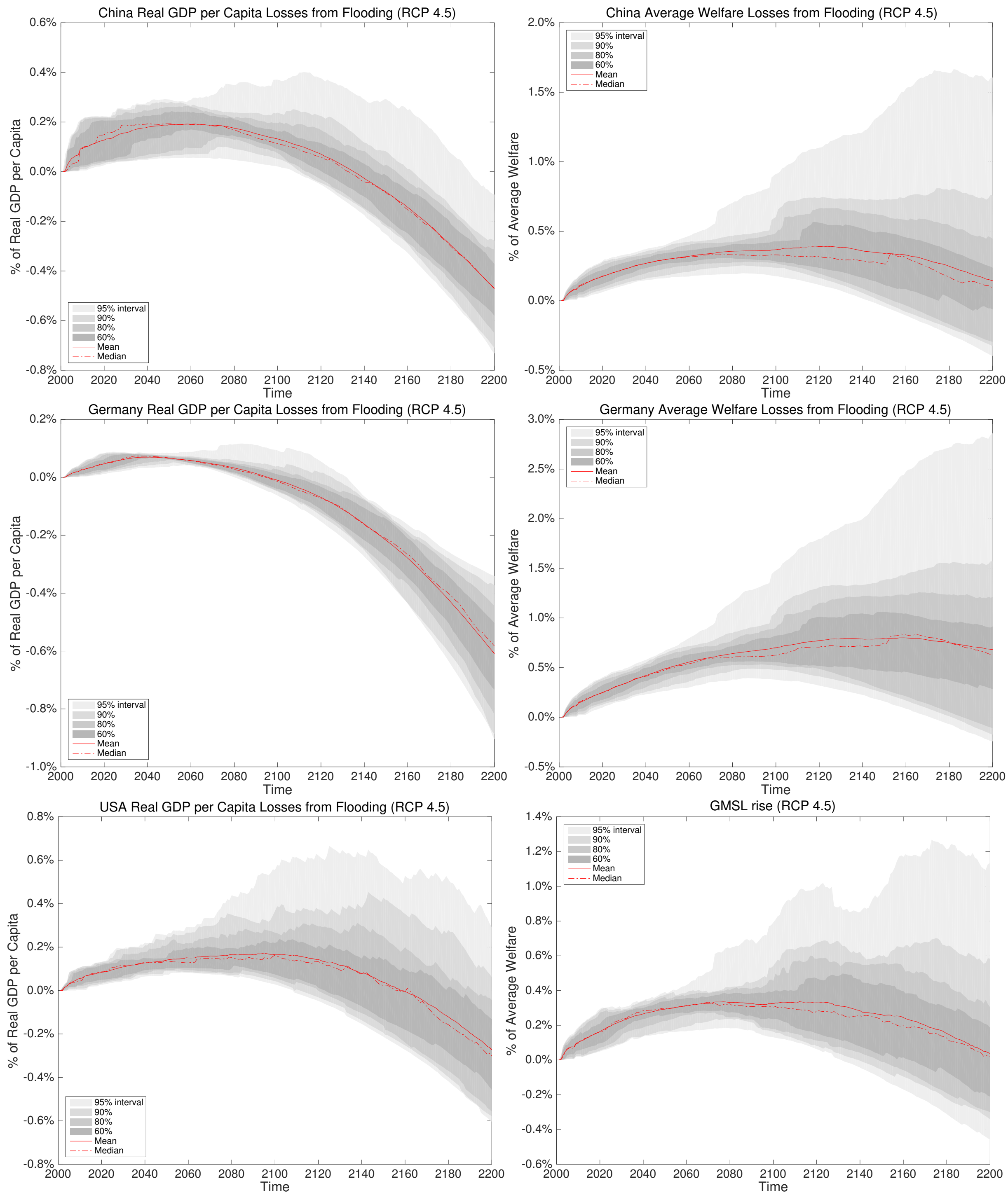

Table S1. Country losses in real GDP, welfare and population

Countries	PDV of Real GDP	PDV of Total Welfare	Peak of diff. in real GDP pc Difference	Year	Population, 200-year avg	Population, 2200	Peak of diff. in population Difference	Year
Albania	0.77%	0.77%	0.31%	2075	0.63%	0.74%	0.84%	2095
Algeria	-0.03%	0.06%	0.11%	2050	-0.13%	-0.45%	0.00%	2009
Angola	0.06%	0.09%	0.17%	2076	-0.05%	-0.28%	0.03%	2100
Anguilla (1)	16.96%	21.65%	29.65%	2186	31.64%	199.04%	203.38%	2186
Argentina	-0.22%	-0.01%	0.05%	2061	-0.34%	-0.66%	0.00%	2001
Armenia	-0.48%	-0.14%	0.04%	2036	-0.50%	-0.96%	0.00%	2001
Australia	1.47%	1.17%	0.88%	2101	1.59%	2.96%	3.05%	2163
Austria	-0.20%	-0.06%	0.04%	2037	-0.33%	-0.94%	0.00%	2001
Azerbaijan	-0.47%	-0.14%	0.04%	2036	-0.50%	-0.96%	0.00%	2001
Bahrain	11.34%	11.71%	2.88%	2134	15.72%	42.02%	42.37%	2197
Bangladesh	0.41%	1.25%	0.10%	2064	0.48%	1.68%	1.68%	2200
Belarus	-0.34%	-0.10%	0.04%	2036	-0.43%	-0.95%	0.00%	2001
Belgium	0.73%	2.06%	0.46%	2123	1.36%	5.49%	5.49%	2200
Belize	5.15%	8.06%	0.78%	2054	5.71%	7.09%	7.93%	2139
Benin	-0.61%	-0.17%	0.04%	2036	-0.55%	-0.96%	0.00%	2001
Bhutan	-0.44%	-0.13%	0.04%	2037	-0.48%	-0.91%	0.00%	2001
Bolivia	-0.39%	-0.11%	0.04%	2036	-0.46%	-0.95%	0.00%	2001
Bosnia & Herzegovina	-0.29%	-0.07%	0.07%	2046	-0.40%	-0.89%	0.00%	2001
Botswana	-0.27%	-0.09%	0.04%	2037	-0.41%	-0.93%	0.00%	2001
Brazil	0.32%	0.62%	0.19%	2053	0.35%	0.77%	0.78%	2197
Brunei	1.92%	7.49%	1.10%	2134	2.50%	6.03%	6.03%	2200
Bulgaria	-0.29%	-0.05%	0.05%	2041	-0.38%	-0.81%	0.00%	2001
Burkina Faso	-0.62%	-0.18%	0.04%	2036	-0.56%	-0.96%	0.00%	2001
Burundi	-0.80%	-0.24%	0.04%	2036	-0.62%	-0.96%	0.00%	2001
Cambodia	0.17%	0.60%	0.14%	2125	0.11%	0.51%	0.51%	2200
Cameroon	-0.50%	-0.15%	0.04%	2036	-0.51%	-0.95%	0.00%	2001
Canada	-0.08%	0.38%	0.03%	2029	-0.15%	-0.51%	0.00%	2001
Cabo Verde	6.47%	7.21%	0.80%	2050	6.57%	6.76%	7.38%	2134
Central African Republic	-0.64%	-0.19%	0.04%	2036	-0.57%	-0.96%	0.00%	2001
Chad	-0.67%	-0.20%	0.04%	2036	-0.58%	-0.96%	0.00%	2001
Chile	0.64%	1.04%	0.43%	2120	0.53%	0.68%	0.84%	2151
China	-0.16%	0.02%	0.19%	2062	-0.32%	-0.65%	0.00%	2001
Colombia	0.04%	0.52%	0.04%	2048	0.02%	-0.23%	0.10%	2062
Comores / Mayotte	1.73%	1.94%	0.39%	2048	1.70%	1.30%	2.15%	2091
Republic of the Congo	-0.43%	-0.12%	0.04%	2037	-0.48%	-0.95%	0.00%	2001
Costa Rica	0.65%	0.94%	0.28%	2048	0.62%	0.90%	0.90%	2200
Cote d'Ivoire	-0.49%	-0.14%	0.04%	2036	-0.49%	-0.90%	0.00%	2001
Croatia	-0.08%	0.42%	0.09%	2045	-0.19%	-0.58%	0.00%	2001
Cyprus	0.09%	0.42%	0.15%	2057	0.13%	0.47%	0.50%	2181
Czech Republic	-0.25%	-0.08%	0.04%	2037	-0.38%	-0.95%	0.00%	2001
DRC	-0.82%	-0.24%	0.04%	2036	-0.63%	-0.95%	0.00%	2001
Denmark	2.30%	2.81%	0.82%	2062	2.93%	6.62%	6.63%	2199
Djibouti	1.33%	1.27%	0.50%	2064	1.14%	1.38%	1.50%	2157
Dominican Republic	0.54%	1.38%	0.15%	2042	0.50%	0.44%	0.68%	2096
Ecuador	0.46%	0.71%	0.31%	2122	0.43%	0.72%	0.85%	2150
Egypt	0.65%	0.80%	0.48%	2147	0.42%	1.16%	1.16%	2200
El Salvador	0.30%	0.53%	0.14%	2029	0.24%	-0.06%	0.37%	2021
Eritrea	0.14%	0.94%	0.16%	2074	0.12%	0.18%	0.23%	2172
Estonia	1.91%	1.51%	0.96%	2101	1.54%	1.99%	2.28%	2131
Ethiopia	-0.71%	-0.20%	0.04%	2036	-0.58%	-0.95%	0.00%	2001
Fiji (2)	3.30%	4.22%	0.52%	2067	3.60%	5.61%	5.61%	2195
Finland	0.83%	1.26%	0.41%	2073	0.75%	0.99%	1.13%	2119
France	-0.03%	0.29%	0.04%	2057	-0.07%	-0.30%	0.00%	2001
Gabon	-0.26%	-0.07%	0.04%	2037	-0.38%	-0.94%	0.00%	2001
The Gambia	0.48%	0.59%	0.18%	2093	0.49%	0.92%	0.92%	2200
Germany	-0.03%	0.35%	0.07%	2041	-0.08%	-0.22%	0.00%	2001
Ghana	-0.62%	-0.18%	0.04%	2036	-0.55%	-0.95%	0.00%	2001
Greece	0.74%	1.08%	0.29%	2006	0.54%	0.61%	0.62%	2184
Greenland	2.15%	2.04%	0.77%	2079	3.12%	7.20%	7.57%	2147
Grenada	7.71%	7.85%	1.17%	2041	8.35%	12.21%	12.55%	2185
Guatemala	0.04%	0.60%	0.14%	2046	-0.09%	-0.46%	0.12%	2018

Table S1. Country losses in real GDP, welfare and population (con't)

Countries	PDV of Real GDP	PDV of Total Welfare	Peak of diff. in real GDP pc Difference	Year	Population, 200-year avg	Population, 2200	Peak of diff. in population Difference	Year
Guadeloupe (3)	-0.08%	0.06%	0.21%	2076	-0.26%	-0.68%	0.00%	2001
Guinea	-0.46%	0.12%	0.06%	2046	-0.44%	-0.73%	0.00%	2001
Guinea-Bissau	4.10%	4.05%	0.67%	2103	3.83%	5.51%	5.52%	2199
Guyana	1.64%	1.27%	0.80%	2158	1.81%	5.00%	5.00%	2200
Haiti	1.18%	3.12%	0.19%	2046	1.18%	1.55%	1.59%	2147
Honduras	0.48%	1.33%	0.18%	2062	0.40%	0.25%	0.54%	2071
Hungary	-0.27%	-0.09%	0.04%	2036	-0.39%	-0.95%	0.00%	2001
Iceland	0.46%	1.05%	0.35%	2080	0.46%	0.61%	0.86%	2111
India	-0.13%	0.22%	0.17%	2080	-0.23%	-0.41%	0.00%	2001
Indonesia / Timor-Leste	1.03%	2.19%	0.21%	2077	1.06%	1.51%	1.51%	2197
Iran	-0.23%	0.01%	0.07%	2016	-0.35%	-0.79%	0.00%	2001
Ireland	0.77%	1.21%	0.33%	2061	0.80%	1.06%	1.29%	2100
Israel	-0.22%	-0.04%	0.04%	2040	-0.32%	-0.67%	0.00%	2001
Italy	0.62%	1.21%	0.18%	2082	0.82%	1.69%	1.69%	2200
Jamaica /Cuba	1.75%	2.06%	0.48%	2082	1.79%	1.95%	2.76%	2088
Japan	0.34%	0.88%	0.18%	2072	0.45%	1.12%	1.12%	2200
Jordan	-0.37%	-0.10%	0.05%	2040	-0.44%	-0.90%	0.00%	2001
Kazakhstan	-0.34%	-0.10%	0.04%	2036	-0.43%	-0.96%	0.00%	2001
Kenya	0.10%	0.54%	0.45%	2048	-0.17%	-0.49%	0.01%	2013
Kuwait	3.87%	3.32%	1.08%	2077	4.53%	10.18%	10.18%	2200
Kyrgzstan	-0.52%	-0.16%	0.04%	2036	-0.52%	-0.96%	0.00%	2001
Laos	-0.46%	-0.12%	0.05%	2046	-0.47%	-0.83%	0.00%	2001
Latvia	0.10%	0.48%	0.26%	2062	-0.10%	-0.39%	0.01%	2048
Lebanon	0.40%	0.69%	0.15%	2040	0.30%	0.09%	0.51%	2053
Lesotho	-0.56%	-0.16%	0.04%	2037	-0.53%	-0.95%	0.00%	2001
Liberia	-0.28%	0.09%	0.13%	2079	-0.24%	-0.47%	0.00%	2001
Lithuania	-0.21%	-0.02%	0.06%	2047	-0.31%	-0.74%	0.00%	2001
Macedonia	-0.26%	-0.07%	0.06%	2044	-0.39%	-0.90%	0.00%	2001
Madagascar	-0.12%	0.45%	0.12%	2052	-0.12%	-0.29%	0.06%	2006
Malawi	-0.66%	-0.19%	0.04%	2036	-0.57%	-0.95%	0.00%	2001
Malaysia	1.92%	2.57%	0.52%	2078	2.13%	3.75%	3.75%	2199
Mali	-0.62%	-0.18%	0.04%	2036	-0.55%	-0.96%	0.00%	2001
Malta	0.09%	0.52%	0.35%	2126	0.57%	3.63%	4.03%	2157
Mauritania	0.05%	0.07%	0.33%	2104	-0.22%	-0.42%	0.00%	2001
Reunion / Mauritius	0.34%	1.31%	0.21%	2095	0.59%	0.94%	1.71%	2105
Mexico	0.03%	0.56%	0.03%	2051	0.05%	0.06%	0.11%	2140
Moldova	-0.53%	-0.15%	0.04%	2037	-0.52%	-0.94%	0.00%	2001
Mongolia	-0.45%	-0.13%	0.04%	2036	-0.49%	-0.94%	0.00%	2001
Morocco	0.38%	0.48%	0.23%	2071	0.21%	-0.03%	0.36%	2027
Mozambique	0.42%	0.77%	0.20%	2072	0.37%	0.33%	0.48%	2111
Myanmar	0.27%	0.46%	0.23%	2086	0.16%	0.20%	0.23%	2140
Namibia	-0.28%	-0.02%	0.09%	2059	-0.40%	-0.86%	0.00%	2001
Nepal	-0.63%	-0.18%	0.04%	2036	-0.56%	-0.95%	0.00%	2001
Netherlands	3.30%	5.24%	1.15%	2108	5.12%	14.53%	14.53%	2200
New Zealand	0.60%	1.17%	0.22%	2059	0.63%	0.79%	0.97%	2101
Nicaragua	0.65%	0.85%	0.34%	2066	0.47%	0.28%	0.66%	2066
Niger	-0.69%	-0.19%	0.04%	2036	-0.58%	-0.96%	0.00%	2001
Nigeria	-0.57%	-0.17%	0.04%	2036	-0.54%	-0.96%	0.00%	2001
Norway	0.83%	0.94%	0.47%	2060	0.70%	0.74%	1.07%	2080
Oman	0.45%	0.69%	0.23%	2043	0.50%	0.78%	0.97%	2138
Pakistan	-0.20%	0.06%	0.17%	2058	-0.28%	-0.56%	0.00%	2001
Panama	0.81%	1.44%	0.18%	2048	0.90%	1.16%	1.30%	2116
Papua-New Guinea	1.38%	3.16%	0.35%	2111	1.30%	1.69%	1.71%	2172
Paraguay	-0.39%	-0.12%	0.04%	2036	-0.46%	-0.96%	0.00%	2001
Peru	2.41%	0.96%	2.32%	2128	1.19%	1.18%	1.52%	2128
Philippines	2.38%	3.68%	0.36%	2029	2.50%	3.36%	3.37%	2198
Poland	-0.16%	0.13%	0.06%	2044	-0.26%	-0.65%	0.00%	2001
Portugal	0.40%	0.64%	0.39%	2043	0.30%	0.22%	0.56%	2048
Puerto Rico	44.95%	51.15%	6.40%	2050	77.12%	296.03%	319.57%	2181
Romania	-0.31%	-0.05%	0.04%	2036	-0.41%	-0.87%	0.00%	2001
Russia (4)	-0.27%	-0.02%	0.04%	2040	-0.38%	-0.84%	0.00%	2001

Table S1. Country losses in real GDP, welfare and population (con't)

Countries	PDV of Real GDP	PDV of Total Welfare	Peak of diff. in real GDP pc Difference	Year	Population, 200-year avg	Population, 2200	Peak of diff. in population Difference	Year
Rwanda	-0.71%	-0.21%	0.04%	2036	-0.59%	-0.96%	0.00%	2001
Saudi Arabia	-0.05%	0.14%	0.17%	2071	-0.16%	-0.42%	0.00%	2001
Senegal	2.22%	0.89%	1.43%	2153	1.66%	3.30%	3.33%	2197
Serbia	-0.30%	-0.08%	0.05%	2039	-0.41%	-0.93%	0.00%	2001
Seychelles	4.80%	5.45%	1.14%	2069	5.78%	8.47%	9.69%	2083
Sierra Leone	0.56%	0.71%	0.35%	2110	0.38%	0.38%	0.52%	2110
Singapore	1.62%	2.13%	0.52%	2044	2.04%	3.24%	3.33%	2101
Slovakia	-0.26%	-0.08%	0.04%	2036	-0.39%	-0.95%	0.00%	2001
Slovenia	-0.21%	-0.05%	0.05%	2046	-0.34%	-0.91%	0.00%	2001
Solomon Islands	4.30%	6.48%	0.52%	2057	4.34%	5.17%	5.20%	2163
South Africa	-0.24%	0.01%	0.05%	2049	-0.35%	-0.75%	0.00%	2001
South Korea	1.08%	1.31%	0.40%	2096	1.20%	2.09%	2.11%	2139
Spain	0.14%	0.42%	0.21%	2056	0.09%	0.19%	0.20%	2141
Sri Lanka	0.55%	1.06%	0.38%	2101	0.49%	0.85%	0.89%	2166
Sudan	-0.52%	-0.15%	0.05%	2050	-0.53%	-0.93%	0.00%	2001
Suriname	0.80%	0.93%	0.21%	2063	1.11%	3.12%	3.12%	2200
Swaziland	-0.36%	-0.10%	0.04%	2043	-0.43%	-0.88%	0.00%	2001
Sweden	1.05%	1.31%	0.52%	2109	1.03%	1.99%	1.99%	2199
Switzerland	-0.20%	-0.06%	0.04%	2037	-0.33%	-0.94%	0.00%	2001
Syria	-0.32%	-0.07%	0.06%	2040	-0.41%	-0.82%	0.00%	2001
Tanzania	3.32%	1.00%	2.50%	2127	1.49%	1.66%	1.93%	2139
Thailand	0.95%	0.59%	1.11%	2110	0.27%	0.24%	0.35%	2110
Togo	-0.66%	-0.19%	0.04%	2036	-0.57%	-0.96%	0.00%	2001
Trinidad & Tobago	1.75%	2.39%	0.52%	2071	2.30%	3.89%	4.31%	2137
Tunisia	0.54%	1.00%	0.26%	2075	0.45%	0.76%	0.76%	2200
Turkey	0.21%	0.18%	0.36%	2066	-0.07%	-0.50%	0.06%	2016
Uganda	-0.66%	-0.19%	0.04%	2036	-0.57%	-0.96%	0.00%	2001
Ukraine	-0.25%	0.11%	0.05%	2040	-0.28%	-0.59%	0.00%	2001
UAE	0.11%	0.86%	0.21%	2064	0.14%	0.78%	0.78%	2200
UK	0.34%	1.17%	0.05%	2040	0.48%	0.97%	0.98%	2184
USA	0.15%	0.33%	0.17%	2095	0.14%	0.56%	0.56%	2200
Uruguay	0.51%	0.36%	0.24%	2050	0.36%	-0.03%	0.59%	2050
Uzbekistan	-0.54%	-0.16%	0.03%	2036	-0.52%	-0.96%	0.00%	2001
Vanuatu	3.12%	3.34%	0.55%	2086	3.29%	4.23%	4.68%	2161
Venezuela	0.62%	0.89%	0.30%	2044	0.53%	0.86%	0.86%	2200
Vietnam	3.22%	3.06%	0.76%	2159	3.94%	12.25%	12.25%	2200
Yemen	-0.22%	0.16%	0.07%	2071	-0.25%	-0.30%	0.00%	2001
Zambia	-0.59%	-0.18%	0.04%	2036	-0.55%	-0.95%	0.00%	2001

Calculated using a simulation over 200 years and an annual discount rate of 4%. Since losses are presented as the percentage increase of the non-flooding scenario relative to the mean flooding scenarios, in some cases losses can exceed 100%. (1) Anguilla, Antigua & Barbuda. (2) Fiji, Wallis & Futuna, Tuvalu. (3) Guadeloupe, Montserrat, St Vincent and the Grenadines, St Lucia, Barbados, St Kitts & Nevis, (4) Russia, Svalbard (NO), Jan Mayen (NO).

Table S2. Present discounted value aggregate world losses in real GDP and welfare: Robustness tests

Test	Real GDP PDV	Welfare PDV
1. Medium Benchmark (RCP 4.5)	0.22%	0.76%
	(0.12–0.31%)	(0.42–1.05%)
2. No production externalities	0.23%	0.77%
	(0.13–0.32%)	(0.43–1.07%)
3. 50% increase in congestion parameter	0.25%	0.93%
	(0.14–0.35%)	(0.52–1.28%)
4. 20% increase in spatial diffusion parameter	0.20%	0.76%
	(0.11-0.29%)	(0.42–1.05%)
5. Lower discount factor of 3%	0.19%	0.96%
	(0.09–0.31%)	(0.58–1.39%)
6. Ramsey discounting with coefficient of relative risk aversion of 2	0.22%	0.55%
	(0.11-0.31%)	(0.26–0.74%)

Primary numbers are mean values; parenthetical numbers are 95% credible intervals. Calculations based on 4% annual discount rate, except in exercise 5 (discount rate 3%) and exercise 6 (Ramsey discounting based on equation (30) in ref. 33, using the path of predicted growth in real GDP under no-flooding and a coefficient of relative risk aversion of 2). Percentage change in PDV refers to (PDV of nonflooding scenario / mean of PDV of flooding scenarios) -1 using a simulation over 200 years.