

Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C

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Abstract

We estimate a median global sea level rise up to 52 cm [25-87 cm, 5th – 95th percentile] and up to 63 cm [27-112 cm, 5th – 95th percentile] for a temperature rise of 1.5 °C and 2.0 °C by 2100 respectively. We also estimate global annual flood costs under these scenarios and find the difference of 11 cm global sea level rise in 2100 could result in additional losses of US\$ 1.4 trillion per year (0.25% of global GDP) if no additional adaptation is assumed from the modelled adaptation in the base year. If warming is not kept to 2 °C, but follows a high emissions scenario (Representative Concentration Pathway 8.5), global annual flood costs without additional adaptation could increase to US\$ 14 trillion per year and US\$ 27 trillion per year for global sea level rise of 86 cm (median) and 180 cm (95th percentile), reaching 2.8% of global GDP in 2100. Upper middle income countries are projected to experience the largest

increase in annual flood costs (up to 8% GDP) with a large proportion attributed to China. High income countries have lower projected flood costs, in part due to their high present-day protection standards. Adaptation could potentially reduce sea level induced flood costs by a factor of 10. Failing to achieve the global mean temperature targets of 1.5 °C or 2 °C will lead to greater damage and higher levels of coastal flood risk worldwide.

1. Introduction

Holding the increase in the global average temperature to below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C, has been agreed by the representatives of the 196 parties of the United Nations as an appropriate threshold beyond which climate change risks become unacceptably high (UNFCCC, 2015). At present more than 600 million people live less than 10 meters above sea level (McGraham et al., 2007). Sea level rise will be one of the more damaging aspects of a warming climate for those living in low-elevation coastal areas with strong socio-economic implications (IPCC, 2013). In a warming climate, global sea level will rise primarily from the melting of land-based glaciers and ice sheets and from the thermal expansion of ocean waters (Church et al., 2013). Currently, sea level projections have been made for emissions scenarios (e.g. IPCC, 2013; Kopp et al., 2014; Jackson and Jevrejeva, 2016; Slangen et al., 2017), temperature scenarios (e.g. Mengel et al., 2018) and socio-economic scenarios (e.g. Nauels et al., 2017). However, the conventional process-based method (e.g. IPCC, 2013) used to project sea level is not designed to address specific temperature targets (e.g. 1.5 °C and 2 °C, SED 2015) and there are no Representative Concentration Pathway (RCP) scenarios that specifically address limiting warming below the 2°C and 1.5 °C targets during the entire twenty-first century and beyond. Previously, specific temperature scenarios, that hold warming below 1.5 °C and 2 °C, were created and used to make global sea level rise projections by 2300 using a semi-empirical model (Schaeffer et al.,

2012), while a suite of temperature scenarios with warming below 2 °C generated by the reduced-complexity climate and carbon model, MAGICC, were used to make global sea level projections with a component-based semi-empirical model (Mengel et al., 2018). Both studies focused on global sea level projections only. While idealised temperature and emission scenarios aimed at addressing 1.5 °C and 2 °C target exist and have been used to project global sea level using semi-empirical and reduced complexity climate models (Schaeffer et al., 2012, Nauels et al., 2017, Mengel et al., 2018), they are yet to be implemented in General Circulation and Earth System models. This prevents us from making regionalised, process-based sea level projections in the conventional manner used in IPCC AR5 (Church et al., 2013). The near-total absence of General Circulation and Earth System model simulations for sea level components for these low level warming scenarios limits our understanding of future sea level change.

The aim of this paper is to develop global and regional sea level rise projections with restricted warming of 1.5 °C and 2 °C and compare them to sea level projections with unmitigated warming following emissions scenario RCP8.5 (Moss et al., 2010). We then assess the economic impact of sea level rise in coastal areas from a global perspective, by World Bank income group (high, upper middle, lower middle and low income countries) and some individual countries using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework.

2. Approach

2.1 Sea level rise scenarios

The RCP scenarios were not designed to keep temperature below 1.5 °C, 2 °C (SED, 2015) or other prescribed thresholds. However, of the models available from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012) there are temperature pathways

close to 1.5 °C and 2 °C. The 5-95% range of CMIP5 models for RCP2.6 and RCP4.5 are 0.91 to 2.31 °C and 1.62 to 3.21 °C relative to pre-industrial levels respectively (IPCC, 2013). We follow the approach of Jackson et al., (2018) and identify models from both RCP2.6 and RCP4.5 whose temperature pathway lies within ± 0.21 and ± 0.28 °C of 1.5 °C and 2 °C respectively over the period 2080-2100 (Figure 1 and Table S1).

Using these 1.5 °C and 2 °C subsets of the CMIP5 models we calculate the contribution to global sea level for the following sea level components (Table S1, Figure 1): ocean steric expansion (*T*), and melting of glaciers (*GIC*). We then calculate an ensemble mean and uncertainties for each of these components for 1.5 °C and 2 °C temperature scenarios (Jackson and Jevrejeva, 2016). In contrast with the approach of Jackson et al., (2018) we utilized RCP2.6 projections for total contributions from Antarctica (*AIS*), Greenland (*GrIS*) (these are in line with recent ice sheet simulations for this RCP, DeConto and Pollard, 2016) and scenario independent projections of land-water storage (*LW*) due to the combined effect of man-made reservoirs and ground water extraction. This allows us to apply a probabilistic approach (Jackson and Jevrejeva, 2016) to the sum of projected sea-level components,

$$GSL = T + GIC + GrIS + AIS + LW, \text{ (eq. 1)}$$

to give global sea level (GSL) projections (Figure 1).

To further explore the GSL response to temperature change, we create a set of idealised warming scenarios for 1.5 °C and 2 °C, where we prescribe the trajectory of the temperature to reach and then stabilize at the two targets in 2030, 2050, 2070 and 2090 (Figure S1, Table 1). We investigate the global sea level response for these idealised scenarios by 2100 and their associated uncertainties using the semi-empirical model by Grinsted et al., (2010). We use our idealised temperature scenarios to understand the sea level response to temperature changes

and do not discuss through which intervention (e.g. the reduction of emissions) our scenarios could be achieved.

To assess the impact of sea level change under these limited warming targets by 2100, we compare our projections to the RCP8.5_J14 sea level rise projections (Figure 1), where the RCP8.5 scenario is supplemented by Greenland and Antarctic contributions elicited by Bamber and Aspinall (2013) (Jevrejeva et al., 2014, henceforth RCP8.5_J14). In our study we refer to the RCP8.5 scenario for temperature projections and RCP8.5_J14 for sea level projections associated with warming under RCP8.5. Differences between 1.5 °C, 2 °C and RCP8.5_J14 are shown in Figure 2 as probability density functions (PDFs) of global sea level and its components in 2100.

Regional sea level rise displays complex spatial patterns due to the dynamic redistribution of ocean mass and the gravitational spatial patterns (so-called "fingerprints") associated with specific geographical distributions of ice loss from mountain glaciers, Greenland and Antarctica ice sheets and changes to land-water storage by man-made reservoirs and ground water extraction. For regional sea level projections we follow the approach by Jackson and Jevrejeva (2016) and combine global projections of each sea level component with their associated normalised fingerprint using a probabilistic method:

$$\text{RSL} = F(T) + F(GIC) + F(GrIS) + F(AIS) + F(LW) + F(GIA) \quad (\text{eq. 2})$$

where RSL is regional sea level, $F(T)$, $F(GIC)$, $F(GrIS)$, $F(AIS)$, $F(LW)$ are the normalised fingerprints scaled by the global average projected sea level ($F()$) respectively of: T , ocean thermal expansion plus dynamical changes in sea surface height; GIC , ice loss from glaciers (surface mass balance); $GrIS$, ice loss from Greenland (surface mass balance and ice dynamics); AIS , ice loss from Antarctica ice sheet (surface mass balance and ice dynamics);

LW, land water storage. GIA refers to glacial-isostatic adjustment, which is a non-climate related component. To generate regional sea level projections we randomly sample the PDF of each sea level component (similar to Figure 2). We produce sea level projections for each component (excluding GIA) by scaling the normalised fingerprint of each component by their associated random samples. We then sum the fingerprints of the sea level components making, in total, 5000 realisations of sea level. This allows us to create a probability density function for each grid point in our map of regional sea level projections. To account for GIA, we add the time-integrated spatial field of GIA induced sea level change from the ICE 6G model (Peltier et al., 2015) to the sum of sea level components (eq. 2). We assume each of the sea level components is uncorrelated and that the spatial pattern of future land-based mass loss will be the same as at present (Jackson and Jevrejeva, 2016).

2.2. Impact modelling

The impacts of sea-level rise were computed using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework (version 2.1.0, database 32), an integrated bio-geophysical coastal systems model, which is driven by (climate change induced) sea level change and socioeconomic development (Vafeidis et al., 2008; Hinkel, 2005; Hinkel and Klein, 2009; Hinkel et al., 2014). Impacts are generated by dividing the world's coast into 12.148 linear segments (excluding Antarctica), each having similar bio-physical and socio-ecological characteristics. Global mean sea level rise is combined with estimates of vertical land movement due to GIA (Peltier, 2004), plus subsidence or uplift in deltaic regions (39 locations with rates from Ericson et al. (2006) and a further 78 where 2 mm yr⁻¹ of subsidence was assumed). This was used to determine changes of local extreme water levels for different return periods for each segment, based on a hydrodynamic modelling reanalysis of storm surges and extreme sea levels (GTSR dataset, Muis et al., 2016). Extreme water level distributions are

assumed to uniformly increase with regional mean sea-level rise, following 20th century observations (Menendez et al., 2010).

Land elevations were derived from the Shuttle Radar Topographic Mission (SRTM) high resolution digital elevation model (Jarvis et al., 2008) and the GTOPO30 dataset (USGS 2015) for land areas poleward of 60°N and 60°S. Linear interpolation was used between grid points to provided discrete elevations at the required resolution. To calculate population exposure to potential flood events, the Global Rural Urban Mapping Project (GRUMPv1) with a spatial resolution of 30 arc seconds was used (CIESIN, 2011; Balk et al., 2006). Shared Socioeconomic Pathway 2 (SSP2) was used to determine socio-economic development, in particular to project future coastal population and national Gross Domestic Product (GDP) (Moss et al., 2010; O'Neill et al., 2014). SSP2 represents a future with a mix of adaptation and mitigation challenges. Global population increases until mid-century, reaching approximately 9 billion people globally before slightly declining. Global GDP increases throughout the century.

Existing protection by dikes was modelled through a generic rule based on income group and population density, as defined by Sadoff et al., (2015) and complemented with protection standards for the 136 biggest coastal cities as defined by Hallegatte et al., (2013). Following current and future guidelines in Kind (2014) and Deltacommission (2008) the Netherlands was treated as a special case, with implemented protection equal to the 1-in-10,000 year water level for the whole country. Further details are available in Table S2. We consider two adaptation option to explore future coastal damages. First, a scenario with no additional adaptation that keeps dike heights constant at the baseline level. Second, a scenario with business-as-usual adaptation where the standard of protection is updated every five years according to a generic rule used in the initialization phase. Thus, dike heights are raised to cope with rising sea levels and changes in population density.

Two kinds of costs were considered: annual sea flood cost and annual adaptation cost consisting of construction cost for raising existing dikes and the cost of maintenance. Reported total annual costs are the sum of annual sea flood cost and annual adaptation cost. Results are presented at the level of World Bank income groups (high, upper middle, lower middle and low income countries) (World Bank, 2013; Table S3).

3. Results

3.1 Global and regional sea level projections by 2100

The range of global mean sea level projections with warming of 1.5 °C and 2 °C is dependent on temperature trajectories (Table 1, Figure S1). Using idealised temperature pathways, the median sea level rise for 1.5 °C warming trajectories by 2100 is up to 52 cm (25-87 cm, 5th - 95th percentile). The difference in projected global sea level rise by 2100 between warming of 1.5 °C and 2 °C is up to 11 cm at the median and up to 25 cm at the 95th percentile (Table 1, Figure S1). The rate of global sea level rise of 7.2 mm yr⁻¹ (median) and up to 12.7 mm yr⁻¹ at the 95th percentile by 2100 is projected for the trajectory of temperature reaching 2 °C in 2040 and kept below the 2 °C target after that. Over the 21st century, sea level rise rates are projected to exceed the highest rate of rise of the 20th century even if emissions are limited sufficiently to reach the 1.5 °C target.

Examining the results of our process-based approach, coastal sea level rise generally exceeds the global average (Figure 3), with exceptions of coastline in the areas close to Greenland and Antarctic ice sheets. The largest differences between 1.5 °C and 2 °C scenarios in 2100 along coastlines are ~15 cm (median) and up to 20 cm (95th percentile) (differences in global averages of 6 cm (median) and 7 cm (95th percentile), Jackson et al. 2018 and Goodwin et al., 2018) and occur for the US east coast and small-island nations in the Pacific and Indian oceans. These low-lying island nations in the Tropics are particularly vulnerable to flooding

from storms today. Potential changes in flooding frequency due in part to sea level rise will further challenge the sustainability of these coastal communities (Vitousek et al., 2017; Woodruff et al., 2013).

In 2040, there is very little difference between RCP8.5_J14 and 1.5 °C scenarios for both global and coastal sea level projections at median or 95th percentiles (Figure 1b, Figure S2 a, c). However, by 2100 (Figure S2 b) the difference between RCP8.5_J14 and 1.5 °C scenario for global sea level is around 39 cm (median), with large areas along the coastline of South and South East Asia, US east coast, Africa and Australia reaching differences up to 50 cm. For the small island states in the Pacific and Indian oceans the difference in median sea level projections with RCP8.5_J14 scenario and 1.5 °C temperature scenario would be more than double the total sea level rise occurring in the 20th century. The difference between these two scenarios for projected sea level rise in 2100 at the 95th percentile (Figure S2 d) is significantly higher: around 117 cm globally and up to 155 cm for small islands in the Western Pacific and 147 cm in the Indian Ocean.

3.2 Flood damage and adaptation costs

Annual sea flood costs and total annual costs are projected under global sea level of 0.52 m with warming of 1.5 °C, 0.63 m with warming of 2 °C (Table 1), 0.86 m for RCP8.5_J14 (median) and 1.8 m RCP8.5_J14 (95th percentile) scenarios using the DIVA modelling framework. It is important to note that these are annual costs, which are dependent on adaptation assumptions in previous time steps.

The difference in 2040 between flood costs associated with 1.5 °C and 2 °C sea level rise (with a 2.8 cm difference in sea level rise in 2040) is projected to be US \$ 0.3 trillion per year (0.1 % of global GDP). By the end of the 21st century global annual flood costs are

projected to be US\$ 10.2 trillion per year (1.8% of GDP) under 1.5 °C and US\$ 11.7 trillion per year (2.0% GDP) under 2 °C scenario, if no further adaptation is undertaken.

By 2100 the difference of 11 cm between global sea level rise with warming of 1.5 °C and 2 °C will result in additional costs of US\$ 1.5 trillion per year (0.25% of global coastal GDP), assuming that there has been no additional adaptation (Figure 4). If the 2 °C target is missed, and we follow the RCP8.5_J14 scenario (median sea level rise of 0.86 m and 95th percentile of 1.8 m in 2100), global annual flood costs without additional adaptation are projected to be US\$ 14.3 trillion per year (2.5% of GDP) for the median scenario and up to US\$ 27.0 trillion per year for the 95th percentile (Figure 4a), accounting for 4.7% of global GDP (Table S5).

Under the assumption of no additional adaptation the greatest annual flood costs by 2100, as a proportion of GDP for all scenarios, are projected for the upper middle income countries (Table S5) ranging from 2.8% with warming of 1.5 °C to 7.3% with the RCP8.5_J14 scenario (Table S5). A large proportion of this cost is attributed to China (Table S6) as it has a long coastline, a large coastal population and a rapidly growing GDP. For the high income group, future annual flood costs tend to be lower as their population falls significantly under SSP2. Large cities in all income groups tend to be well protected because significant levels of infrastructure and assets tend to be (though are not exclusively) located there (Hallegatte et al., 2013; IPCC, 2014). Global sea level rise under the 2 °C warming scenario shows that all income groups are projected to experience increased annual flood costs compared to the sea level rise with 1.5 °C warming, up to 0.4% of GDP in 2100 (Table S5).

Table S6 shows the top 10 countries with the largest values of annual sea flood costs (US\$ per year) in 2100 with sea level rise associated with warming of 1.5 °C (52 cm) assuming no additional adaptation. The largest flood cost in 2100 is projected for China, which is an order of magnitude large than the USA and Japan. However, the countries affected most

strongly in terms of percentage of country-level GDP (Figure 5; Table S7) are Kuwait (24%), Bahrain (11%), United Arab Emirates (9%) and Vietnam (7%). Changes in sea level rise by 2100 with warming from 1.5 °C to 2 °C could result in an increasing annual flood cost for China of US\$ 0.4 trillion per year and for Vietnam up to US\$ 0.07 trillion per year (S6-S9).

While the annual sea flood cost projections without additional adaptation are mainly used for analytical purposes to explore risk and enable long term decision making, such losses are unlikely to be tolerated by society and adaptation is expected to be widespread (e.g. Hinkel et al., 2014; IPCC, 2014, Wong et al., 2014; Diaz, 2016). By 2100 global flood cost with additional adaptation is estimated to be 0.2 % GDP for both 1.5 °C and 2 °C sea level projections, lower than 1.8% GDP (1.5 °C) and 2% GDP (2 °C) projected without additional adaptation. The difference in annual flood costs for each income group is illustrated in Figure 6 and indicates that low income countries may experience greater flood cost as percentage of GDP compared to higher income groups because of their limited means to implement adaptation measures. Despite this, there is a large potential for coastal adaptation across all income groups.

4. Discussion

The main challenge to generate sea level projections is due to uncertainties in radiative forcing and mitigation measures to keep temperature below 1.5 °C and 2 °C targets, as global sea level rise is an integrated climate system response to changes in radiative forcing, and sea level projections strongly depend on the trajectory of the forcing (Church et al., 2013). Even if a halt in global air temperatures could be immediately achieved using geoengineering (e.g. Kravitz et al., 2015), global sea level would respond with considerable delay due to the huge inertia of the climate system resulting from the century scale response times of oceans and ice sheets (Jevrejeva et al., 2010; Moore et al., 2010; Irvine et al., 2012). Thus, while it seems that

mitigation will be less effective in stabilising sea level than in stabilising temperature, the level of mitigation will strongly impact the equilibrium response of sea level on a much longer, centennial to millennial, timescale (Clark et al., 2016).

The largest gap in our understanding of future sea level changes is due to the response of the Greenland and Antarctic ice sheets to future warming (Kopp et al., 2017; Slangen et al., 2017; Wong et al., 2017). Several studies suggest that the global mean temperature threshold for decline of the Greenland ice sheet is 1.6 °C with a 95% credible interval of 0.8–3.2 °C above pre-industrial (e.g. Robinson et al., 2012; Church et al., 2013). However, crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia) as the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical level (Robinson et al., 2012).

The projected difference of 10-20 cm in coastal sea level between 1.5 °C and 2 °C scenarios (Figure 3) by 2100 will more than double the frequency of extreme sea levels in tropical areas (Vitousek et al., 2017) leading to a potential increase in flood risk. This has been well documented with historic sea level rise. For instance, 20th century sea level rise (approximately 20 cm) is estimated to have cost New York City an additional US\$ 2 billion from the effects of Hurricane Sandy (Leifert et al., 2015). Over the 21st century, the same rise could cause even greater damage without further adaptation given the growing number of assets on the coast.

While the present analysis has focused upon the potential costs of flooding in the absence of additional adaptation from the existing baseline, it is clear that all coastal nations have, and will continue to adapt by varying degrees to sea level rise. Standards of protection are likely to improve particularly with economic growth (IPCC, 2014; Hinkel et al., 2014; Scussolini et al., 2016) and changing forms of protection are envisaged. Presently our adaptation analysis is based on the building of dikes to protect vulnerable coastlines, but

adaptation costs will also vary depending on the type of protection implemented (Dasgupta et al., 2009; Hinkel et al., 2014; Scussolini et al., 2016). For example, flood protection by ecosystem creation and restoration may be cheaper or more effective in reducing the threat of flooding (Temmerman et al., 2013). Furthermore, the indirect cost of sea floods could affect the wider country-level economy, not least because coastal regions are hubs for trade, tourism and transport. This has already been observed for extreme events such as Hurricanes Katrina, Rita and Sandy (Hibbard, 2006; Hoffman and Bryan, 2013). Coastal nations could also face further socio-economic challenges associated with sea-level rise such as human migration, land loss, agriculture and ecosystem degradation (IPCC 2014, Wong et al., 2014; Dasgupta et al., 2009; Brown et al., 2018).

Some of the most fragile coastal regions are low-lying small islands (e.g. Maldives, Kiribati) which could be severely impacted by sea level rise and broader coastal change unless adaptation is undertaken. Many small island nations are also developing nations, and face the dual threats of development challenges (e.g. Jamero et al., 2017) and sea level rise. Adaptation challenges include their remoteness and therefore at times limited resources once a disaster has occurred (IPCC, 2014; Wong et al., 2014). Even sea level rise with warming below 2 °C could adversely affect the development capabilities of these small islands by aggravating pressures on natural resources and the environment. The vulnerability of small islands has been internationally recognised (e.g. Nurse et al., 2014 and in the Paris Agreement, United Nations 2015) and while numerous studies have analysed their present and future adaptation strategies (e.g. Robinson and Gilfillan, 2016; Robinson and Dornan, 2016; Warrick et al., 2016) there remains significant debate on their long-term existence. We have not attempted to assess flood or adaptation costs of small island nations in this paper due to model complexity. This partly due to the resolution of global data sets, which do not sufficiently portray the elevation of small islands. This needs to be addressed in further research, taking into account the close ties in

trade, finances, development and local physical and socio-economic processes of small island nations.

5. Conclusion

We provide global and coastal sea level projections with warming of 1.5 °C and 2 °C by 2100. We project global sea flood costs of US\$ 10.2 trillion per year (1.8% of GDP) without additional adaptation for sea level projections with warming of 1.5 °C by 2100. Adaptation is a worthwhile investment as costs could decrease to US\$ 1.1 trillion per year (0.2% GDP) for the same 1.5 °C scenario in 2100. If warming is not mitigated and follows the RCP8.5 scenario, global mean sea level could rise to 86 cm (median) or even 180 cm (95th percentile) by 2100. This could result in annual sea flood costs of US\$ 14 trillion per year and US\$ 27 trillion per year respectively if no further adaptation were undertaken and the latter would equate to 2.7% of global GDP. If adaptation were considered, total flood costs, could decrease to US\$ 1.7 trillion per year and US\$ 3.2 trillion per year for the median and 95th percentile sea level rise respectively. Thus, adaptation could greatly reduce flood costs, potentially by an order of magnitude and regardless of the future climate scenarios. Consequently, sea level rise with a warming of 1.5 °C and 2 °C will remain a challenge for all nations and particularly small island states, while adaptation can greatly reduce risk.

Flood cost estimates without adaptation raises the awareness about the role of adaptation and stimulates the discussion about how the reduction of emissions can limit future sea level rise as well as for designing strategies to adapt to increasing coastal flood risk. We have shown that failing on the 1.5 °C and 2 °C target will result in a greater socio-economic cost. Recent work by Millar et al. (2017) indicates that current emissions pledges coupled with strengthened pledges in 2030 and deep/rapid mitigation allows for warming limited to 1.5 °C above pre-industrial to be achieved. Though global sea level will continue to rise, even in these

strong mitigation scenarios it will rise far less than it would for strong emissions scenarios. The impact of this reduced rise, coupled with appropriate adaptation measures will reduce future risk and economic losses.

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Figures

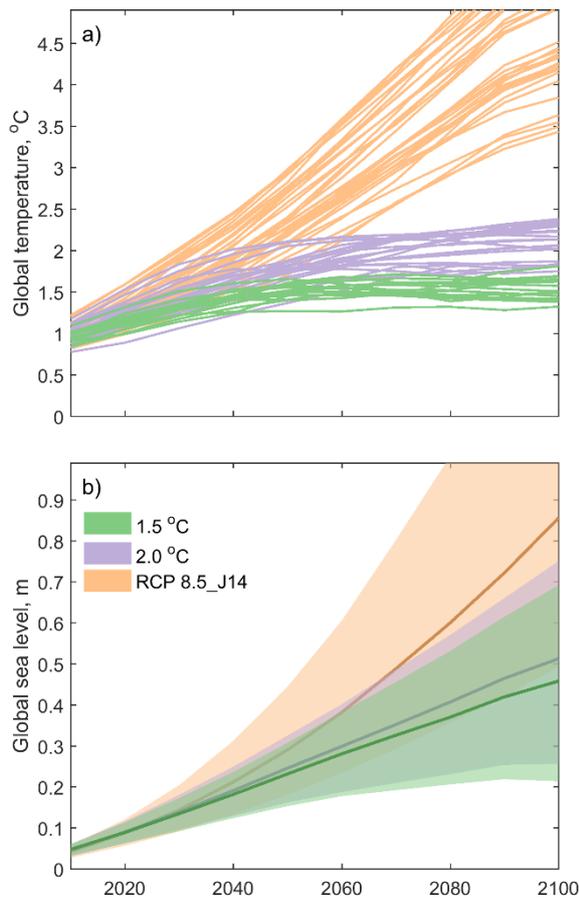


Figure 1: (a) Global temperature pathways of CMIP5 models (Table S1) from RCP2.6 and RCP4.5 satisfying 1.5 and 2.0 °C by end-of-century (relative to 1986-2005, plus 0.61 °C to show relative to pre-industrial) and RCP8.5 scenario. (b) Global sea-level projections estimated using process-based approach for 1.5 °C and 2.0 °C temperature pathways and RCP8.5_J14. Line and shaded areas are median and 17th-84th percentile range respectively.

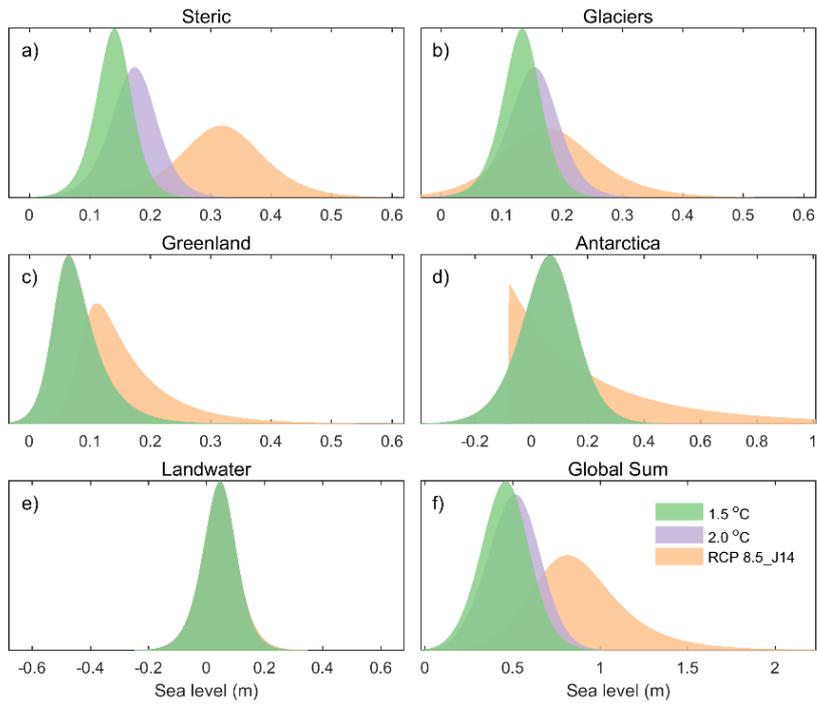


Figure 2: Probability density functions for global sea level and its components in 2100 for warming of 1.5 °C, 2 °C and RCP8.5_J14. Note that the land based water component is scenario independent.

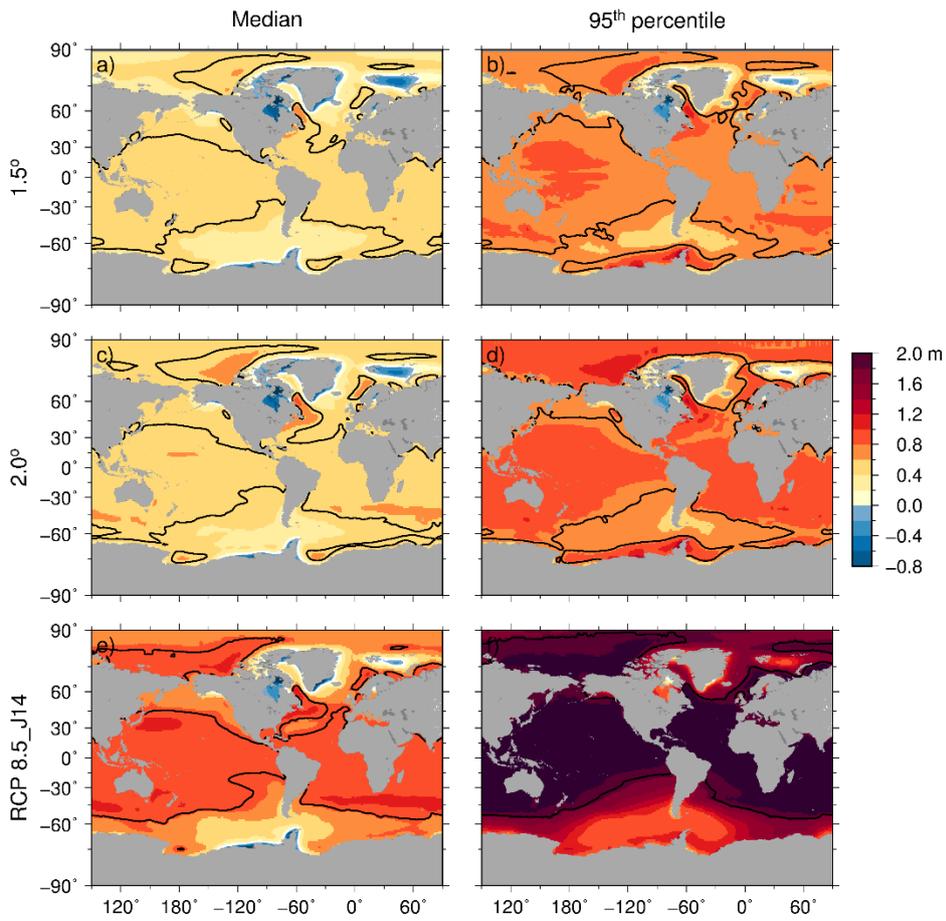


Figure 3. Median (a, c and e) and 95th percentile sea-level projections (b, d, and f) for 1.5 °C and 2 °C temperature pathways and RCP8.5_J14 (Jackson and Jevrejeva, 2016) in 2100.

Black contour represents global average estimates.

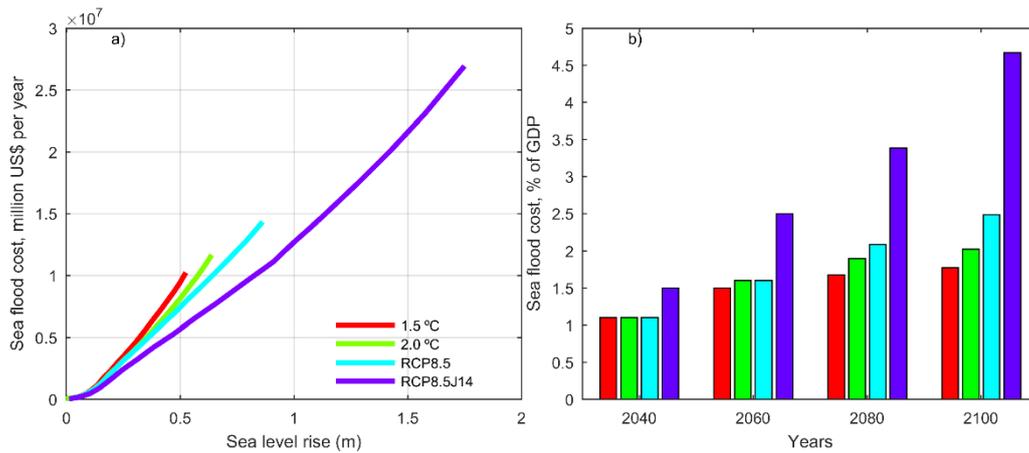


Figure 4. a) Global annual sea flood costs (million US\$ per year) without additional adaptation for 1.5 °C (red solid line), 2 °C (green), RCP8.5 (50th percentile, light blue) and RCP8.5_J14 (95th percentile, dark blue) scenarios. b) Global annual flood costs as percentage of global GDP (Table S2) without additional adaptation for sea level rise with 1.5 °C 2 °C, RCP8.5 (50th percentile) and RCP8.5_J14 (95th percentile) at 2040, 2060, 2080 and 2100, colour on b panel are representing the same scenarios as at the panel a).

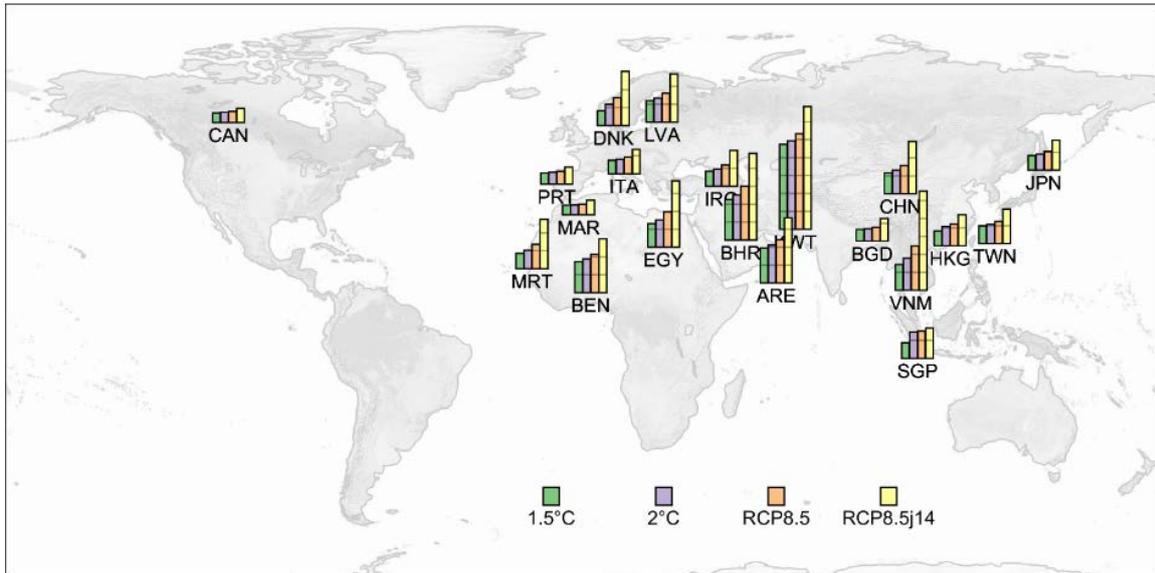


Figure 5. The top 20 countries (with a GDP > US\$50 billion per year, small island States are excluded, see SI for details) with the greatest annual sea flood costs using the SSP2 scenario, assuming no additional adaptation as a percentage of GDP in 2100 for the four projected sea level rise scenarios. Climate scenario marked as RCP8.5 corresponds to the median of RCP8.5_J14 (0.86 m); RCP8.5J14 corresponds to the 95th percentile of RCP8.5_J14 (1.8 m)

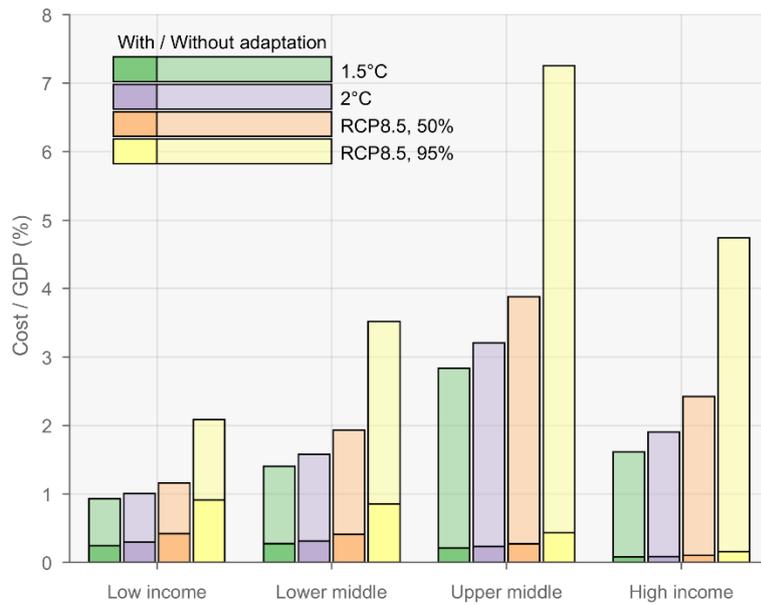


Figure 6. Annual total flood costs (as a percentage of GDP in income groups) with adaptation (darker colour, the lower part of the bars) and without additional adaptation (lighter colour, the upper part of the bars) for the World Bank income groups with four climate scenarios. Climate scenario marked as RCP8.5 corresponds to the median of RCP8.5_J14 (0.86 m); RCP8.5J14 corresponds to the 95th percentile of RCP8.5_J14 (1.8 m)

Table 1. Projected global sea level rise (m) by 2100 with warming of 1.5 °C and 2.0 °C reached by 2030, 2050, 2070, 2090 and kept constant

1.5 °C peak at	SLR (m) by 2100		
	5%	50%	95%
2030	0.27	0.52	0.87
2050	0.26	0.51	0.84
2070	0.25	0.47	0.82
2090	0.25	0.46	0.74

2 °C peak at	SLR (m) by 2100		
	5%	50%	95%
2030	0.29	0.63	1.12
2050	0.28	0.62	1.04
2070	0.27	0.59	0.98
2090	0.27	0.54	0.92

Supplementary Information (Tables, text and figure captions)

Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C

S. Jevrejeva¹, L. Jackson², A. Grinsted³, D. Lincke⁴, B. Marzeion⁵

Table S1. Subsets of CMIP5 models with temperature simulations of 1.5 °C and 2 °C above pre-industrial in the 21st century with RCP2.6 and RCP4.5 scenarios. Values in columns 2 - 5 are global temperature averaged from 2080-2100 relative to 1986-2005 (plus 0.61°C above pre-industrial level) and used in Figure 1 (panel a).

Model	1.5 °C		2 °C	
	RCP2.6	RCP4.5	RCP2.6	RCP4.5
BCC-CSM1-1	1.44			2.2
BCC-CSM1-1-m	1.43			2.12
BNU-ESM			1.75	
CanESM2			2.19	
CCSM4	1.48			2.25
CESM1-BGC				2.22
CESM1-CAM5			2.11	
CNRM-CM5	1.66			
CSIRO-Mk3-6-0				2.02
EC-EARTH	1.54			
FIO-ESM		1.64		
GFDL-ESM2M	1.28			1.79
GFDL-ESM2G		1.61		
GISS-E2-H	1.4			2.3
GISS-E2-H-CC				1.99
GISS-E2-R				2.03
GISS-E2-R-CC				1.79
HadGEM2-AO	1.75			
HadGEM2-ES			2.06	
inmcm4				1.86
IPSL-CM5A-LR			1.83	
IPSL-CM5A-MR			1.73	
IPSL-CM5B-LR				2.25
MIROC5	1.64			2.32
MIROC-ESM			2.26	
MPI-ESM-LR	1.41			
MPI-ESM-MR	1.4			2.3
MRI-CGCM3	1.59			2.29
NorESM1-M	1.49			2.24
NorESM1-ME	1.6			

Table S2. Standards of protection at country level assumed in this study. Exceptions were made for the Netherlands and 136 megacities.

Gross national income group	Standard of protection based on population density		
	Urban (> 1000 people / km ²)	Rural (30 – 1000 people / km ²)	Uninhabited / very sparsely populated (> 30 people / km ²)
High income (>\$12,615)	1:200	1:50	No protection was assumed
Upper middle income (\$4085-\$12615)	1:100	1:20	No protection was assumed
Lower middle income (\$1036-4085)	1:25	No protection was assumed	No protection was assumed
Low income (<\$1035)	1:10	No protection was assumed	No protection was assumed

Table S3. Countries by World Bank income groups, World Bank classification in 2013 (World Bank, 2013)

	High Income countries
1	Aaland
2	Anguilla
3	Antigua and Barbuda
4	Aruba
5	Australia
6	Bahamas
7	Bahrain
8	Barbados
9	Belgium
10	Bermuda
11	Bonaire, Saba and Saint Eustatius
12	Bouvetisland
13	British Indian Ocean Territory
14	British Virgin Islands
15	Brunei Darussalam
16	Canada
17	Cayman Islands
18	Chile
19	Christmas Island
20	Cocos Islands
21	Cook Islands
22	Croatia
23	Curacao

24	Cyprus
25	Denmark
26	Estonia
27	Falkland Islands
28	Faroe Islands
29	Finland
30	France
31	French Guiana
32	French Polynesia
33	French Southern Territories
34	Germany
35	Gibraltar
36	Greece
37	Greenland
38	Guadeloupe
39	Guam
40	Guernsey
41	Heard Island and McDonald Islands
42	Hong Kong, China SAR
43	Iceland
44	Ireland
45	Isle of Man
46	Israel
47	Italy
48	Japan
49	Jersey
50	Korea, Republic
51	Kuwait
52	Latvia
53	Lithuania
54	Macau
55	Malta
56	Martinique
57	Mayotte
58	Monaco
59	Montserrat
60	Nauru
61	Netherlands
62	New Caledonia
63	New Zealand
64	Niue
65	Norfolk Island
66	Northern Mariana Islands
67	Norway
68	Oman
69	Poland

70	Portugal
71	Puerto Rico
72	Qatar
73	Reunion
74	Russian Federation
75	Saint Barthelemy
76	Saint Kitts and Nevis
77	Saint Martin
78	Saint Pierre and Miquelon
79	Saudi Arabia
80	Singapore
81	Slovenia
82	South Georgia and the South Sandwich Islands
83	Spain
84	Svalbard and Jan Mayen
85	Sweden
86	Trinidad and Tobago
87	Turks and Caicos Islands
88	United Arab Emirates
89	United Kingdom
90	United States Minor Outlying Islands
91	United States of America
92	Uruguay
93	Virgin Islands, U.S.
94	Wallis and Futuna

	Upper middle income
1	Albania
2	Algeria
3	American Samoa
4	Angola
5	Argentina
6	Belize
7	Bosnia and Herzegovia
8	Brazil
9	Bulgaria
10	China
11	Colombia
12	Costa Rica
13	Cuba
14	Dominica
15	Dominican Republic
16	Ecuador

17	Fiji
18	Gabon
19	Grenada
20	Iran, Islamic Republic
21	Iraq
22	Jamaica
23	Jordan
24	Lebanon
25	Libya
26	Malaysia
27	Maldives
28	Marshall Islands
29	Mauritius
30	Mexico
31	Montenegro
32	Namibia
33	Palau
34	Panama
35	Peru
36	Pitcairn Islands
37	Romania
38	Saint Helena
39	Saint Lucia
40	Saint Vincent and Grenadine
41	Seychelles
42	South Africa
43	Suriname
44	Taiwan, Province of
45	Thailand
46	Tonga
47	Tunisia
48	Turkey
49	Tuvalu
50	Venezuela

	Lower middle income
1	Cameroon
2	Cape Verde
3	Congo
4	Cote de Ivoire
5	Djibouti

6	East Timor
7	Egypt
8	El Salvador
9	Georgia
10	Ghana
11	Guatemala
12	Guyana
13	Honduras
14	India
15	Indonesia
16	Kiribati
17	Mauritania
18	Micronesia, Federal State of
19	Morocco
20	Nicaragua
21	Nigeria
22	Pakistan
23	Papua New Guinea
24	Philippines
25	Samoa
26	Sao Tome and Principe
27	Senegal
28	Solomon Islands
29	Sri Lanka
30	Sudan
31	Syrian Arab Rep
32	Ukraine
33	Vanuatu
34	Vietn Nam
35	West Bank and Gaza
36	Yemen

	Low income
1	Bangladesh
2	Benin
3	Cambodia
4	Comoros
5	Congo, Democratic Republic
6	Equatorial Guinea
7	Eritrea
8	Gambia
9	Guinea
10	Guinea-Bissau

11	Haiti
12	Kenya
13	Korea, Democratic Peoples Republic
14	Liberia
15	Madagascar
16	Mozambique
17	Myanmar
18	Sierra Leone
19	Somalia
20	Tanzania, United Republic
21	Togo
22	Tokelau
23	Western Sahara

Table S4. Annual sea flood costs (as a percentage of GDP in that same year), using the SSP2 scenario and the four sea level rise projections. No additional adaptation from the base year has been assumed.

Scenario	2020	2040	2060	2080	2100
1.5 °C	0.3	1.1	1.5	1.7	1.8
2 °C	0.3	1.1	1.6	1.9	2.0
RCP8.5_J14 (50 th percentile)	0.3	1.1	1.6	2.1	2.5
RCP8.5_J14 (95 th percentile)	0.4	1.5	2.5	3.4	4.7

Table S5. Annual sea flood costs by income groups (% of GDP per income group for coastal countries only) for sea level projections of 1.5 °C, 2 °C, and RCP8.5 (median) and RCP8.5 (95%) scenarios, using the SSP2 scenario. No additional adaptation was assumed. Time periods correspond to those in Figure 4b.

Groups by income	Climate scenarios			
	1.5 °C	2 °C	RCP8.5_J14 (50 th percentile)	RCP8.5_J14 (95 th percentile)
2100				
High	1.6	1.9	2.4	4.7
Upper middle	2.8	3.2	3.9	7.3
Lower middle	1.4	1.6	1.9	3.5
Low	0.9	1.0	1.2	2.1
Global mean	1.8	2.0	2.5	4.7
2080				
High	1.3	1.6	1.8	3.0
Upper middle	2.7	3.0	3.3	5.3
Lower middle	1.3	1.4	1.6	2.5

Low	0.9	1.0	1.1	1.5
Global mean	1.7	1.9	2.1	3.4
2060				
High	1.0	1.2	1.2	1.9
Upper middle	2.4	2.7	2.6	3.9
Lower middle	1.2	1.3	1.3	1.8
Low	0.8	0.9	0.9	1.3
Global mean	1.5	1.7	1.6	2.5
2040				
High	0.6	0.7	0.5	1.0
Upper middle	1.9	2.1	1.9	2.4
Lower middle	0.8	0.9	0.8	1.2
Low	0.6	0.6	0.5	0.8
Global mean	1.1	1.2	1.0	1.5

Table S6. Top 10 countries with largest annual flood cost (millions US \$ per year) in 2100 with sea level rise projected for warming of 1.5 °C (53 cm) using the SSP2 scenario, assuming no additional adaptation to baseline defences. Small islands were omitted from this analysis due to data resolution.

Country	Annual sea flood cost (billion US \$ per year)	Annual sea flood costs as a percentage GDP (%)
China	3407	5.9
India	1366	1.5
Egypt	602	6.5
United States of America	394	0.9
Japan	349	4.1
Vietnam	297	7.2
Bangladesh	263	3.3
Indonesia	261	1.3
United Arab Emirates	241	9.8
United Kingdom	241	2.5

Table S7. The top 10 countries with largest annual flood cost as a percentage of GDP in 2100 with sea level rise projected for warming of 1.5 °C (53 cm) using the SSP2 scenario, assuming no additional adaptation to baseline defences. Small islands were omitted from this analysis due to data resolution.

Country	GDP (billion US \$ per year) in 2100	Annual sea flood cost as a percentage of GDP (%)
Kuwait	825	23.7

Bahrain	352	11.3
United Arab Emirates	2466	9.8
Benin	1074	8.6
Viet Nam	4153	7.2
Egypt	9204	6.5
China	58209	5.9
Taiwan	1234	4.9
Iraq	2396	4.2
Denmark	986	4.1

Table S8. The top 10 countries with largest flood cost (millions US \$ per year) in 2100 with sea level rise associated with warming of 2 °C (64 cm) using the SSP2 scenario, assuming no additional adaptation to baseline defences. Small islands were omitted from this analysis due to data resolution.

	Annual sea flood cost (billion US \$ per year)	Annual sea flood costs as a percentage GDP (%)
China	3825	6.6
India	1470	1.6
Egypt	702	7.6
United States of America	446	1.0
Japan	383	4.5
United Kingdom	383	3.9
Vietnam	371	8.9
Indonesia	300	1.5
Bangladesh	277	3.4
United Arab Emirates	260	10.6

Table S9. Top 10 countries with largest flood cost as a percentage of GDP in 2100 with sea level rise projected for warming of 2 °C (64 cm) using the SSP2 scenario, assuming no additional adaptation to baseline defences. Small islands were omitted from this analysis due to data resolution *.

Country	GDP (billion US \$ per year) in 2100	Annual sea flood cost as a percentage of GDP (%)
Kuwait	204	24.7
Bahrain	44	12.6
United Arab Emirates	260	10.6
Benin	101	9.4

Vietnam	371	8.9
Iceland	8	8.2
Egypt	702	7.6
Latvia	13	6.7
China	3825	6.6
Denmark	580	5.9

* Due to their scale, small islands are not located well on global elevation models (e.g. Shuttle Radar Topography Mission (SRTM)) and are challenging to resolve in impact models across multiple disciplines. However, we do recognise that they have significant costs as they have a high proportion of people and infrastructure directly on the coast. Thus low-lying coastal fringes will require significant amounts of protection, relatively more so than mainland nations. Their special attention is well recognised (e.g. Nurse et al. 2014 and in the Paris Agreement (United Nations 2015). Numerous studies have analysed adaptation in small islands (e.g. Robinson and Gilfillan, 2016; Robinson and Dornan, 2016), but there remains a significant debate on how and whether islands can adapt to many aspects of climate change.

Methods

1. Sea level projections with semi-empirical model

To study the global sea level response to rising temperatures by 2100 and explore the uncertainties in sea level projections we use a semi-empirical model by Grinsted et al., (2010). Despite some limitations, discussed in our previous publications (Moore et al., 2013; Jevrejeva et al., 2012), semi-empirical models (Rahmstorf, 2007; Grinsted et al., 2010; Jevrejeva et al., 2009; Kopp et al., 2016) are a fast and useful tool for exploring the uncertainties in future sea level rise.

Our semi-empirical model is constrained by the 300 years of global sea level records from tide gauges (Jevrejeva et al., 2008) and driven by the temperatures over the past 1000 years (Jones and Mann, 2002; Moberg et al., 2005). We assume that global sea level is an integrated response of the entire climate system to the changes in temperature that reflects alteration in the dynamics and thermodynamics of the atmosphere, ocean and cryosphere. Sea level rise in semi-empirical model is caused by changes in global ice volume and global ocean heat content as a response to changes in global temperature with a characteristic response time (Grinsted et al, 2010). This characteristic response time is estimated by the model as a probability density function spanning a wide range of time scales (up to few 1000 years). In our previous studies (Grinsted et al., 2010; Moore et al., 2010; Jevrejeva et al. 2009, 2010; Moore et al., 2013) we have demonstrated that semi-empirical models reproduce climate system modelled sea level behaviour at scales from multi-annual to centennial, e.g. simulation of 1993–2006 sea level rate is 3–4 mm/yr, which is very similar to the rate of 3.3 mm/yr calculated from satellite altimetry observations (Grinsted et al., 2010).

In this study we generate more than 1000000 possible realisations for future sea level rise under each specifically designed temperature trajectory (Figure S2). Each realisation is drawn from the probability density function describing the characteristic response time, thus allowing us to estimate the median, 5th and 95th percentiles for global sea level.

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2. Globally and World Bank income groups flood cost estimates

The standards of protection were based on Sadoff et al. (2015) at country level and Hallegatte et al. (2013) for 136 of the world's largest cities. These ranged from 1:10 (for 28 cities mostly in developing nations) to 1:2000 (Singapore), and 1:10,000 for Amsterdam and Rotterdam, Netherlands. Each coastline segment was allocated a standard of protection based on population density (Table S2) and local GDP per capita according the World Bank income group (World Bank, 2013). These income groups were based on the World Bank classification in 2013 (World Bank, 2013) as defined in Table S3. Furthermore, protection standard reflected urban, rural, and uninhabited land per country based on records (e.g. Scussolini et al. (2016) and expert judgement. The only country that did not follow these rules was the Netherlands, where a standard of protection of 1:10,000 was assumed nationally following current and future guidelines (Kind et al. 2014; Deltacommissie, 2008). Standard of protection vary globally for

a number of reasons, not just population density, but this provided a simple method in a field where precise standards of protection are not widely recorded or known.

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Figure

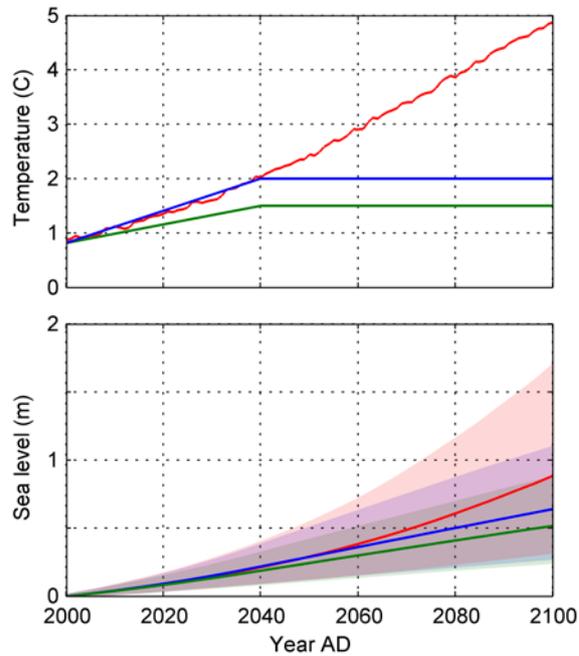


Figure S1. Top panel: idealistic temperature trajectories with warming of 1.5 °C (green line) and 2 °C (blue line) by 2100; both reaching the target temperature at 2040 and the temperature projections with RCP8.5 (red line). Bottom panel provides sea level projections with temperature scenarios from the top panel, colour scheme is corresponds to temperature scenarios on the top panel.

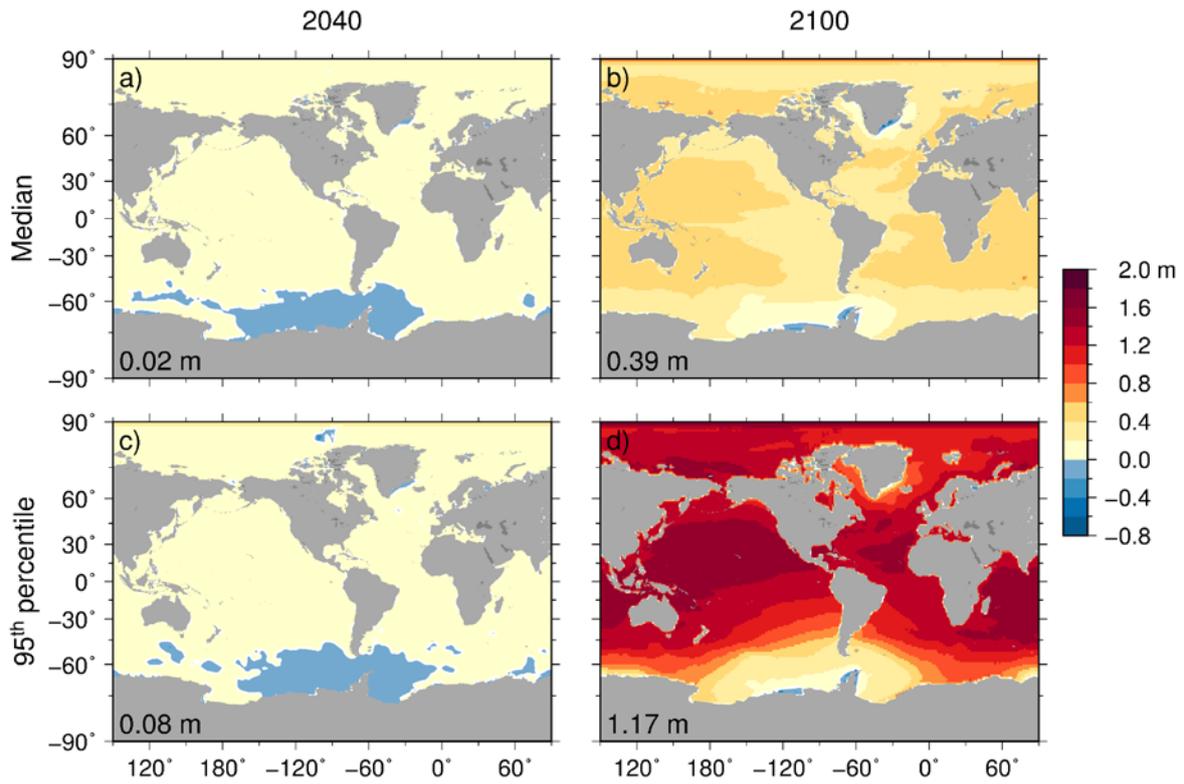


Figure S2. The difference between the median (50th percentile) of sea level projections with RCP8.5_J14 scenario and 1.5 temperature scenario at 2040 (panel a) and 2100 (panel b). The difference between the 95th percentile of sea level projections with RCP8.5_J14 scenario and 1.5 temperature scenario at 2040 (panel c) and 2100 (panel d). Numbers in the left corner correspond to the global sea level differences for each panel.