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The effects of adaptation and mitigation on coastal flood impacts during the 21st century. An application of the DIVA and IMAGE models

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Abstract This paper studies the effects of mitigation and adaptation on coastal flood impacts. We focus on a scenario that stabilizes concentrations at 450 ppm-CO_2-eq leading to 42 cm of global mean sea-level rise in 1995–2100 (GMSLR) and an unmitigated one leading to 63 cm of GMSLR. We also consider sensitivity scenarios reflecting increased tropical cyclone activity and a GMSLR of 126 cm. The only adaptation considered is upgrading and maintaining dikes. Under the unmitigated scenario and without adaptation, the number of people flooded reaches 168 million per year in 2100. Mitigation reduces this number by factor 1.4, adaptation by factor 461 and both options together by factor 540. The global annual flood cost (including dike upgrade cost, maintenance cost and residual damage cost) reaches US$ 210 billion per year in 2100 under the unmitigated scenario without adaptation. Mitigation reduces this number by

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factor 1.3, adaptation by factor 5.2 and both options together by factor 7.8. When assuming adaptation, the global annual flood cost relative to GDP falls throughout the century from about 0.06 % to 0.01–0.03 % under all scenarios including the sensitivity ones. From this perspective, adaptation to coastal flood impacts is meaningful to be widely applied irrespective of the level of mitigation. From the perspective of a some less-wealthy and small island countries, however, annual flood cost can amount to several percent of national GDP and mitigation can lower these costs significantly. We conclude that adaptation and mitigation are complimentary policies in coastal areas.

1 Introduction

The increase of mean and extreme sea levels due to climate change threatens the world's coastal zones with a range of impacts including increased flooding, permanent inundation of low-lying coastal areas, increased erosion of beaches and cliffs, degradation of coastal wetlands and salinisation (Nicholls et al. 2007). Questions on how effective mitigation and adaptation are in reducing coastal and other impacts are central to the current climate policy debate (van Vuuren et al. 2011). With the emerging global political consensus to limit global warming to 2 ° the effectiveness of stringent mitigation that stabilizes greenhouse gas (GHG) concentrations at 450 ppm CO_2-eq or lower is of particular importance (van Vuuren et al. 2008).

Few impact studies have, however, assessed the impacts of low-stabilization scenarios using dedicated climate and impacts models and taking into account adaptation. Most impact assessments have been carried out with climate projections based on the Special Report on Emission Scenarios (SRES; Nakicenovic and Swart 2000) of the Intergovernmental Panel on Climate Change (IPCC), which do not consider mitigation policy. Exceptions within the coastal sector are Nicholls and Lowe (2004) and Tol (2007) who explore the effects of mitigation on coastal impacts by considering scenarios that stabilize GHG concentrations at 550 ppm and 750 ppm CO_2-eq. Both of these assessments are, however, based on simple damage functions taken from Hoozemans et al. (1993), which do not explicitly take into account the spatial distribution of assets and population across different elevation levels.

This paper explores how effective mitigation and adaptation measures are in reducing coastal flood impacts, as possibly the most important impact of sea-level rise with widespread and potentially significant consequences for coastal populations. The assessment is carried out using two connected modeling systems. We use IMAGE to generate scenarios representing socio-economic development, climate change and sea-level rise, which are subsequently fed into the DIVA model to assess coastal flood impacts. We focus on a no-mitigation scenario leading to about 64 cm of global mean sea-level rise in the period 1995–2100 (about 4 °C global mean temperature increase in 2100 compared to pre-industrial) and a mitigation scenario that stabilizes concentrations at 450 ppm CO_2-eq leading to about 42 cm of global mean sea-level rise in the period 1995–2100 (about 2 °C global mean temperature increase in 2100 compared to pre-industrial). Note that this paper should not be interpreted as a full cost-benefit analysis of mitigation and adaptation. The benefits of mitigation are only evaluated in terms of reducing coastal flood impacts. If other avoided climate impacts are accounted for the benefits of mitigation are obviously much larger.

The remainder of the paper is organized as follows. Section 2 describes the development of the socio-economic, climate and sea-level rise scenarios with the IMAGE model. Section 3 describes the DIVA model and Section 4 presents the coastal impacts attained. Section 5 discusses the results and Section 6 concludes.

2 Scenario development

The IMAGE 2.4 model is used here to create a set of consistent scenarios representing socio-economic development, climate change and sea-level rise which are then used to drive the DIVA model. The scenarios are described in full detail by van Vuuren et al. (2011). The IMAGE 2.4 Integrated Assessment model (Bouwman et al. 2006) consists of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change. It includes a slightly adapted version of the MAGICC-4 climate model (Wigley and Raper 2001).

In this study, we use only one socio-economic development pathway, because this paper focuses on the effects of mitigation and adaptation and not on the uncertainty of baseline projections. The socio-economic development pathway used reflects medium estimates. Population growth for 21st century is based on the UN projections, which are lower than those used for the development of the SRES scenarios (van Vuuren et al. 2007). Economic growth lies between those of the SRES B1 and B2 scenarios (Fig. 1).

The first scenario (termed BAU hereafter) describes a "business-as-usual" world that develops according to medium assumptions, without any policy efforts towards mitigation of climate change and leading to 4 °C increase in 2100 compared to pre-industrial and 64 cm of global mean sea-level rise in 1995–2100. Autonomous technological progress and the worldwide diffusion of goods and services result in a partial convergence between world regions in terms of, among others, per capita income and energy consumption levels.

The second scenario is a stringent mitigation scenario (termed 450 ppm hereafter) corresponding to the ambition to limit global mean temperature increase to no more than 2 °C compared to pre-industrial levels and leads to 42 cm of global mean sea-level rise in 1995–2100. Using a best-guess value for climate sensitivity, staying below 2 °C requires a stabilisation of greenhouse gas concentrations in the atmosphere at around 450 ppm CO_2eq. den Elzen and van Vuuren (2007) have shown that allowing for a limited overshoot (here to 510 ppm CO_2eq) implies that temperature targets can be achieved at lower costs. Still, even with such an overshoot emissions would need to peak around 2020 and subsequently decline to zero (or lower) by the end of the century to achieve the 2 °C target (den Elzen and van Vuuren 2007; Meinshausen et al. 2009).

As a third scenario, we also consider a less stringent mitigation scenario, aiming at 550 ppm CO_2eq (termed 550 ppm hereafter). This scenario has around a 0-40 % probability of staying below 2 °C (Meinshausen et al. 2006).

In the BAU scenario annual emissions increase from around 10 GtC-eq today to 25 GtC-eq in 2100 and as such it forms a medium scenario in the full range of scenarios without climate policy

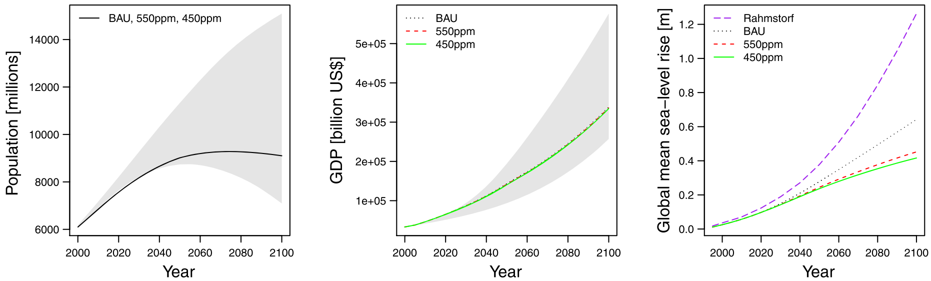

Fig. 1 Global population (left), GDP (middel) and global mean sea-level rise (right) under the scenarios considered in this study. Shaded areas indicate the SRES scenario ranges for global population and GDP

published in the literature. The 450 ppm and 550 ppm scenarios require significantly lower greenhouse gas emissions. In 2100, the reductions amount to about 80 % compared to the BAU scenario for the 550 ppm case and 90 % for the 450 ppm case. Emission reduction is achieved in various ways. One element is increased energy efficiency. Other measures are increased use of non-fossil energy sources, particularly bio-energy and reduction of non-CO_2 GHG emission. Carbon capture and storage is applied in stationary fossil fuel uses. In the short term, also some emission reduction is achieved by switching from coal and oil use to natural gas. For a more detailed discussion of the scenarios see van Vuuren et al. (2011).

The IMAGE modeling framework is also used to calculate the mitigation costs, i.e. the additional annual expenditures to reduce greenhouse gas emissions. While mitigation costs are zero in the BAU scenario, they amount to 0.9 % and 1.4 % of global GDP in 2050 for the 550 ppm and 450 ppm scenario, respectively. In 2100, these costs are 0.5 % and 0.7 % of global GDP, respectively. These costs estimates are subject to uncertainty regarding technology development and the assumed possibilities for substitution – but are in the range of other costs estimates (van Vuuren et al. 2007).

The macro-economic costs of mitigation are estimated using a simple macro-economic model in the IMAGE modeling framework (the so-called FAIR model, see Hof et al. 2008). In these calculations, the regional macro-economic impacts are based on assuming full emission trading after an initial allocation of emission rights on the basis of a per capita convergence regime in 2050. In 2050, the macro-economic impacts of stabilizing at 550 ppm CO_2-eq reduces GDP growth compared to BAU by 1.0 % for the 550 ppm CO_2-eq scenario, and by 1.9 % for the 450 ppm CO_2-eq scenario, respectively.

Note that the macro-economic costs indicated here only capture mitigation costs. In order to fully capture the macro-economic costs of the scenarios, other cost estimates would need to be included such as the coastal damages to global GDP development. This would, however, require a consistent modeling system that fully couples the climate policy costs with regional sea-level rise impacts and adaptation. Such a system that includes the detail of the DIVA system is currently not available. It is clear that diverting funds to mostly non-productive adaptation measures could severely impact regional and global economic growth (Hallegatte and Ghil 2008).

Finally, for sensitivity analysis we also include a sea-level rise scenario (termed Rahmstorf hereafter) that was derived independently from IMAGE, based on Rahmstorf (2007) and leading to 126 cm global mean sea-level rise in the period 1995–2100. A number of recent papers using semi-empirical and other approaches have suggested that a global mean sea-level rise of up to 2 m in the 21st century cannot be ruled out due to a potential large contribution of the melting of the ice sheets of Greenland and Antarctica (see Nicholls et al. 2010b). IMAGE and other climate models currently do not included this effect due to a lack of robust physical models capturing ice sheet discharge. We include the Rahmstorf scenario to give some indication on how the effects of mitigation relate to the uncertainty in global mean sea-level rise associated with the melting of the large ice sheets.

3 Coastal flood impact and adaptation assessment

Population, GDP, temperature change and sea-level rise scenarios developed with the IMAGE model as described above are used to drive the DIVA model. DIVA is an integrated model of coastal systems that assesses biophysical and socio-economic impacts of sea-level rise, socio-economic development and adaptation (http://www.diva-model.net; DINAS-COAST Consortium 2006; Hinkel and Klein 2009). DIVA uses a dedicated global coastal database that divides the world's coast into 12,148 variable length coastal segments (Vafeidis et al. 2008). This paper uses the DIVA model version 3.4.0 together with the DIVA database version 1.8.0, which is based on elevation data and coastal area extents derived from the Shuttle Radar Topography Mission (SRTM) digital elevation model (Rabus et al. 2003; http://srtm.usgs.gov/).

DIVA first downscales the global mean sea-level rise calculated by IMAGE to relative sea-level rise by combining the sea-level rise scenarios with the vertical land movement. The latter is a combination of glacial-isostatic adjustment according to the geo-physical model of Peltier (2000) and a uniform 2 mm/year subsidence in deltas. Human-induced subsidence (due to ground fluid abstraction or drainage) is not considered due to the lack of consistent data or scenarios.

The flooding of the coastal zones caused by mean sea-level rise and associated extreme water level events (e.g., storm surges, tropical cyclones) is assessed for sea floods and the lower reaches of 115 major rivers (river floods). Extreme water level probability distributions are displaced upwards with the rising sea level, as there is no clear evidence that climate change will further alter the distributions. Analysis of global tide gauge datasets shows an increase in extreme high water levels since 1970 worldwide, but also shows that mean sea-level rise is the major factor for this increase (Menendez and Woodworth 2011). For tropical cyclones specifically, a trend towards more intense hurricanes can be detected over the past 35 years, but the data records are not long enough to attribute this trend to climate change as opposed to climate variability (Webster et al., 2005; Knutson et al. 2010). Global modeling studies project a 2–11 % increase in mean maximum wind speeds of tropical cyclones by 2100 and a 6–34 % decrease in globally averaged frequency (Knutson et al. 2010). Contrary to this, some downscaled modeling studies project increases in frequency (e.g., Bender et al. 2010). Irrespective of these uncertainties, it is unknown how increases in wind speed would translate into increases in extreme water levels.

Despite the lack of evidence, increased storminess in terms of an increase of extreme water levels beyond mean sea-level rise is a concern in particular for tropical cyclones due to the potential high damages associated with it. We therefore include, as sensitivity analysis, a modified BAU simulation with increased storminess (termed BAU + S). Due to the lack of evidence discussed above, we follow Nicholls et al. (2010a) and arbitrarily increase extreme water levels of the 1-in-10, the 1-in-100 and the 1-in-1000 year events by 10 %, 20 % and 30 % respectively, in 2100 compared to 2000 for areas subject to tropical cyclones.

The social damage of flooding is assessed in terms of the expected number of people subject to annual flooding (people flooded). For the calculation of these population numbers, the Gridded Population of the World dataset has been used (CIESIN, CIAT 2004). For the economic damage of flooding we only focus on direct cost in the form of expected annual damage caused by sea and river floods based on a damage function logistic in flood depth. Both assessments take into account dikes. Since there is hardly any empirical data on actual defense levels or other adaptation around the world, we model this assuming the defenses are provided by dikes. Dike heights were estimated for the base year of 1995 using the demand function for safety described below. The indirect damages in terms of disruption of economic growth are not considered. These might be significant, in particular for poor countries and major events (Hallegatte et al. 2007).

DIVA takes a stylized view of adaptation based on protection via dikes following earlier studies (e.g., Hoozemans et al. 1993; Fankhauser 1995; Yohe et al. 1996; Nicholls 2002; Nicholls and Lowe 2004). Without adaptation, potential impacts are assessed in a traditional impact analysis manner. Dike heights are maintained, but not raised, so flood risk increases with time as relative sea level rises. With adaptation, dikes are raised following a demand function for safety which was derived econometrically based on data of protection levels, GDP, population density and dike costs taken from Hoozemans et al. (1993). This function is increasing in per capita income and population density, reflecting that as societies grow richer and population density increases, the demand for safety rises and higher dikes are built (Tol 2006). A threshold of 1 person per square kilometer is assumed below which no dikes are built. Dike costs include capital cost of building and upgrading dikes as well as maintenance costs, which are assumed to be 1 % of capital cost for sea-dikes and 0.5 % for river-dikes, following Nicholls et al. (2010a). The unit costs of dikes are based on data from DELTARES and are assumed to be constant over time and linear in dike height.

It should be noted that many more adaptation options are available including protection via "soft" measures such as mangrove or dune rehabilitation as well as retreat (e.g., establishing set-back zones, relocating settlements to higher elevated land and restricting coastal development) and accommodation (e.g., flood resilience for buildings and development of agriculture using salt-resistant crops) strategies (Klein et al. 2001). DIVA as well as the above mentioned earlier studies focus on protection via hard structures, because other, in particular "softer" options are difficult to simulate at broad scales and cost estimates are less developed. Even for coastal protection via hard defenses only stylized adaptation models can be built as coastal protection is a public good whose provision involves collective action amongst various decision makers at different levels. The dynamics of such socio-institutional processes cannot be captured "realistically" in a global and quantitative model. Many factors play a role in this kind of adaptation, an important one being when a coastal population last experienced a major flood event (Hinkel et al. 2009).

We apply DIVA to each of the five scenarios described above (450 ppm, 550 ppm, BAU, BAU+S, Rahmstorf) once with adaptation (symbolized as 450 ppm+AD, 550 ppm+AD, etc.) and once without adaptation (symbolized as 450 ppm+NO, 550 ppm+NO, etc.).

4 Coastal flood impacts

This section presents the flood impacts in terms of the expected number of people flooded per year (people flooded) and the annual flood cost. We define the annual flood cost as the sum of the incremental annual costs of upgrading and maintaining dikes and the residual damage cost in terms of the expected annual damage cost caused by flooding. It is worth noting that coastal flooding is an existing problem due to a variety of causes, and hence climate change and sea-level rise, socio-economic development and adaptation modify this issue, as shown below.

4.1 Global level

Without adaptation, the number of people flooded increases during the 21st century and reaches between 117 million people per year (1.3 % of the global population) under the lowest sea-level rise scenario (450 ppm + NO) and 262 million people per year (2.9 % of the global population) under the highest sea-level rise scenario (Rahmstorf + NO) in 2100 (Fig. 2). Increased storminess (BAU + S + NO) increases the number of people flooded by 5 % in 2100 compared to BAU + NO. With adaptation, these figures are about two orders of magnitude smaller and actually fall during the century. This reflects that as societies become wealthier during the century, their demand for safety grows and dikes are raised which in turn more than compensates for the higher damage potential caused by rising sea levels.

Compared to 168 million people flooded per year in 2100 under the "business as usual" case (BAU + NO), stringent mitigation (i.e. 450 ppm + NO) reduces the number of people flooded by factor 1.4, adaptation (i.e. BAU + AD) by factor 461 and both options together

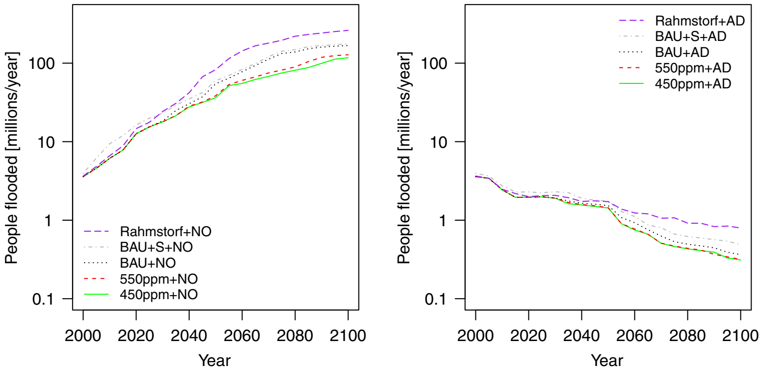

Fig. 2 Global annual number of people flooded without adaptation (*left*) and with adaptation (*right*). People flooded is in log space

(i.e. 450 ppm + AD) by factor 540. Without adaptation, the effects of mitigation become more visible over time, given the inertia in the climate system (including sea-level rise) and associated inertia in policy response. Note that without adaptation, the impacts are growing with time under all scenarios, including the most stringent mitigation. With adaptation, the numbers of people flooded hardly differ between the five scenarios.

The annual cost of coastal flooding (defined as annual adaptation cost plus residual damages cost) at the global level grows throughout the century under all simulations. In 2100, global cost are estimated to US$ 164–300 billion per year under the simulations without adaptation and US$ 27–93 billion per year under the simulations with adaptation (Fig. 3). Compared to an estimated global cost of US$ 210 billion per year in 2100 under the “business as usual” case (BAU + NO), adaptation (i.e. BAU + AD) reduces cost by factor 5.2, mitigation (i.e. 450 ppm + NO) by factor 1.3 and both options together (i.e. 450 ppm+AD) by factor 7.8.

Global annual flood cost relative to global GDP increases from about 0.01 % at the beginning of the century to between 0.05 % under 450 ppm + NO and 0.09 % under Rahmstorf + NO, if no adaptation measures are taken (Fig. 4). If adaptation measures are taken the relative annual flood costs fall during the century from levels around 0.06 % at

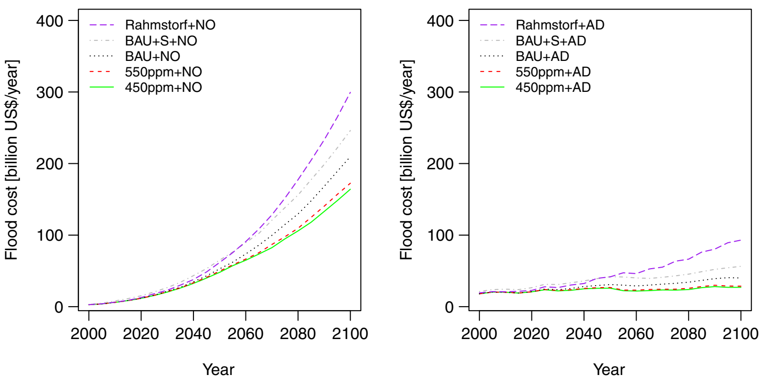

Fig. 3 Global annual cost of flooding (comprising dike upgrade, dike maintenance and residual flood damage cost) without adaptation (*left*) and with adaptation (*right*)

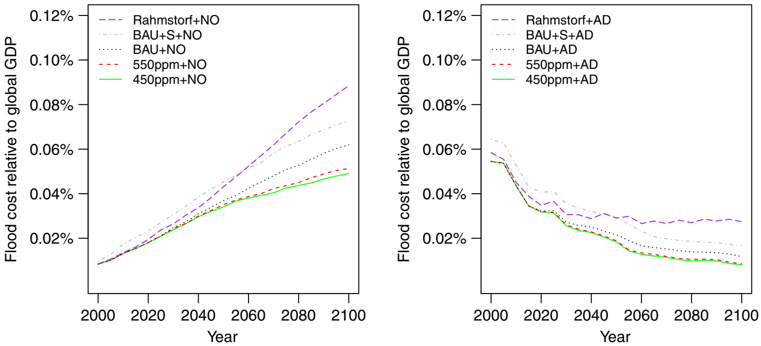

Fig. 4 Global annual cost of flooding (comprising dike upgrade, dike maintenance and residual flood damage cost) as fraction of global GDP without adaptation (*left*) and with adaptation (*right*)

the beginning of the century to levels below 0.02 % for all scenarios except the high-end Rahmstorf scenario in which relative costs stabilize at about 0.03 % by the end of the century. At the beginning of the century, costs are higher under the simulations with adaptation compared to those without, because of high initial investments that need to be made in coastal protection.

4.2 Country level

The relative number of people flooded, that is the fraction of national population flooded at least once per year, ranges between 0.0001 % and almost 20 % for the coastal countries in 2100 under the BAU scenario if no adaptation measures are taken. The group of countries most affected under the BAU + NO simulation in 2100 includes Small Island Developing States (SIDS) such as the Marshall Islands (14 % of national population flooded annually), the Maldives (11 %) and Kiribati (5 %). Other highly affected countries are the densely populated, low-lying and deltaic ones such as Kuwait (18 %), Viet Nam (18 %), Guinea-Bissau (14 %), Mozambique (11 %), Myanmar (10 %) and Bangladesh (7 %).

With adaptation, the number of people flooded relative to national populations is generally about two orders of magnitude smaller compared to the simulations without adaptation and lies below 0.2 % for all countries in 2100. This means that, in accordance with the global picture, adaptation offers an effective response to flooding risks for most countries from a non monetary perspective.

Countries also differ significantly in terms of their annual flood costs relative to national GDP. Without adaptation, the countries most affected under the BAU scenario are again the SIDS as well as other low lying countries such as the Philippines (0.5 % of GDP), the Netherlands, Vietnam and Thailand (0.3 % of GDP each). With adaptation, the most affected countries under the BAU scenario are Kiribati (8.6 % of GDP), Solomon Island (7.1 % of GDP), Vanuatu (5.6 % of GDP) and Tuvalu (4.8 % of GDP). For these and other SIDS, the annual flood costs are higher under the simulations with adaptations compared to those without, which shows that from a pure monetary perspective (i.e., disregarding people flooded) adaptation in the form of building dikes as simulated here does not offer an efficient response. These countries cannot afford such an adaptation strategy without external financial support. The benefits of mitigation in terms of reducing relative annual flood costs, however, are also high for SIDS. Stringent mitigation (i.e. the 450 ppm+AD) reduces relative annual costs in 2100 for Kiribati by 4.1 % of national GDP, for the Solomon Islands by 3.3 % of national GDP, for Vanuatu by 2.7 % of national GDP and for Tuvalu by 2.3 % of national GDP compared to the unmitigated simulation (BAU+AD).

5 Discussion

The results presented above suggest that for most countries adaptation (in this paper characterized as hard flood defenses) is an efficient approach to reduce the costs of coastal flooding independent from the level of mitigation. When adaptation measures are taken, sea-level rise actually becomes "less of a problem" through the century as with increasing global wealth the fraction of GDP that is lost in terms of flood damage and that needs to be spent on dike upgrade and maintenance decreases globally. Combining adaptation with mitigation measures brings additional benefits. Generally, the global effects of mitigation are small to 2050 due to the slow response of sea-level rise to global warming. The magnitude of coastal impacts increases mainly due to growing population and wealth. In the second half of the century, the differences between scenarios with and without mitigation become significant.

From the perspective of some developing countries, in particular SIDS and poor countries with densely populated deltas, mitigation remains crucial. Some of these countries are facing growing flood damages and protection costs in the order of several percent of national GDP, which can only be reduced by mitigation. Failure to mitigate would increase damage costs significantly, and it would transfer the costs of the current economic activities to future generations. Irrespective of the level of mitigation, these countries will need financial support to make the necessary investments in adapting to climate-induced sea-level rise. It is also important to note that sea levels will continue to rise for centuries beyond 2100 due to the large time scales of ocean warming and the melting of the large ice sheets and that only mitigation can reduce the risks of these long-term impacts.

The global results of this paper are broadly similar to previous studies, although the numbers are difficult to compare due to the different assumptions and scenarios used. Nicholls and Lowe (2004) assess impacts in terms of people flooded, but with a larger coastal population scenario, lower global mean sea-level rise scenarios and disregard river flooding. Crucially, the authors assume improving sea defenses due to growing wealth, which this paper does not assume under the "no adaptation" simulations. Hence, the estimates of people flooded according to Nicholls and Low (Nicholls and Lowe 2004) are lower than the ones given here. These authors find that under an unmitigated (medium climate sensitivity) scenario that leads to about 58 cm sea-level rise in the 2110 s about 140 million people are estimated to be flooded every year if no adaptation to sea-level rise takes place. The benefits of mitigation are estimated to be greater than in this paper: Stabilization at 550 ppm reduces the number of people flooded by factor 2 in 2110. Tol (2007) finds, in accordance with our paper, that the benefits of adaptation are significant in that they reduce impacts by factors 10 to 100. The benefits of mitigation are smaller than estimated here: Stabilizing emissions at 550 ppm reduces global economic impacts by about 10 % in 2100.

This paper did not consider the trade-offs involved in reducing flood risk through coastal protection via hard defenses. Natural or artificially constructed barriers prevent the inland migration of coastal habitat when sea-level is rising leading to a loss of intertidal habitat through coastal squeeze (Nicholls et al. 2007; McFadden et al. 2007). This may lead to further ecological consequences such as the loss of abundance and diversity of macro invertebrates, which reduces the ability of coasts to support current populations of shorebirds (e.g., Dugan and Hubbard 2006). Furthermore, coastal armouring in one location may have negative consequences on other locations as reduced long-shore sediment transport through protection measures may increase both flooding and erosion risk at other locations (e.g., Dawson et al. 2009). These trade-offs and processes need to be further explored at local scales.

The purpose of this paper was to give a global overview of coastal flood impacts and to show how global and national perspectives with respect to mitigation and adaptation policy may differ. In many ways it confirms earlier work that adaptation and mitigation should be considered complimentary policies in the coastal zone (Nicholls et al. 2007): adaptation is needed to deal with the inevitable rise (and other socio-economic drivers of risk) and mitigation is needed to make sure that the rise is kept to a manageable magnitude. Future work should explore impacts and adaptation in more detail for specific regions and countries, in particular in Small Islands States and deltas as highlighted in this paper. A larger variety of coastal adaptation strategies including "soft" protection measures as well as accommodate and retreat strategies need to be considered as well as post-2100 changes. Future work also needs to consider the current adaptation deficit in that many countries or regions are not adapted to the current climate and sea-level variability, which has not been consider in this study. While this has not been assessed in great detail, preliminary analysis, for example for Africa (Hinkel et al. 2011) shows that many developing countries are facing a high current adaptation deficit and this may constitute a major barrier to coastal adaptation.

6 Conclusions

We presented an assessment of the effects of mitigation and adaptation on coastal flood impacts using the two connected modeling systems IMAGE and DIVA. Under the simulations without adaptation, the number of people flooded increases substantially during the century from about 4 million per year in 2000 to 117–262 million per year in 2100 for the range of scenarios considered here. With adaptation the number of people flooded is two orders of magnitude smaller and falls during the century, because the increase in wealth makes building dikes increasingly more cost-effective and compensates for the rise in sea level. Compared to the impacts under the IMAGE no-mitigation scenario without adaptation, stabilizing emissions at 450 ppm reduces the number of people flooded in 2100 by a factor of 1.4, adaptation by a factor of 461 and both options together by a factor of 540.

The annual cost of coastal flooding grows under all simulations throughout the century and reaches US$ 164–300 billion per year under the simulations without adaptation and US$ 27–93 billion per year under those with adaptation. Compared to impacts in 2100 under the IMAGE no-mitigation scenario without adaptation, mitigation reduces annual flood costs by a factor of 1.3, adaptation by a factor of 5.2, and both options together by a factor of 7.8. The global annual flood cost expressed as fraction of global GDP increases throughout the century when assuming no adaptation and falls when assuming adaptation under all sea-level rise scenarios considered here.

From the perspective of most countries, these figures suggest that, independent of the level of mitigation, protection through dikes is meaningful to be widely applied. While significant investments are needed, they seem to be affordable at the global scale. This does, however, not provide an argument to policy-makers to favor adaptation over mitigation, because such an argument would need to consider all damages avoided through mitigation in all relevant sectors, as well as the consequences of sea-level rise and other impact beyond 2100. Furthermore, for some less-wealthy countries, in particular Small Island Developing States, annual costs of flood damage and adaptation can amount to several percent of GDP and only mitigation can lower these costs significantly. Hence, from the point of view of these most affected countries as well as from a precautionary point of view, mitigation remains crucial. We conclude that adaptation and mitigation should be seen as complimentary policies for coastal areas.

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