Global costs of protecting against sea-level rise at 1.5 to 4.0 ℃

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Abstract
Sea levels will rise, even with stringent climate change mitigation. Mitigation will slow the rate of rise. There is limited knowledge on how the costs of coastal protection vary with alternative global warming levels of 1.5 to 4.0 °C. Analysing six sea-level rise scenarios (0.74 to 1.09 m, 50th percentile) across these warming levels, and five Shared Socioeconomic Pathways, this paper quantifies the economic costs of flooding and protection due to sea-level rise using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework. Results are presented for World Bank income groups and five selected countries from the present to 2100. Annual sea flood damage costs without additional adaptation are more influenced by socio-economic development than sea-level rise, indicating that there are opportunities to control risk with development choices. In contrast, annual sea dike investment costs are more dependent on the magnitude of sea-level rise. In terms of total costs with adaptation, upper middle, low middle and low income groups are projected to have higher relative costs as a proportion of GDP compared with high income groups. If low income countries protected now, flood costs could be reduced after 2050 and beyond. However, without further adaptation, their coasts will experience growing risks and costs leaving them increasingly reliant on emergency response measures. Without mitigation or adaptation, greater inequalities in damage costs between income groups could result. At country level, annual sea flood damage costs without additional adaptation are projected to rapidly increase with approximately 0.2 m of sea-level rise, leaving limited time to plan and adapt.

1 Introduction

The Paris Agreement sets a roadmap to limit warming to well below 2 °C and to pursue 'efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (United Nations 2015). However, it does not mention sea-level rise (SLR), which even with stringent climate change mitigation and temperature stabilization, will keep rising. Over periods of greater than

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50 years, mitigation can have a notable effect on rates and magnitude of SLR (Oppenheimer et al. 2019; Goodwin et al. 2018; Jevrejeva et al. 2018; Nicholls et al. 2018; Rasmussen et al. 2018; Nicholls and Lowe 2004). Additionally, as there are large uncertainties around future ice melt (Bamber et al. 2019; Levermann et al. 2020) and potential non-linear responses (Edwards et al. 2019; Martin et al. 2019; Pattyn et al. 2018), adaptation remains essential. A better understanding of potential damage and adaptation costs given uncertainties in SLR can help prepare for this.

In the Intergovernmental Panel on Climate Change's Special Report on 'Global Warming of 1.5°C' (Hoegh-Guldberg et al. 2018), the costs of coastal flooding and protection were not assessed as data were unavailable. Since then, Jevrejeva et al. (2018) analysed this at 1.5 and 2.0 °C, but did not assess costs associated with higher levels of warming. There is increasing evidence that limiting warming to 1.5 °C will be challenging to achieve (Gambhir et al. 2019; Hoegh-Guldberg et al. 2019) and there is significant uncertainty concerning what future emissions we could follow (Ho et al. 2019). As we cannot exclude Representative Concentration Pathway (RCP) 8.5 scenario (Ritchie and Dowlatabadi 2017; Schwalm et al. 2020) despite potential shifts to RCP6.0 (Hausfather and Peters 2020) with approximately 3 °C rise in temperatures (Rogelj et al. 2016), the assessment of costs across the full range of possible warming remains essential to inform climate policy. Hence, the goal of this paper is to quantify the economic costs associated with coastal flooding and protection at temperatures rises of ~ 1.5 to 4.0 °C and the implications for adaptation focusing on five coastal countries (Brazil, China, Egypt, Ghana and India) in line with other outputs in this Special Issue (Warren et al. n.d., this Special Issue). These countries were selected to span different levels of development over three continents (Warren et al. n.d., this Special Issue). This is achieved by:

- Assessing how much sea-levels could rise globally from ~ 1.5 to 4.0 °C (Section 2)
- Analysing flood damage and protection costs to 2100 by income group and for the selected countries (Section 3)
- Examining wider implications and responses to coastal flooding in practice (Section 4)

2 How much could sea levels rise globally?

Future SLR projections differ depending on future emissions and the methods employed to generate projections (e.g. Garner et al. 2018; IPCC 2013; Jackson et al. 2018; Kopp et al. 2017; Oppenheimer et al. 2019). Nevertheless, future SLR scenarios with 1.5 and 2.0 °C of warming result in similar projections in 2100 (Goodwin et al. 2018; Hoegh-Guldberg et al. 2018, 2019; Oppenheimer et al. 2019; Jackson et al. 2018; Nicholls et al. 2018). For example, Jackson et al. (2018) found a difference of around 0.06 m in the best estimate of SLR between 2.0 and 1.5 °C scenarios for both semi-empirical and process-based approaches. This 0.06-m difference in best estimate SLR between scenarios is much smaller than the projected uncertainty in SLR for a specified scenario: The 90% SLR uncertainty ranges in 2100 are of order 0.5 m for process-based approaches and 0.8 m for semi-empirical approaches (Ibid.). Importantly, by the end of the century, the mitigated scenarios start to show a decline in the rate of SLR or stabilization, whereas scenarios associated with the highest rises show a strong acceleration in SLR.

This study employed the hybrid SLR projection approach of Goodwin et al. (2018; 2017), combining a process-based treatment of ocean heat uptake and a semi-empirical treatment of global ice melting. This was embedded within a large ensemble of observation-constrained

simulations of the efficient Warming, Acidification and Sea-level Projector (WASP) model (Goodwin 2016). First, global mean temperature anomaly time series were generated for scenarios which reach global warming levels of < 1.5 °C (at 1.4 °C), < 2.0 °C (at 1.8 °C), 2.5 °C, 3.0 °C, 3.5 °C and 4.0 °C in 2100 (Warren et al. n.d., this Special Issue) using the global integrated assessment model IMAGE (van Vuuren et al. 2018) and the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC6) (Meinshausen et al. 2011). The < 1.5 and < 2.0 °C scenarios are pathways that provide a 66% probability of limiting warming to be 1.5 and 2 °C warming respectively, given current uncertainties in climate change modelling. For further details, see Warren et al. ((Warren et al. n.d., this Special Issue). Then, the temperature scenarios were used to force an ensemble of 6.7×10^3 historically constrained WASP simulations after Nicholls et al. (2018). The SLR representations in WASP (Goodwin et al. 2018; Goodwin et al. 2017) were extended by imposing an additional component to SLR corresponding to ice sheet dynamics after the semi-empirical approach of Jackson et al. (2018). This imposed ice sheet dynamics component was varied randomly from 0 to 0.22 m between simulations, independently of the future warming scenario (Ibid.), and linearly applied over the 95 years from 2005 to 2100 (the baseline for SLR in 1986–2005). It should be noted that the SLR component from ice sheet dynamics in the AR5 analysis (IPCC 2013) does not vary greatly between scenarios. However, ice sheet dynamics may cause larger SLR contributions with increased future warming this century (Bamber et al. 2019), and this would likely have the effect of increasing our SLR projections for scenarios with greater warming. Following Brown et al. (2018a), a spatial (regional) pattern of SLR was imposed based on Slangen et al. (2014), based on RCP8.5 for the non-mitigation scenarios, and RCP4.5 for the mitigation scenarios (up to 3.5 °C).

The projections of SLR considered here are shown in Table 1 and Fig. 1. The following results are presented for the 50th percentile, with brackets in text and tables indicating the uncertainty range at the 5th and 95th percentiles. In 2050, the mean SLR ranges from 0.39 m (0.31 to 0.47 m) at < 1.5 °C to 0.41 m (0.32 to 0.49 m) at 4 °C across all scenarios (i.e. the difference in SLR is relatively small). By 2100, larger differences in SLR emerge, ranging from 0.74 m (0.57 to 0.91 m) under the < 1.5 °C scenario to 1.09 m (0.88 to 1.32 m) at 4 °C scenario. However, following the commitment to SLR, Fig. 1b indicates that even if global temperatures decline with successful mitigation (the < 1.5 °C scenario), sea levels will keep rising throughout the twenty-first century. The more stringent the mitigation and the sooner this occurs, the lower the rate of SLR. Whilst not considered here, this trend continues beyond 2100 (Goodwin et al. 2018; Nicholls et al. 2018). Thus, there are increasing benefits of climate change mitigation to coastal areas beyond 2100 (Brown et al. 2018a; Nicholls and Lowe 2004).

Table 1 Temperature with respect to pre-industrial and sea-level rise with respect to 1986–2005 (50th percentile) for the climate change scenarios studied. Sea-level rise in brackets indicate the 5th and 95th uncertainty range. For a full time series, see Supplementary Material Figure SM1

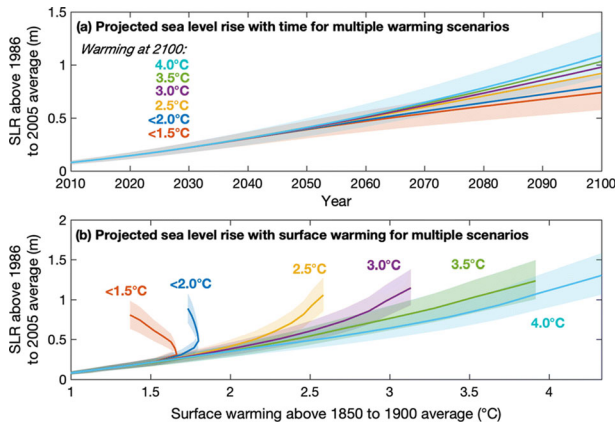|		Climate change scenario					
		< 1.5 °C	< 2.0 °C	2.5 °C	3.0 °C	3.5 °C	4.0 °C
2050	Temperature (°C)	1.65	1.77	1.98	2.06	2.16	2.21
	Sea-level (m)	0.39	0.39	0.40	0.40	0.41	0.41
		(0.31–0.47)	(0.31–0.48)	(0.32–0.48)	(0.32–0.49)	(0.32–0.50)	(0.32–0.49)
2100	Temperature (°C)	1.44	1.76	2.51	2.98	3.54	3.95
	Sea-level (m)	0.74	0.80	0.92	0.98	1.03	1.09
		(0.57–0.91)	(0.63–0.97)	(0.74–1.12)	(0.79–1.19)	(0.83–1.25)	(0.88–1.32)

Fig. 1 Sea-level rise for scenarios of < 1.5 to 4 °C (lines are best estimates, shaded regions are 90% uncertainty)

3 Projected damage and protection costs at World Bank income group and country level

3.1 Methods

Annual sea flood damage costs and annual sea dike capital investment costs due to SLR were analysed using the Dynamic Interactive Vulnerability Assessment modelling framework (DIVA model 2.0.1, database 32) (Hinkel 2005; Hinkel et al. 2014; Vafeidis et al. 2008). DIVA's coast (excluding Antarctica) is represented by 12,148 linear segments (Vafeidis et al. 2008), with each segment having different (but homogeneous per segment) biophysical and socio-ecological characteristics. To determine local relative SLR, a patterned value of SLR is taken (see Section 2) and combined with vertical land movement due to isostatic effects (Peltier 2004), plus vertical land movement (normally subsidence) in 117 of the world's delta (with 39 deltas from Ericson et al. (2006) and the assumed subsidence of 2 mm/year in other major deltas). Extreme water levels and their return periods are from Muis et al. (2016) and were mapped to the coastal segments. Future extreme water levels were assumed to uniformly increase with SLR, following the twentieth century observations (Menéndez and Woodworth 2010). Elevation was derived from the Shuttle Radar Topographic Mission (SRTM) high resolution digital elevation model (Jarvis et al. 2008) and the GTOPO30 dataset (USGS 2015) for areas above 60° N and 60° S, and accounting for topographic changes. SRTM has spatial resolution of approximately 90 m at the equator (30 arc sec). Initial population exposed to flooding is calculated through the Global Rural Urban Mapping Project (GRUMPv1) elevation dataset with a spatial resolution of 30 arc sec (Balk et al. 2006; Center for International Earth Science Information Network - Columbia University (CIESIN) et al. 2011). This provides the spatially explicit population density for the base year per coastline segment. To consider future population (Moss et al. 2010; O'Neill et al. 2014), the base year population is multiplied by a scenario-specific national growth factor depending on the Shared Socioeconomic Pathways (SSP) (IIASA 2015) with 5-year increments from 2015 to 2100 for each SSP (KC and Lutz 2014) (Figure SM2.1). A similar process was employed projecting gross domestic product (GDP).

    DIVA projects impacts by combining the frequency and magnitude of flooding with elevation and population density, taking into account the effects of coastal defences. In the model, dikes were built in the base year (1995, noting this is a different baseline to that for

SLR) according to a demand-for-safety function (based on population density and GDP per capita following Yohe and Tol (2002)). This assumes that there are higher protection levels in coastal zones where there are high population densities and income. Two future scenarios are then analysed: One assumed no additional adaptation and one assumed there will be additional adaptation. Under no additional adaptation, it was assumed that dikes were constructed in 1995 and maintained at this height to 2100, but not raised. Under the with additional adaptation scenario, the level of protection increases with socio-economic change and SLR according to the demand for safety function. Three parameters were analysed:

- Annual sea flood damage costs (US $/year, 2014 prices)
- Annual sea dike investment costs (US $/year, 2014 prices, capital costs only)
- Total annual costs with additional adaptation (i.e. damage costs + investment costs) (US $/year, 2014 prices)

These results presented are indicative of plausible future protection levels, and in reality, the level of future protection provided is likely to be between these scenarios, as there is continued investment in defences. Furthermore, areas with low population density may have greater protection than modelled here, e.g. where high-value, low-lying agricultural land needs protection. New elevation data indicating higher exposure (e.g. Kulp and Strauss 2019) would also lead to changes in protection level. Additionally, our view of adaptation is stylised and based only on protection a greater range of adaptation measures to increase resilience would be expected to occur, but applicability of analysing these at global scales is just starting to be explored (e.g. Aerts 2018). This will be discussed further in Section 4.2.

To compare across similar economies, costs are analysed by World Bank income groups (Section 3.2.1) and then for the five countries (Section 3.2.2). World Bank income groups are defined in Supplementary Material 1 and include the following: (1) high income (OECD), (2) high income (non-OECD), (3) upper middle, (4) lower middle and (5) low income groups (OECD 2019; World Bank 2020). Analysis across such groups provides a greater understanding as to how and why future risks may emerge, and potential responses from groups with similar economic levels. Country-level analysis remains important as income groups can hide significant geographic variations or sub-national responses, as noted in Section 3.2.2. All data are analysed centred around 1995 (as modelled for the coastal protection). Climate scenarios referenced to the mean of 1985 to 2005.

3.2 Annual sea flood damage and sea dike investment costs

3.2.1 World Bank income group costs

Annual sea flood damage costs assuming no additional adaptation, annual sea dike investment costs with additional adaptation and total costs with additional adaptation were analysed with respect to the magnitude of SLR (50th percentile) in Figs. 2, 3 and 4, respectively (for 5th and 95th percentiles, see Figs. SM2.2–SM2.7). As the number of countries in each income group differs, it is important to compare relative change, rather than considering the absolute costs across income groups.

Annual sea flood damage costs assuming no additional adaptation (Fig. 2) indicate that the highest costs in absolute terms are for all upper middle income countries (due to the number and size of countries with respect to current protection levels) at up to $22,000 ($19,000 to
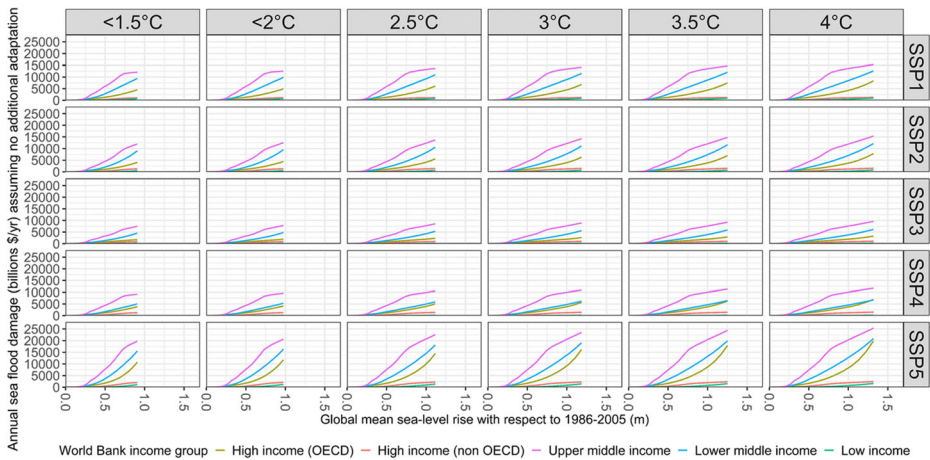
Fig. 2 Annual sea flood damage costs (billions US$/year) assuming no additional adaptation plotted against global sea-level rise, per climate change and socio-economic scenario for World Bank income groups (for the 50th percentile of sea-level rise). No additional adaptation was assumed with respect to the modelled 1995 baseline

$25,000) billion/year in 2100 (SSP5 for the 4 °C scenario), equating to 9.1% of GDP for the group. The lowest projected costs are for the low income group (due to fewer countries and less costly coastal assets) at $97 ($83 to $114) billion/year in 2100 (SSP4 for the < 1.5 °C scenario), equating to 1.2% of GDP. Overall costs are driven more by socio-economic scenario and income groups rather than climate change scenario. Thus, sea flood damage costs assuming no additional adaptation increase throughout the twenty-first century are lowest where there are the least amount of assets at risk or where there are relatively higher protection standards.

Absolute costs are lower under SSP3 as GDP per capita is lower compared with the other SSPs (see Fig. SM2.1). For all income groups, the magnitude of sea flood damage costs
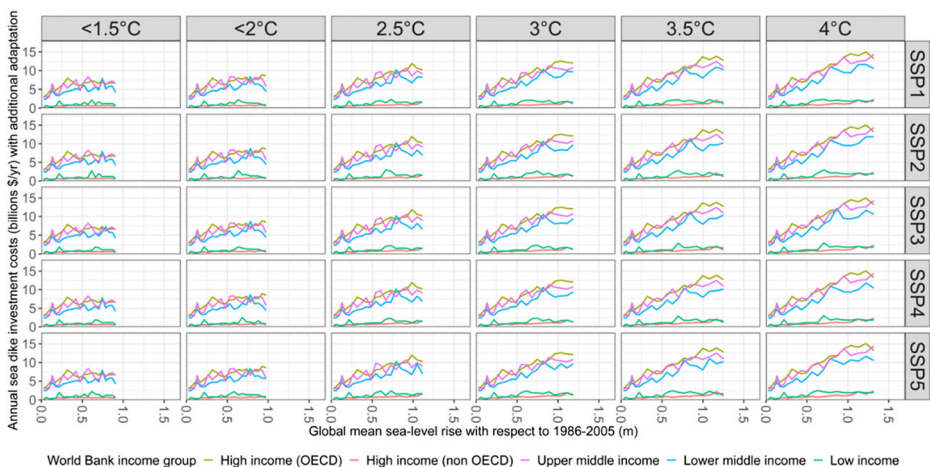

Fig. 3 Annual sea dike investment costs (billion US$/year) with additional adaptation plotted against global sea-level rise, per climate change and socio-economic scenario for World Bank income groups (for the 50th percentile of sea-level rise). Adaptation was assumed with respect to the modelled 1995 baseline
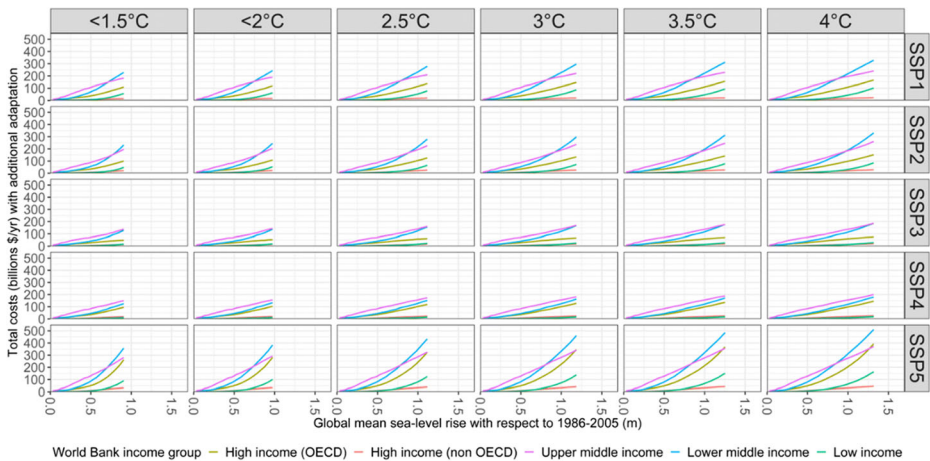
Fig. 4 Total costs (billion US$/year) with additional adaptation plotted against global sea-level rise, per climate change and socio-economic scenario for World Bank income groups (for the 50th percentile of sea-level rise). Total costs represent annual sea flood damage costs with additional adaptation plus annual sea dike investment costs with additional adaptation with respect to the modelled 1995 baseline

assuming no additional adaptation are more dependent on socio-economic scenario, rather than SLR. For the upper middle income group, the rate of increase of annual costs starts to decline with approximately 0.7 m of SLR, which corresponds with a time period of after the 2080s. Costs for the 95th and 5th percentiles of SLR are of a similar order of magnitude, with rates of annual sea flood damage costs assuming no additional adaptation declining with approximately 0.7 m of SLR (see Figs. SM2.2 and SM2.3).

Annual sea dike investment costs with additional adaptation (Fig. 3) are lower at < 1.5 and < 2.0 °C than 4.0 °C as the rate of SLR has declined (in 2100, globally costs are approximately halved with mitigation), where annual cost levels are maintained after approximately 0.3 m of SLR with respect to 1986–2005 (approximately the mid-2030s). Hence, annual sea dike investment costs with additional adaptation start to stabilize when rates of SLR begin to stabilize, as indicated for < 1.5 and < 2 °C scenarios. However, for scenarios where stabilization does not occur, annual sea dike investment costs with additional adaptation continue to rise, and the range of costs also increases. In absolute values, costs are relatively low for the high income (non-OECD) and low income groups as there are only a small number of nations in these groups.

Sea dike investments costs as a proportion of GDP in 2005 (i.e. relative costs, no absolute costs) are highest for low income countries (SSP5 for the 4 °C scenario) at 0.04% (0.02 to 0.04%) and lowest for the high income (non-OECD) group (SSP5 for the 3.5 °C scenario) at 0.003% (0.002 to 0.004%) due to higher levels of GDP. In 2100, the highest sea dike investment costs are projected for the low income group (SSP4 for the 4 °C scenario) at 0.02% (0.02 to 0.02%) of GDP. The lowest relative costs in 2100 are for the high income (non-OECD) group (SSP5 for the 2 °C scenario) at 0.001% (0.001 to 0.001%). Thus overall, regardless of socio-economic scenario, sea dike investment costs remain relatively small. However, it is noted that these are annual values and costs fluctuate due to differing rates of SLR, but similar trends remain when considering longer term averages (e.g. 30-year means). Hence, in contrast to annual sea flood damage costs assuming no adaptation, annual sea dike

costs are more dependent on the magnitude of SLR than socio-economic scenario. Tiggeloven et al. (2020) found a similar result.

The high relative costs experienced by low income groups, suggests a benefit to building to higher defence standards than the modelled baseline. This is particularly notable in the first half of the century. Therefore, to limit flood costs, investment (particularly in lower income countries) needs to be considered in the coming decades (i.e. up to the middle part of the century to allow time to build defences), otherwise, flood costs will increase towards the end of the century. Conversely, the lowest relative sea dike investment costs are projected for the high income (non-OECD) group. This is because there is already a high standard of protection relative to the wealth of these nations.

Total costs with additional adaptation, shown in Fig. 4, are much lower for the mitigation scenarios compared with scenarios with higher temperature rise. In absolute terms, the greatest total costs with additional adaptation are projected for the lower middle income groups in 2100. This is due to a fast rate of growth in GDP, even though there is a declining population after 2050. In relative terms, the greatest total costs with adaptation are projected for the low income group at 0.18% (0.10 to 0.23%) of GDP in 2100 (SSP4 for the 4 °C scenario). The lowest relative costs are projected for the high income (non-OECD) group at 0.06% of GDP (0.05 to 0.07%) in 2100 (SSP5 for the < 1.5 °C). Hence, as the total costs with additional adaptation are mainly comprised of residual flood costs, rather than sea dike investment costs, total costs are more influenced by socio-economic change rather than SLR.

Total costs with additional adaptation as a percentage of GDP are shown in Fig. 5 in 2050 and 2100 per income group for the climate change scenarios (50th percentile) and SSP1–5. The highest percentage cost in terms of GDP is projected for nations with lower income (i.e. the upper middle, lower middle and low income nations). For all SSPs, total costs with additional adaptation increased in 2100 from 2050. Across both time periods, total costs as
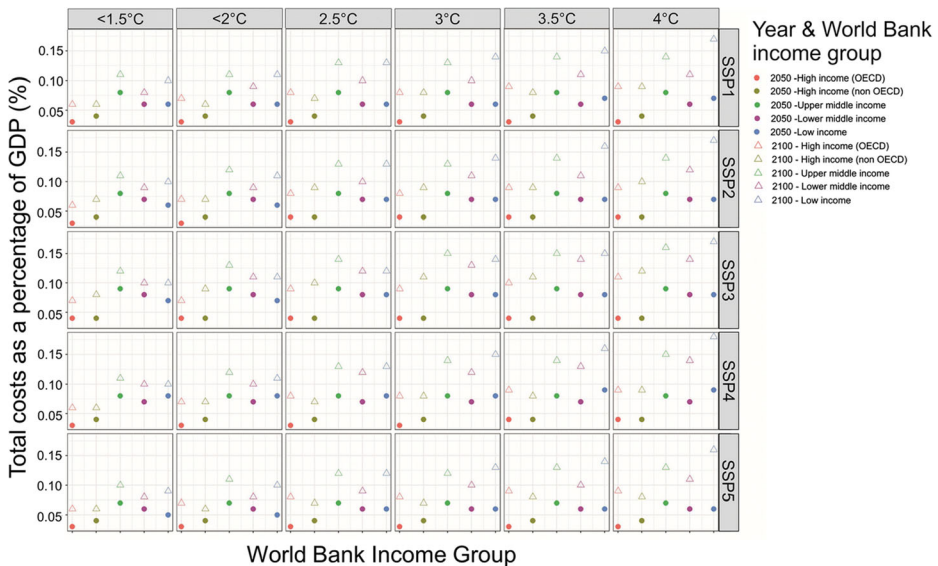

Fig. 5 Total costs with additional adaptation as a percentage of GDP for World Bank income groups in 2050 and 2100, per climate change (for the 50th percentile of sea-level rise) and socio-economic scenario. Total costs represent annual sea flood damage costs with additional adaptation plus annual sea dike investment costs with additional adaptation with respect to the modelled 1995 baseline

a percentage of GDP (for the 50th percentile only) range from 0.03 to 0.18%. Hence, in relative terms, the lower income groups are projected to have the highest percentage of total costs with additional adaptation compared with GDP and will be harder hit than high income groups leading to greater inequality in impacts.

3.2.2 Country level costs

This section highlights regularities and differences in annual sea flood damage costs assuming no additional adaptation, sea dike investment costs with additional adaptation and total costs with additional adaptation, at a country level. Countries in the upper middle (China, Brazil) and lower middle (Egypt, Ghana and India) income groups have different morphologies, topographies, flood plain area and levels of development. Understanding country level risks is useful to determine how adaptation strategies may occur in practice. Country level results are presented under the SSP2 socio-economic scenario (Fig. 6). This scenario was selected as the 'middle of the road' scenario and for compatibility of findings with other climate metrics in this Special Issue (Warren et al. n.d., this Special Issue).

All costs are projected to be higher in 2100 (Fig. 6) than in 2050 (see Fig. SM2.8), although annual costs vary per country. For instance, in Ghana, sea flood damage costs assuming no additional adaptation in 2100 are projected to be $74.4bn at < 1.5 °C ($61.4bn to $87.8bn) and $101.4bn at 4.0 °C ($85.5bn to $118.2bn). Sea flood damage costs assuming no additional adaptation in China in 2100 are significantly larger, ranging from $8903bn at < 1.5 °C ($6865bn to $9904bn) to $10,952bn at 4.0 °C ($9736bn to $12,301bn) compared with the 1986–2005 baseline. Many of the costs will occur even with lower rises of sea level, as would be expected from the < 1.5 °C scenario.

Following previous studies (e.g. Hinkel et al. 2014; Jevrejeva et al. 2018) and evidence presented in Section 3.2.1, costs are significantly reduced by several orders of magnitude through adaptation, with sea dike investment costs significantly smaller than sea flood damage costs assuming no additional adaptation. In 2100, total costs with additional adaptation in Ghana are 98% lower than sea flood damage costs assuming no additional adaptation, costing $1.25bn at <1.5 °C ($1.1bn to $1.5bn) and $1.8bn at 4.0 °C ($1.5bn to $2.4bn). In China, total costs with additional adaptation are 99% lower than sea flood damage costs assuming no additional adaptation, costing $67.8bn at < 1.5 °C ($61.4bn to $74.1bn) and $81.6bn at 4.0 °C ($73.7bn to $91.5bn).

When considered a proportion of national GDP, sea flood damage costs assuming no additional adaptation in 2100 are lowest in Brazil, ranging from 1.1% (0.9–1.2%) at < 1.5 °C to 1.36% (1.2–1.6%) at 4.0 °C. In China, losses range from 15.3 (11.8–17.0%) at < 1.5 °C to 18.8% (16.7–21.1%) at 4.0 °C. In comparison, total costs with additional adaptation are substantially lower. Costs are lowest in Egypt, ranging from 0.03% (0.02–0.03%) at < 1.5 °C to 0.04% (0.03–0.04%) at 4.0 °C, and highest in Brazil, ranging from 0.12% (0.07–0.15%) at < 1.5 °C to 0.17% (0.15–0.23%) at 4.0 °C (see Table SM2.1 for full results). These benefits are particularly large for nations with high population densities in low-lying deltas (including China, Egypt, Ghana and India), as they could be most affected by rising sea-levels.

At the country level, some lower middle income countries, such as Egypt and India, are projected to experience higher sea flood damage costs assuming no additional adaptation than some upper middle income countries, such as Brazil (where the coastal plain is smaller with respect to where people live). In contrast, for total costs with additional adaptation, lower middle income nations were projected to face the greatest losses as standards of protection are
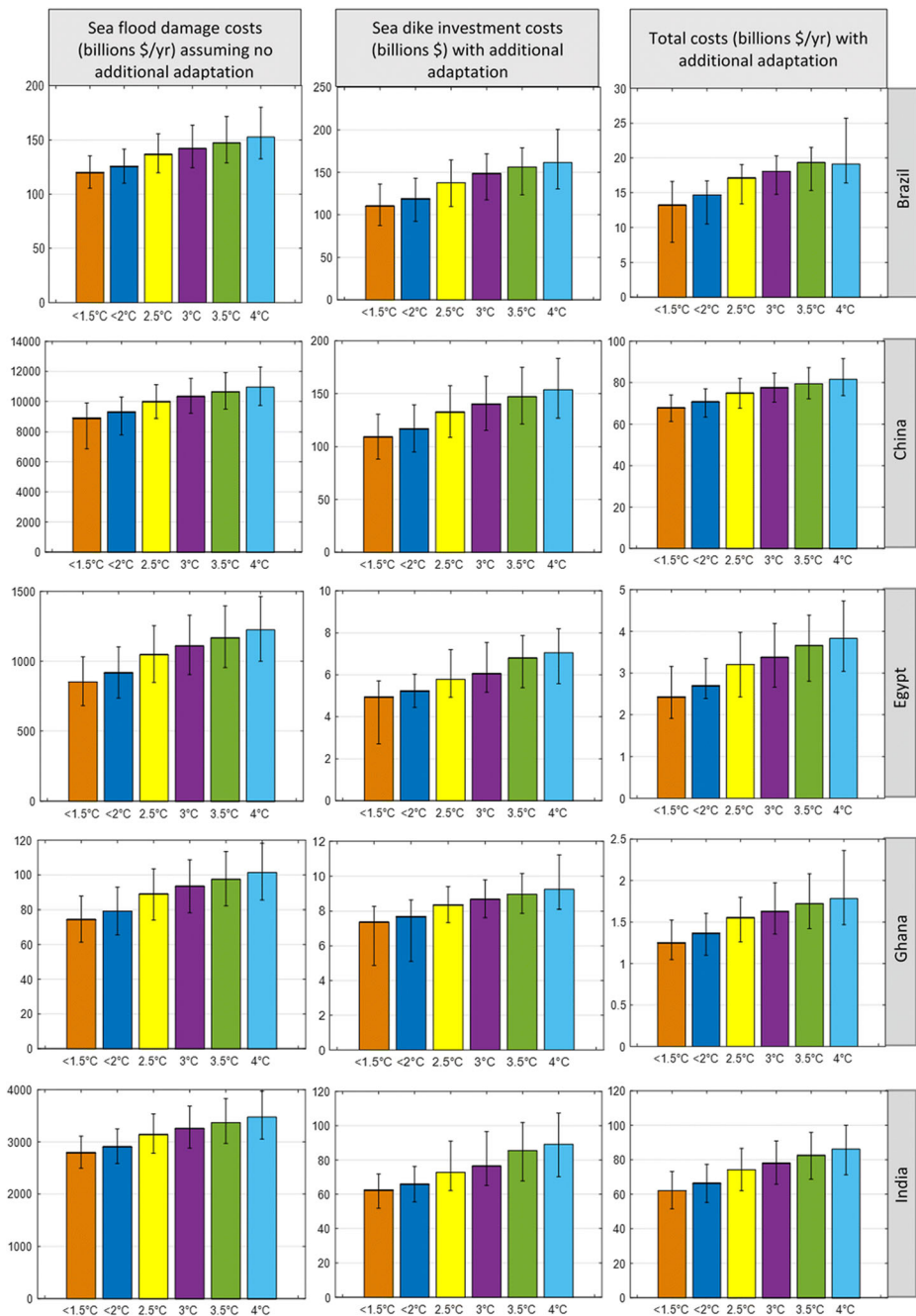
less likely to be sufficient enough to protect against all floods, as indicated for India in Fig. 6. This highlights the importance of understanding of local conditions and knowledge in adapting to SLR.

◀ **Fig. 6** Bar graphs showing country level (i) sea flood damage costs (billions US$/year) in 2100 assuming no additional adaptation. No additional adaptation was assumed with respect to a modelled 1995 baseline; (ii) accumulated sea dike investment costs (billions US$) from 2000 to 2100 with additional adaptation. Adaptation was assumed with respect to a modelled 1995 baseline; and (iii) total costs with additional adaptation (billions US$/year) in 2100. Total costs represent annual sea flood damage costs with additional adaptation plus annual sea dike investment costs with additional adaptation with respect to the modelled 1995 baseline. Results are plotted for each climate change scenario under SSP2. Bars represent the 50th percentile of sea-level rise, with the whiskers representing the 5th and 95th percentiles. Note variable y-axis scale

Figure 6 highlights how the uncertainty in costs at < 1.5 °C (depicted by the whiskers) can overlap with median values under higher warming scenarios for the different countries. Given the overlap in costs, planning for the worst case scenario within any warming scenario, could provide protection for higher levels of warming too. A large proportion of all costs will occur even with scenarios of aggressive mitigation as sea levels will rise under mitigation due to the commitment to SLR. Adaptation, largely through protection, will remain essential. The costs presented here reflect highly ambitious investment in adaptation. In practice, this may not occur or may occur in different ways, such as through raised buildings or early warning systems (see Section 4.2).

Figure 7 presents annual sea flood damage costs assuming no additional adaptation; annual sea dike investment costs with additional adaptation; and total costs with additional adaptation plotted against SLR per country (equivalent from 2000 to 2100), for each climate change scenario (see Figs. SM2.9 and SM2.10 for 5th and 95th percentile). For annual sea flood damage costs assuming no additional adaptation, deviations in costs between the climate scenarios become more noticeable from the 2050s in all countries apart from China, as this is when SLR starts to accelerate and greater deviations are seen between the scenarios. This equates to a range of 0.48 to 0.51 m of SLR in Brazil (for the < 1.5 to 4.0 scenario); 0.48 to 0.44 m to 0.46 m of SLR in Egypt; 0.60 to 0.62 m of SLR in Ghana; and 0.46 to 0.48 m of SLR in India (across a range of timescales from 2050 to 2100). Differences in the range of sea level in each country are due to the regional pattern of SLR. In China, this is not seen as damage costs are already high due significant infrastructure investment and population in large delta regions.

Annual sea flood damage costs assuming no additional adaptation emerge at different rates per country, highlighting potential differences in the need and rate for additional investment. For instance, in China, annual sea flood damage costs assuming no additional adaptation are projected to rapidly increase from around 0.2 m of SLR until approximately 1 m of SLR. For total costs with additional adaptation, costs rise rapidly to approximately 0.6 m, before the rate of rise declines. This indicates that in China, continued and increased investment is needed in the coming decades (where the rate of cost increase is greatest) to have time to adapt. In contrast, annual sea flood damage costs assuming no additional adaptation in Ghana are projected to remain relatively stable for approximately 0.6 m of SLR, before accelerating more rapidly. Even so, for nations that do not have an immediately apparent risk, planning for SLR is still advisable so that unwise decisions are not made today which could lead to increased risk and lock-in for the future. Figure 7 also illustrates the cumulative annual sea dike investment costs with additional adaptation from 2000 to 2100, for the five countries. As noted above, sea dike investment costs are more dependent on the rate of SLR and follow very similar trajectories for the different climate scenarios, although the rate of increase in costs and subsequently final costs in 2100 are lower for the more stringent scenarios. This means that the action needs to occur at a range of paces for the anticipated conditions.
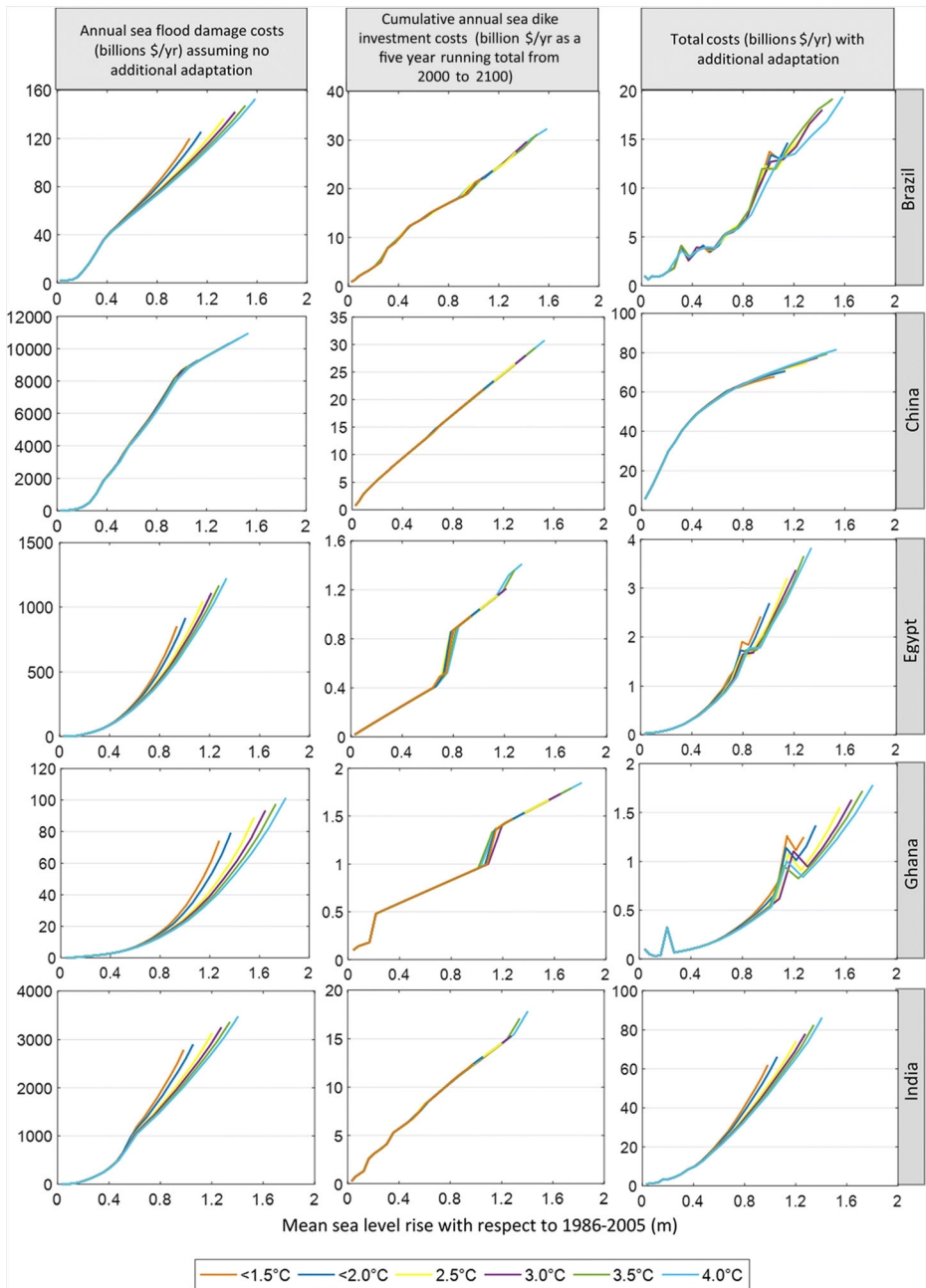
Fig. 7 (i) Annual sea flood damage costs (billions $/yr) assuming no additional adaptation plotted against sea-level rise, per climate change scenario. No additional adaptation was assumed with respect to a modelled 1995 baseline; (ii) cumulative annual sea dike investment costs (billion $/yr as a five year running total from 2000 to 2100) with additional adaptation plotted against sea-level rise, per climate change scenario. Adaptation was assumed with respect to a modelled 1995 baseline; and (iii) total costs (billions $/year) with additional adaptation plotted against sea-level rise, per climate change scenario. Total costs represent annual sea flood damage costs with additional adaptation plus annual sea dike investment costs with additional adaptation with respect to the modelled 1995 baseline. Results are plotted for the 50th percentile of sea-level rise under SSP2

4 Discussion

4.1 Reducing risk

Climate change mitigation, of any magnitude, benefits coastal zones by reducing the rate of SLR, leaving more time to adapt. Globally, avoided SLR (when comparing the 4.0 °C and < 1.5 °C) could be 0.02 m (0.01 to 0.02 m) in 2050 reducing total costs with no adaptation by approximately 5%. By 2100, more significant benefits of mitigation are seen: 0.35 m (0.30 to 0.41 m) of SLR are avoided when comparing the 4.0 °C and < 1.5 °C scenario, reducing global total costs with no additional adaptation by approximately one-quarter under a SSP2 scenario. Even so, for high income countries (or cities regardless of location), flood damage costs could be more substantial due to significant infrastructure investments. However, as a high standard of protection is projected, flood risk may be relatively lower compared with a lower income nation where lower standards of protection have been projected.

These results indicate that for low income countries, damage costs will increase substantially, without significant adaptation investment, particularly as coastal development is likely to increase with national wealth, compounded by the levee effect (increased development behind defences). Protection against flooding will affect a greater proportion of GDP for lower income nations than higher income nations. Hence, lower income nations may invest in defence today or the near future (to allow time to plan and build) to minimize costs later in the century, or spend less now, but face a greater cost later on and rely on emergency response measures. As sea flood damage costs are more driven by socio-economic change than SLR, there are opportunities to minimize costs, but this topic within the climate change field has received limited attention. Furthermore, from an engineering perspective, decisions regarding when to adapt are not so simple in practice. Even if initial funds are available, defences need to be maintained and improved as protections standards decline as sea levels rise.

Costs associated with coastal flooding are financially less equal to income groups with lower income compared with groups with a higher income, which is compounded by developing nations projected to experience more extreme conditions than the global average (Harrington et al. 2016). If significant global climate change mitigation ambition is not achieved, greater inequalities of flood costs between higher income and lower income countries are projected.

4.2 Defending the coast in the long term

Costs presented in Section 3 assume that sea dikes are the only form of protection. With larger rises in sea level, alternative measures of large-scale protection need to be considered, whilst acknowledging that it is not prudent to protect everywhere from a simple benefit-cost view (Lincke and Hinkel 2018), among others. Protection could include storm surge protection barriers, as seen protecting London, UK and the Netherlands, Venice, Italy, St Petersburg, Russia and New Orleans, USA, today. Costs of storm surge barriers range from $0.27 to $3.26 billion/km for capital costs, with maintenance $0.6–$22 million/year (Aerts 2018). Per kilometre of defence (including those presented in Section 3), these costs are substantially higher than dikes, but have the potential to protect a larger area, often in complex morphological estuarine environments, which is why they have been applied in practice. Storm surge barriers have operational limits with SLR as ultimately they have to be closed continuously (Nicholls et al. 2015). Nonetheless, London can be protected up to at least a 5-m rise in sea level (Reeder et al. 2009), but this involves closing the Thames Estuary to

sea and pumping the river flow over a fixed barrier. In Indonesia, the government is concerned that limits to protect the capital, Jakarta, against relative SLR (due primarily to rapid human-induced subsidence), have already been reached leading to suggested relocation to a new city in Borneo (BBC 2019).

Adapting coasts to rising sea level requires planning and preparation, according to when exposure and damage costs will escalate (Section 3.2.2. and Fig. 7). For example, Fig. 7 illustrated that Ghana may have more time to plan adaptation compared with China or Brazil. Coastal adaptation could start to be considered where there is limited long-term management of the coast today, for instance, in Ghana (Sagoe-Addy and Appeaning Addo 2013) or Brazil (Simões et al. 2017), or where coastal planning is already constrained by financial, regulatory and management challenges, such as in Egypt (World Bank 2005), China (Moore 2018) or India (Black et al. 2017). Other nations face similar challenges.

For coastal zones that cannot afford or do not want protection and must live with the inevitable rise, change ideally needs to happen slowly in a controlled way so that adjustments can be made as the situation evolves, rather than reacting as an emergency response measure. This could include shifting from hard defences sooner to soft defences or to greater use of accommodation measures and ultimately retreat (Haasnoot et al. 2019). For more densely populated areas, these adjustments may include land raising or raised infrastructure (Oppenheimer et al. 2019). As socio-economic change is also significant having greater effect on costs than the magnitude of SLR itself, land use planning offers important opportunity to adapt, particularly where future assets that demand protection have not yet been built, such as emerging, growing cities. For instance, Neumann et al. (2015) note significant projected growth in many coastal cities such as Lagos, Luanda, Chennai and Tianjin.

4.3 Cross-cutting issues

The five countries analysed have challenging coastlines to manage due to extensive low-lying areas and densely populated coastal zones (Brazil has less people in the flood plain so is slightly less at risk). As with other low or middle income countries (Satterthwaite et al. 2007), their capacity to adapt is often limited by financial constraints, knowledge or data or at times a lack of technical expertise. Whilst the results in Section 3.2.2 have focused on defence, adaptation also needs to be considered for natural ecosystems, agriculture and aquaculture, in the context of sustainable development. Typical challenges include the following:

- The need for a portfolio of adaptation approaches, including ecosystem natural based approaches (e.g. mangroves which attenuate waves energy) or soft adaptation (e.g. nourishment). Further research is needed to explore the full benefits of mangroves as natural protection strategy (Menéndez et al. 2020; Du et al. 2020) as coastlines evolve with SLR.
- Greater recognition of land subsidence or uplift in contributing to relative SLR and response. Subsidence is most enhanced due to groundwater withdrawal, which may be rapid in agriculture and urban areas. In many deltas (e.g. Nile, Pearl, Yangtze, Sao Francisco, Ganges-Brahmaputra), subsidence may pose a greater risk than eustatic SLR (Syvitski et al. 2009). Locally, subsidence management can be as important as adapting to eustatic SLR alone (Kaneko and Toyota, 2011; Nicholls et al. 2021).
- Damming and removal of sediment from rivers or the shoreface (e.g. Volta delta, Ghana) can lead to an increased likelihood of flooding, erosion of beaches and degraded natural

protection (Ly 1980; Gyau-Boakye 2001; Bendixen et al. 2019; Joevivek and Chandrasekar 2013; Saintilan et al. 2020). This challenge transcends national boundaries and livelihoods; thus, goals of enhancing livelihoods and climate action need to be carefully balanced (Brown et al. 2018b).

- Land reclamation has been extensive along many coastlines, especially in Asia (e.g. Shanghai, Tianjin) (Sengupta et al. 2018). At times, this may be at lower elevations than the original land area or was constructed without consideration of SLR. It is increasingly undertaken with the loss of coastal ecosystems (Oppenheimer et al. 2019) that no longer offer full protective function. Raising land as a form of adaptation is an emerging issue (Brown et al. 2020) that may become more widespread.

These issues reflect important trade-offs and competing demands for resources. Decisions around large-scale adaptation strategies require substantial support and years or decades to plan, develop and implement (in Fig. 7, losses increase steeply after ~ 0.2-m rise in 2025, so planning in Brazil or China may need to start earlier than other nations). In this case, an increased focus on disaster response rather than risk reduction measures is needed. Whilst not necessarily the most cost-effective path, there is evidence that many countries allocate significantly more funds to disaster response than risk reduction measures such as coastal defences (OECD 2019). For instance, Huang et al. (2020) report that the disaster prevention and mitigation work in China's coastal cities primarily pays attention to the emergency response during the disaster. Similarly in Brazil, it is reported that governments tend to concentrate on emergency response and recovery and have been slow to adopt an integrated disaster prevention and preparedness approach (Leal Filho et al. 2018). Hence, preparing to adapt and act on rising sea-levels is likely to be a slow process or given less of a priority, particularly when risks are not yet apparent.

4.4 Study uncertainties

In recent years, there have been increased global efforts to improve the coverage and accuracy of digital elevation models, by reducing vertical errors and higher resolution (Schumann and Bates 2018). Methods include comparison of SRTM derived data with Light Detection and Ranging (LIDAR) data, national elevation datasets and interferometric synthetic aperture radar (InSAR) datasets (Sanders 2007; Kulp and Strauss 2019). In places, these indicate significant variations in flood area, and therefore those exposure to flooding. This may mean that changes to local defence standards may be required earlier or later than projected here. Whilst highly populated areas will always demand protection regardless of socio-economic scenarios analysed, towns with medium to low population densities may consider different pathways and methods of adaptation.

This study also assumed protection levels proportional to levels of GDP at segment level, yet protection levels vary for a wide range of reasons (Tiggeloven et al. 2020), such as local governance levels, types of protection, economics, funding, insurance and resources. With continued SLR, questions may be asked to how much protection standards can be maintained or raised, and when retreat may be the only option (Haasnoot et al. 2019). Furthermore, in some localities, there is a greater emphasis on emergency response, rather than protection standard. Hence, further research on types and standards of protection plus other response measures would be welcomed.

Elevation and standards of protection are just two major uncertainties in global modelling. Population density, especially coastward migration, is also uncertain. Using regionalised coastal projections (e.g. Merkens et al. 2018) may enhance projections. Local effects of SLR

and coastal processes (e.g. sediment movement) also play a significant role in coastal flood risk (Cazenave and Le Cozannet 2014) as can local subsidence (Nicholls et al. 2021). Furthermore, finer scale modelling can enhance impacts (Wolff et al. 2016) and/or provide a more detailed explanation as to how impacts can evolve.

5 Conclusion

With rising emissions and global mean temperatures, sea levels are projected to rise, even under temperature stabilization scenarios. Climate change mitigation is beneficial as it reduces the rate of SLR, leaving a longer time window to adapt. SLR raising extreme water levels has the potential to cause significant damages, so adaptation remains essential. Using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework, six climate change scenarios from < 1.5 to 4.0 °C were analysed with five socio-economic scenarios (Shared Socioeconomic Pathways 1–5) throughout the twenty-first century for the World Bank income groups and selected countries. The following conclusions were drawn:

- Under scenarios of < 1.5 and < 2.0 °C, 0.74 m (0.57 to 0.91 m) and 0.80 m (0.63 to 0.97 m) of global mean SLR is projected respectively in 2100, and for higher rises of 3.5C and 4.0 °C, 1.03 m (0.83 to 1.25 m) and 1.09 m (0.88 to 1.32 m) are projected, respectively.
- When comparing the 4.0 °C scenario with the < 1.5 °C, 0.35 m (0.30 to 0.41 m) of SLR could be avoided in 2100. This reduces total costs with no additional adaptation globally by approximately one-quarter under a SSP2 scenario.
- In absolute terms and across all climate change and socio-economic scenarios, annual sea flood damage costs assuming no additional adaptation in 2100 are projected to be highest for the upper middle income group (equating to 9.1% of GDP) and lowest for the low income group (equating to 1.2% of GDP). Costs are more dependent on socio-economic development than the magnitude of SLR.
- Annual sea dike investment costs with additional adaptation are roughly constant after approximately 0.3 m of SLR with respect to 1986–2005 (approximately the mid-2030s) under the most stringent mitigation scenarios but will accelerate under the non-mitigation scenarios reflecting accelerating SLR. Costs are more dependent on the magnitude and rate of rise, rather than socio-economic development.
- For nations with lower income, total costs with additional adaptation as a proportion of GDP are projected to be lower in 2100 than 2050 as investment is required to increase protection standards today. If defences are built now, long-term damage costs can be reduced. If not, a greater investment is needed for emergency response measures. Flood costs across World Bank income groups will become more unequal with SLR.
- For the five countries studied, the greatest annual sea flood damage costs assuming no additional adaptation are projected for China ranging from $8903bn at < 1.5 °C ($6865bn to $9904bn) to $10,952bn at 4.0 °C ($9736bn to $12,301bn). They are lowest in Ghana, ranging from $74.4bn at < 1.5 °C ($61.4bn to $87.8bn) to $101.4bn at 4.0 °C ($85.5bn to $118.2bn).
- Adapting to SLR takes time, and this can be under-appreciated, particularly for areas where costs may rise steeply due extensive flood plains and low standards of protection.
- Protection by hard defence is analysed here. However, a broader range of adaptation needs to be considered in the context of wider development and sustainability issues. Flexible

investment options, including their planning and management, are particularly important given continued SLR into the twenty-second century and beyond.

Author contribution RW conceived the wider project in this Special Issue and experimental design of the climate scenarios including country level selection. PG ran and analysed the sea-level rise scenarios and wrote the corresponding section of the manuscript. SB ran and analysed the DIVA simulations and wrote much of the manuscript with KJ, with both contributing ideas to the structure and vision of the paper. DL, RN, RT and AV contributed through input in the DIVA model and analysis of an early version of the manuscript, with ASA, SJ and IH. RJ assisted with country level analysis.

Data Availability For outputs from figures, see supplementary material.

Code availability Not available as it also belongs to third parties.

Declarations

Conflict of interest The authors declare no competing interests.

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