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LETTER

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 (McGranahan *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 available at stacks.iop.org/ERL/13/074014/mmedia).

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,

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

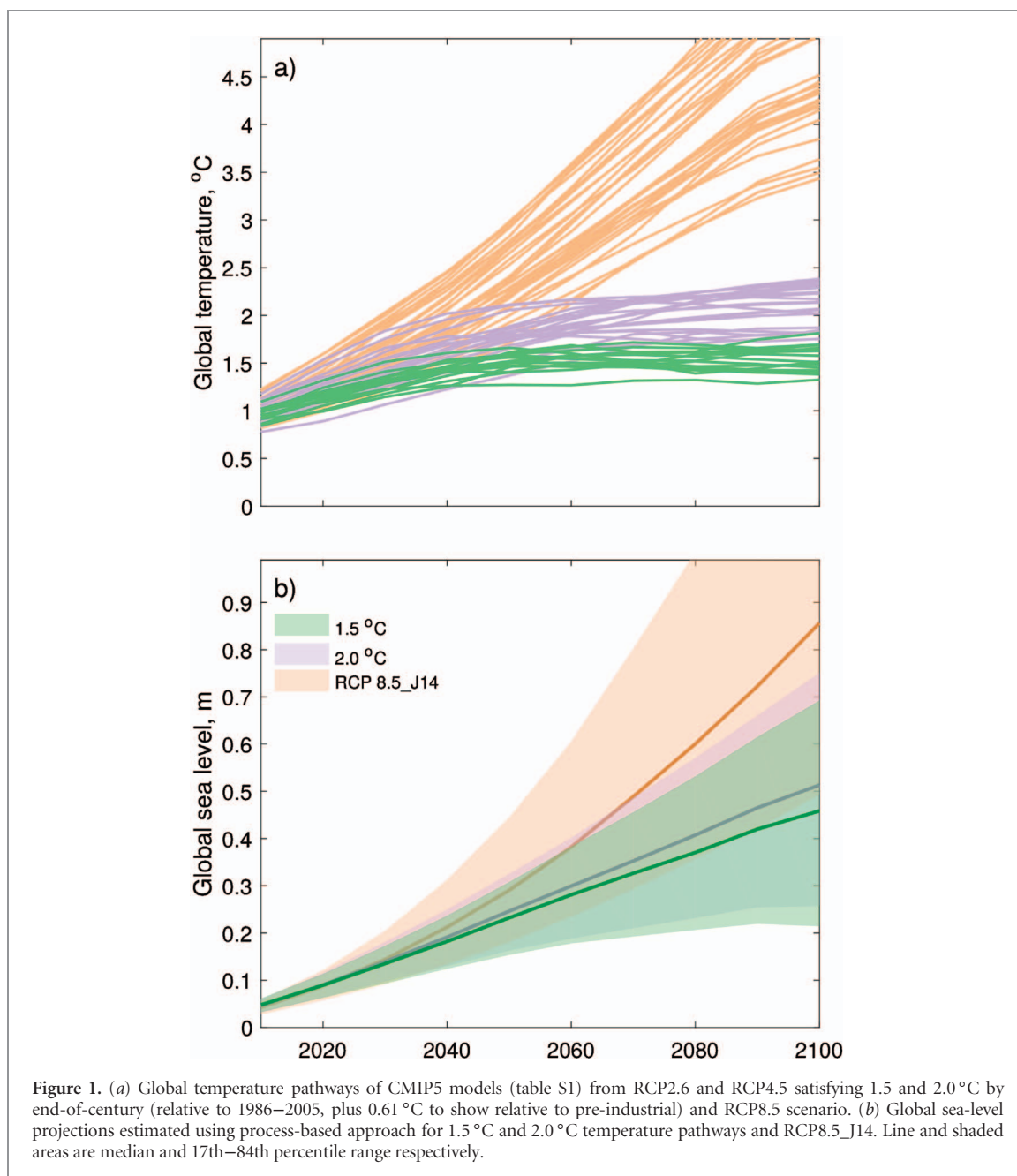to give global sea level (GSL) projections (figure 1).

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:

$$\begin{aligned} \text{RSL} = F(\text{T}) + F(\text{GIC}) + F(\text{GrIS}) \\ + F(\text{AIS}) + F(\text{LW}) + F(\text{GIA}) \end{aligned} \quad (2)$$

where RSL is regional sea level, $F(\text{T})$, $F(\text{GIC})$, $F(\text{GrIS})$, $F(\text{AIS})$, $F(\text{LW})$ 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
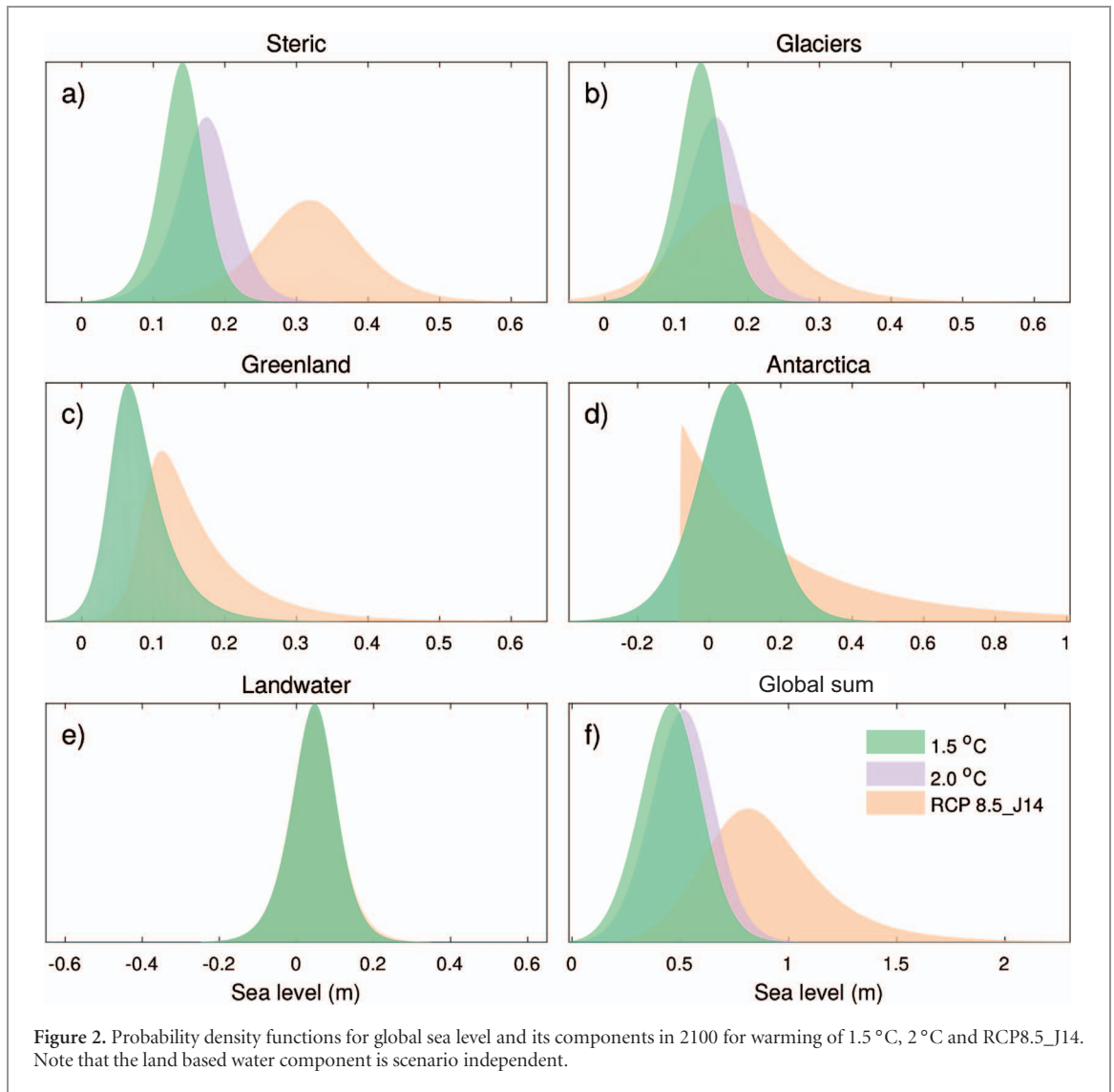
Figure 1. (*a*) Global temperature pathways of CMIP5 models (table S1) from RCP2.6 and RCP4.5 satisfying 1.5 and 2.0 °C by end-of-century (relative to 1986−2005, plus 0.61 °C to show relative to pre-industrial) and RCP8.5 scenario. (*b*) Global sea-level projections estimated using process-based approach 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.

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 equation (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 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

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.

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 (Menéndez and Woodworth 2010).

Land elevations were derived from the shuttle radar topographic mission 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 Deltacommissie (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 1(b), figures S2(a), (c)). However, by 2100 (figure S2(b)) the difference between RCP8.5_J14

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.

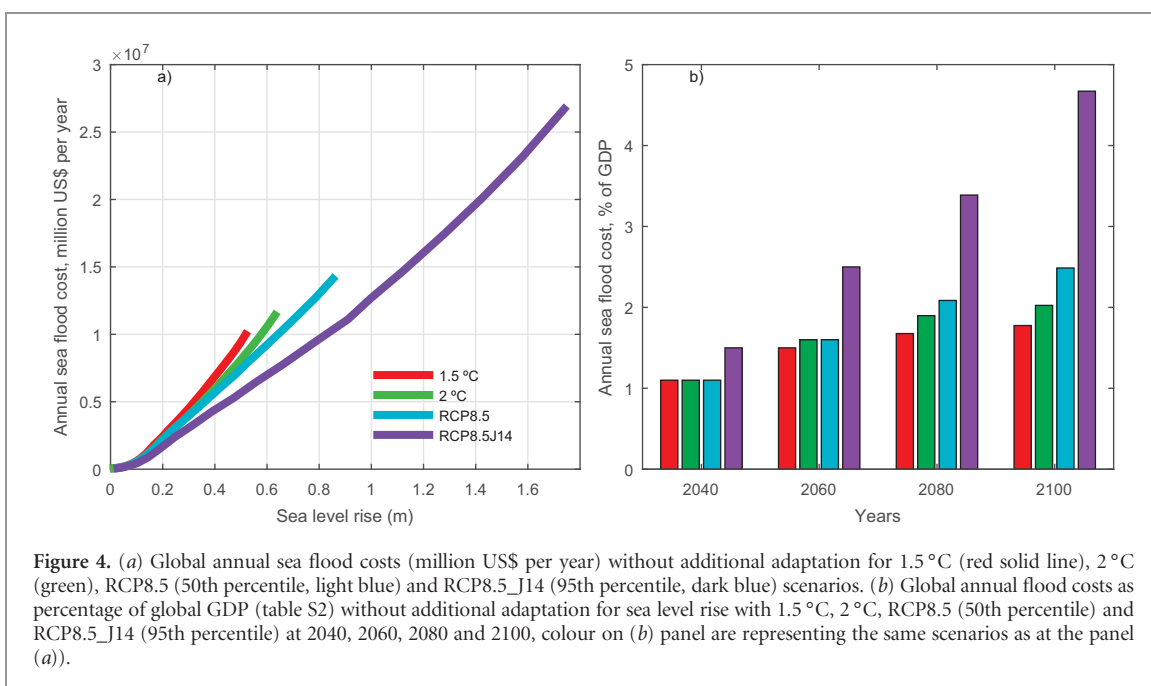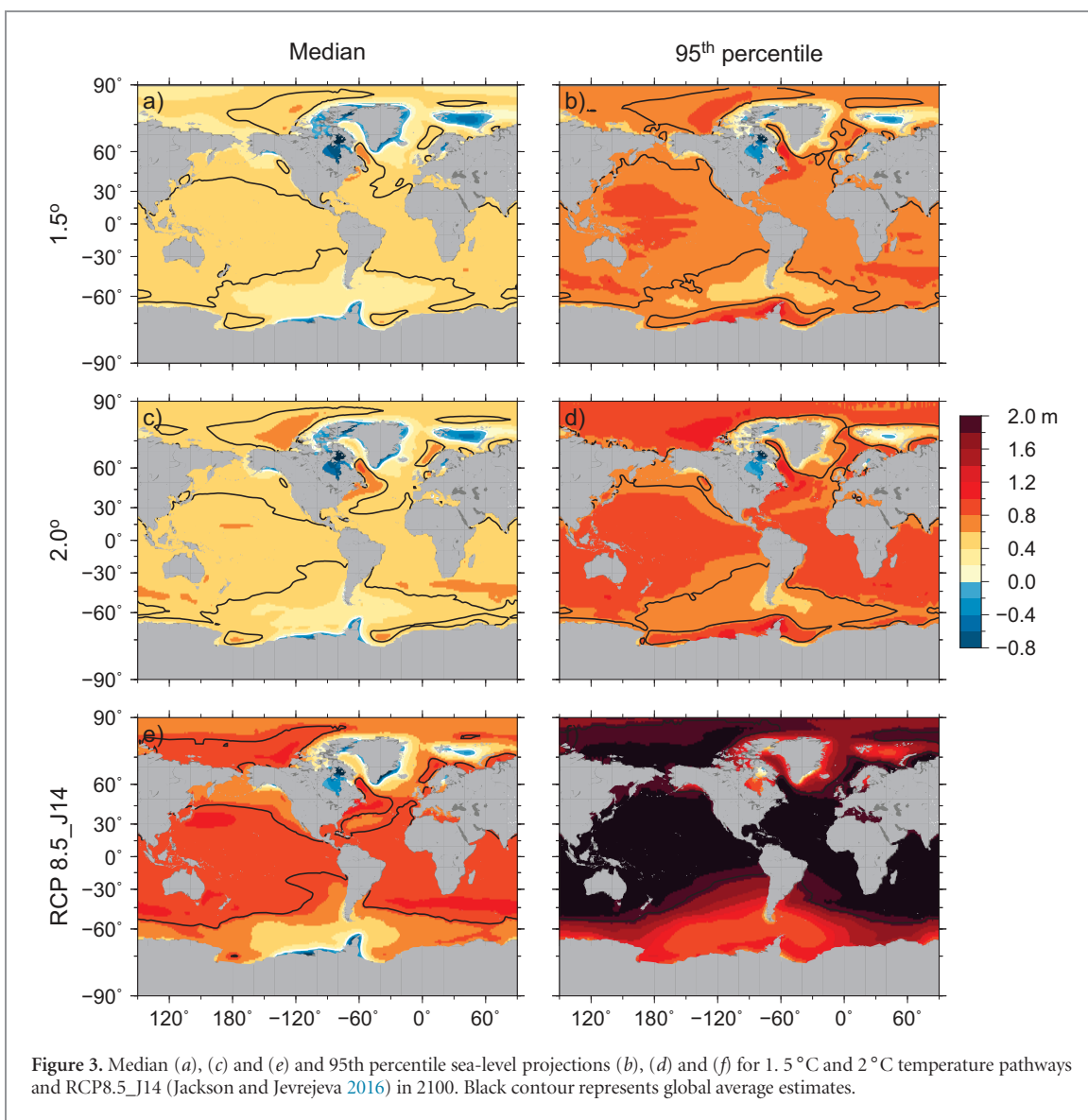| 1.5 °C peak at	SLR (m) by 2100		
	5%	50%	95%
2030	0.27	0.52	0.87
2050	0.26	0.51	0.84
2070	0.25	0.47	0.82
2090	0.25	0.46	0.74
2 °C peak at			
	5%	50%	95%
2030	0.29	0.63	1.12
2050	0.28	0.62	1.04
2070	0.27	0.59	0.98
2090	0.27	0.54	0.92

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.
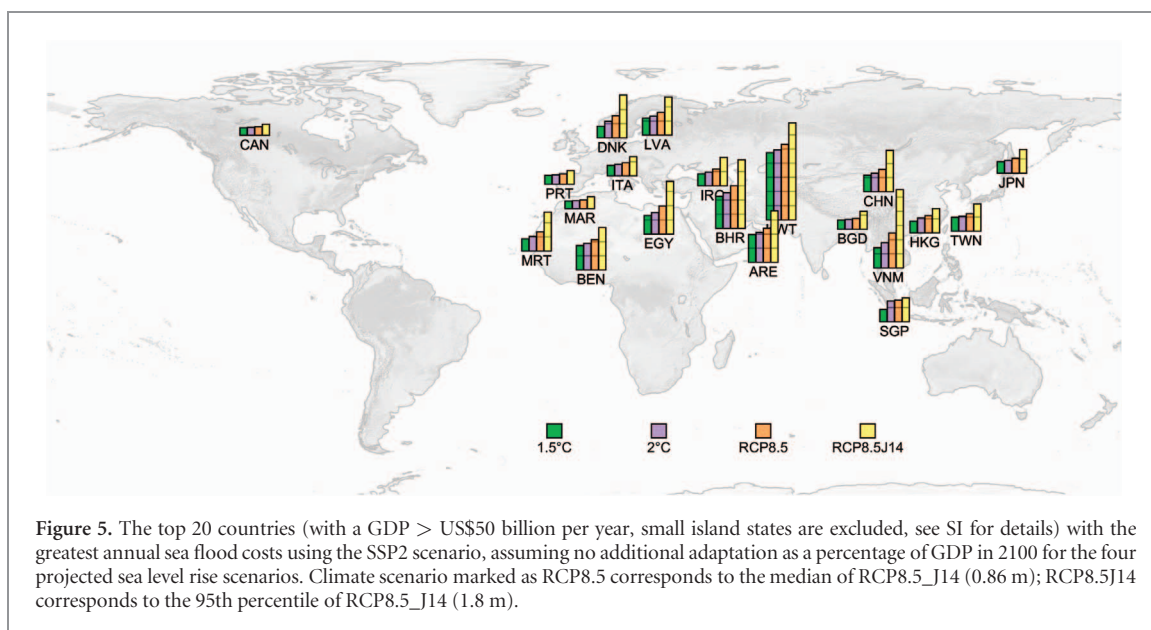
3.2. Flood damage and adaptation costs
Annual sea flood costs and total annual coasts are projected under global sea level of 0.52 m with warming of 1.5 °C, 0.63 m with warming of 2 °C (table 1), 0.86 m for RCP8.5_J14 (median) and 1.8 m RCP8.5_J14 (95th percentile) scenarios using the DIVA modelling 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 4(a)), accounting for 4.7% of global GDP (table S4).

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).

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–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.
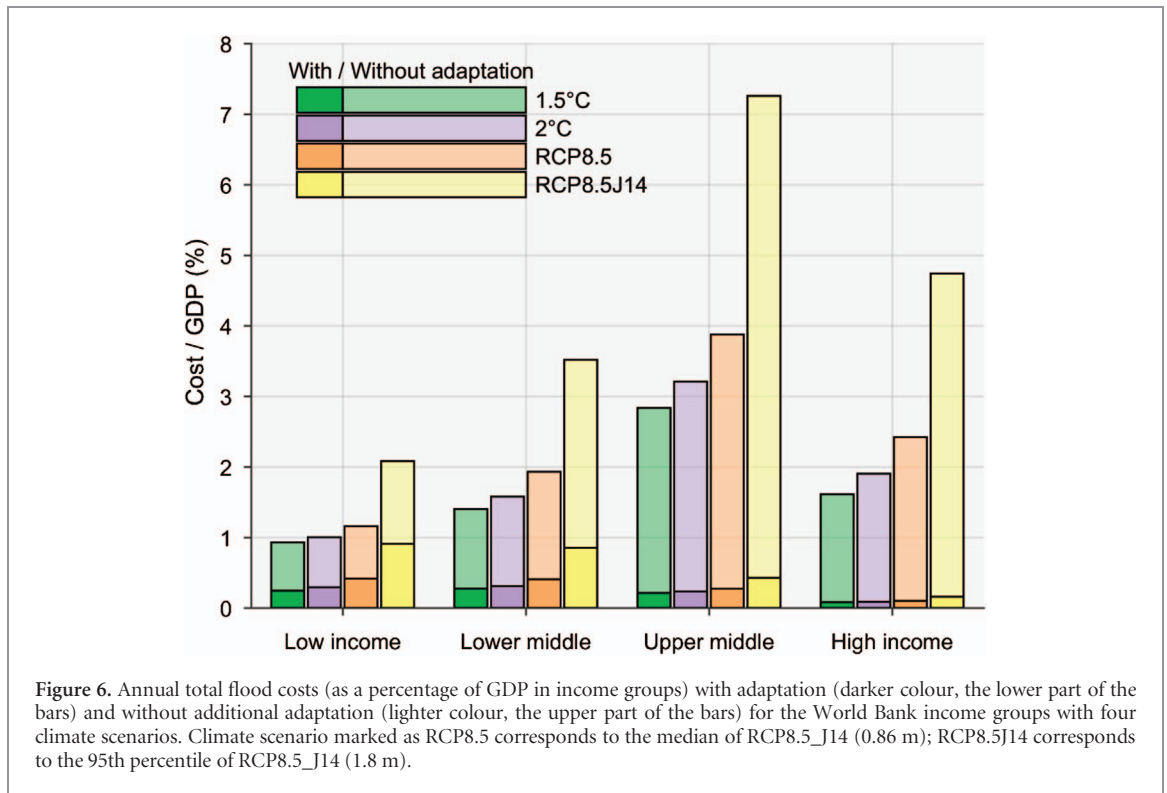
Hinkel *et al* 2014, IPCC 2014, Wong *et al* 2014, Diaz 2016). By 2100 global flood cost with additional adaptation is estimated to be 0.2% GDP for both 1.5 °C and 2 °C sea level projections, lower than 1.8% GDP (1.5 °C) and 2% GDP (2 °C) projected without additional adaptation. The difference in annual 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

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).

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 °C–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 2015). Over the 21st century, the same rise could cause even greater damage without further adaption 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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