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Long-term sea-level rise necessitates a commitment to adaptation: A first order assessment

Marjolijn Haasnoot[a,b,*,1], Gundula Winter[a,2], Sally Brown[c,e,3], Richard J. Dawson[d,e,4], Philip J. Ward[f,5], Dirk Eilander[a,f,6]

[a] Deltares, Delft, Boussinesqweg 1, 2629 HV Delft, the Netherlands
[b] Utrecht University, Department of Geosciences, Princetonlaan 8a, Utrecht, the Netherlands
[c] Department of Life and Environmental Science, Bournemouth University, Poole, Dorset BH12 5BB, UK
[d] School of Engineering, Newcastle University, Newcastle upon Tyne NE3 4BD, UK
[e] Tyndall Centre for Climate Change Research, UK
[f] Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1111, 1081 HV Amsterdam, the Netherlands

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A B S T R A C T

Without adaptation, sea-level rise (SLR) will put more people at risk of flooding. This requires a timely and adequate commitment to adaptation. In this paper, we show how adaptation needs to unfold over time to manage climate-induced SLR. We use a novel scenario-neutral approach, applied globally and subsequently combined with SLR and population scenarios, to assess when, where, and how fast to adapt up to 2150. As rates of SLR accelerate, adaptation needs to occur at an increasing pace or at a larger scale. While it is certain that adaptation will be necessary, it is uncertain when and how fast. After only ~ 0.15 m SLR relative to 2020, 1 million people need to adapt to permanent submergence and the amount of people at risk of a 100-year flood increases with 21% to 83 million people. This would occur in the next 30 (20–45) years for RCP4.5 and within 25 (18–36) years under RCP8.5, assuming no change in protection or population. The uncertainty in timing increases with higher SLR, albeit for some impacts it can still a matter of time. Population at risk of a 100-year flood doubles after 0.75 m SLR which could occur by ~ 2080 (2068–2088), 2100 (2085–2130), or 2150 (2115-beyond 2150) under a high-end, RCP8.5, or RCP4.5 scenario respectively. The rate, at which the risk increases, differs strongly per country. In some countries an additional 1–5 million people of the present population will be at risk of a 100-year flood within the next two decades, while others have more time to adapt but will see rapid growth of risk past 2100. Combining SLR impacts with projected population change further increases the number of people at risk of a 100-year flood by ~13% between 2040–2060 (under both RCP8.5-SSP5 and RCP4.5-SSP2). This can be managed through protecting, floodproofing or limiting developments in high-risk areas. A commitment to adaptation is inevitable to maintain risk at present levels. With increasing warnings of the potential for accelerated SLR due to rapid

* Corresponding author at: Deltares, Delft, Boussinesqweg 1, 2629 HV Delft, the Netherlands.
E-mail address: Marjolijn.haasnoot@deltares.nl (M. Haasnoot).
[1] 0000-0002-9062-4698.
[2] 0000-0002-7455-1687.
[3] 0000-0003-1185-1962.
[4] 0000-0003-3158-5868.
[5] 0000-0001-7702-7859.
[6] 0000-0002-0951-8418.

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ice sheet melt, adaptation may need to happen faster and sooner than previously anticipated which can have consequences for how to adapt. Failure to acknowledge the potential and long-term (including beyond 2100) adaptation commitment in development and adaptation planning may lead to a commitment gap and subsequently expensive retrofitting of infrastructure, creation of stranded assets, and less time to adapt at greater cost. In contrast, considering the long-term adaptation commitment can support timely adaptation and alignment with other societal goals.

1. Introduction

Low-lying coastal regions contain fertile ground, host logistics hubs, and generate approximately $1tn of the world's wealth (Kirezci et al., 2020). Approximately 11% (~900 million people) of the global population currently live within 10 m above mean sea level (see Table S1 in supplementary materials). Coastal flood risk increases in many locations due to coastal development, sea level rise (SLR), storm surge change, and local subsidence (Neumann et al., 2015; Brown et al., 2018; Oppenheimer, 2019; Vousdoukas et al., 2018; Tiggeloven et al., 2020; Nicholls et al., 2021; Arns et al., 2017). Global action to reduce greenhouse gases could reduce future SLR impacts by trillions of dollars (Nicholls et al., 2018; Jevrejeva et al., 2018). However, even ambitious emissions reduction cannot reverse the commitment to SLR (Mengel et al., 2018; Clark et al., 2018; Levermann et al., 2013). While rates of SLR beyond 30 years are uncertain, it is clear that some SLR is inevitable, which will necessitate adaptation assuming most coastal inhabitants do not accept an increase in risk. Just as increased greenhouse gas emissions or even a stabilization of global temperatures lock-in a SLR commitment (Clark et al., 2018; Levermann et al., 2013), that in turn requires an adaptation commitment to contain flood risk; meaning that some form of adaptation will need to be considered. This commitment to adaptation has been acknowledged already in the IPCC 3rd assessment (Watson, 2001; Nicholls and Lowe, 2004), but so far the pathways and regional implications of this commitment have not been assessed.

Past studies (see Table S2 in supplement and (McMichael et al., 2020) for an overview) suggest that global coastal flood risk will increase 2–3 orders of magnitude by the end of the century (Oppenheimer, 2019) depending on the climate and socio-economic scenarios, the datasets used for elevation and population (Hinkel et al., 2014; Kulp and Strauss, 2019), assumptions on coastal protection (Tiggeloven et al., 2020) and the approach for inundation modelling (Vafeidis et al., 2017). Adaptation through coastal protection has been shown to have a positive benefit-cost ratio for 13% of the global coastline across futures with a low to high SLR, accounting for 90% of the population and 96% of the assets in the floodplain (Lincke and Hinkel, 2018).

These past studies have typically focused on potential impacts and adaptation benefits for a fixed epoch within the 21st century (e.g., Brown et al., 2018; Nicholls et al., 2018, Jevrejeva et al., 2018, Hinkel et al., 2014, Kulp and Strauss, 2019). Whilst this quantifies the magnitude of change in impacts between current and future epochs, it does not provide insights into the pathways taken for these potential impacts to occur. Consequently, this misses important information on the timing and rate of change of risk that is essential for adaptation planning. For instance, a different strategy would be required, under a gradual increase of risk over a century than if risk change starts slowly and then changes rapidly within one or two decades. The latter can occur due to a rapidly accelerating SLR (e.g. under RCP8.5) but can also occur as a result of local topography, protection and development when large areas get exposed (e.g. deltas). An assessment of rate of impacts has been done at local scales up to 2100 (Kulp and Strauss, 2017). Moreover, impacts extend beyond 2100 (Brown et al., 2018) due to SLR commitment (Mengel et al., 2018; Clark et al., 2018; Levermann et al., 2013), which means that the need for adaptation also extends beyond 2100. Limiting climate risk analysis to 2100 may impede the detection of rapid increase of risk beyond 2100. These far away, long-term impacts have implications for near-term decisions due to (1) the high inertia and path-dependency of coastal adaptation and development choices that may open, foreclose or trigger follow-up decisions, (2) the long lead time for adaptation planning and implementation, and (3) the typically long design life and societal impact of adaptation measures, especially protection (e.g., Ürge-Vorsatz et al., 2018; Sadoff et al., 2015; Haasnoot, 2020).

This study aims to understand the adaptation commitment to SLR at global to regional scales. In particular, we aim to understand how the adaptation needs to SLR unfold over time, and to assess the implications of these for adaptation decision making. This is supported by a new assessment of the adaptation challenge that coastal inhabitants face in terms of the timing, location and rate of change of the population at risk of coastal flooding to address the shortcomings of previous assessments described above. We start with a scenario-neutral approach (Kwadijk et al., 2010; Ranger et al., 2013; Broderick et al., 2019) to stress-test the system and then integrate the results with SLR and population change scenarios to explore time-dependent impacts up to 2150. As an indicator of the adaptation commitment, we analyse the population at risk of permanent submergence, i.e. when mean sea level exceeds the present level of protection. At this threshold, some form of adaptation– whether to relocate people, modify urban areas, or accept daily inundation – becomes inevitable. We also assess the population at risk of a 10 and 100-year flood (typical indicators for coastal flood risk studies (McMichael et al., 2020) and defining adaptation standards (Tiggeloven et al., 2020), assuming present day coastal defence crest levels. We then assess when thresholds of risk (Stephens et al., 2018) (in terms of people at risk) are exceeded to derive a first order assessment of when, and how rapidly, countries will need to adapt. We use this to explore the implications for adaptation pathways (Haasnoot et al., 2013) for structural adaptation (i.e. engineered, nature-based and technological options). Information on when, where, and how fast adaptation needs to take place is necessary to identify initial (low-regret) measures (e.g., Haasnoot et al., 2013; Barnett et al., 2014) and long-term options to prepare for future risk. Uncertainties in the timing and rate of the people affected by coastal flooding arise not only from uncertainties about future emissions and the related impacts of SLR, the contribution from ice sheets to SLR, and population changes as explored in this study, but also from other uncertainties (e.g. in the system representation) such as the elevation model, regional relative SLR as a result of local subsidence, extreme sea level estimates, the flood modelling approach and adaptation responses.

In this study we focus on the concept of adaptation commitment and uncertainties in climate-induced SLR. We also assess the sensitivity for population change and discuss how population change scenarios affect the timing of impacts. We acknowledge that other drivers can have a large influence on such analyses, especially at the local level. Our results should therefore be considered as a first order assessment of the adaptation commitment over time.

2. Methods

Our analysis comprises two main stages. First, we stress-test the system following a scenario-neutral approach (Broderick et al., 2019), based on (Kwadijk et al., 2010), that calculates flood risk change conditional on global mean sea level and population change (Section 2.1). This provides insight into the Global Mean SLR (GMSLR) range under which large changes may occur and allows for a relatively easy update of the results when new SLR projections become available. Such scenario-neutral analyses are increasingly applied to evaluate climate impacts on water and environmental systems (Broderick et al., 2019), but so far have not been applied globally. Second, we analyse the timing of the flood risk changes and their implications for adaptation using different SLR scenarios up to 2150 and SSP scenarios up to 2100 (Section 2.2). Supplement Fig. S1 provides a comprehensive flow diagram of the approach.

2.1. Coastal flooding and population at risk (scenario-neutral)

2.1.1. Coastal flooding

Sea level boundary conditions under current and future SLR scenarios are calculated for each country, or sub-national, unit where available.

$$SL_i = GMSLR_i + ESL_{RP,i} + \Delta_i - \varepsilon_{MSL,i} \tag{1}$$

where SL_i is the sea level at unit i, $GMSLR_i$ is the global mean sea level rise value, $ESL_{RP,i}$ is the extreme sea level due to tide and surge for a given return period derived from the global tide and surge reanalysis (GTSR version 2.0) dataset (Muis et al., 2016). The GTSR contains sea levels for various return periods assuming a Gumbel distribution of extreme sea levels for the period 1974–2014. Tides for this reanalysis were retrieved from the FES2012 model that has a grid resolution of 1/16° and performs data assimilation with satellite altimetry data. Surge levels were generated with the Global Tide and Surge Model (GTSM) using the Delft3D Flexible Mesh software developed by Deltares. The model has a globally varying grid resolution, which is refined to ca. 5 km along the coast. The model is forced with wind and atmospheric pressure data from the ERA-Interim dataset by The European Centre for Medium-Range Weather Forecasts (ECMWF). The spatial (0.75°) and temporal (6 h) resolution of the meteorological forcing smooth out extreme pressure and wind speed gradients so that extreme sea levels are slightly underestimated particularly in the tropics where cyclones are prevalent. Δ_i is the 'sea level rise fingerprint' that accounts for spatial variability in SLR around the world. It is calculated by scaling the sea level rise fingerprint of the 95th percentile RCP8.5 SLR scenario in 2085 normalised by its GMSLR of 0.65 m, as derived from a study (Slangen et al., 2014) that includes ice-sheet contributions. We acknowledge that SLR fingerprints are different for the various SLR components and can change over time (Palmer, et al., 2020; Perrette et al., 2013). To follow the scenario-neutral approach we use a time-independent scaling approach to include SLR fingerprints as was done by Perrette et al. 2013 (Perrette et al., 2013). We therefore chose a SLR fingerprint for the middle (2085) of the time frame considered in this paper (2020–2150). The 95%-percentile is used to be able to scale up to SLR values of 3 m. $\varepsilon_{MSL,I}$ is the vertical deviation of mean sea level from the EGM96 (Earth Gravitational Model, 1996) (Rio et al., 2014) to be consistent with the vertical datum of the DEM.

We use the multi-error-removed improved-terrain digital elevation model (MERIT DEM Yamazaki et al., 2017) which has been shown to be a Global DEM that provides a good predictor of flood extent (McClean and Dawson, 2020; Hawker et al., 2018). Global elevation data is expected to further improve, building on recent advances (e.g. CoastDem (Kulp and Strauss, 2019), AW3D30 Global Digital Surface Model (Almar et al., 2021), subsidence data (Nicholls et al., 2021)), in particular with recent LiDAR data (Hooijer and Vernimmen, 2021). Although the original MERIT DEM has a resolution of 3 arc-seconds (~90 m at the Equator), we use 30 arc-seconds (1x1km at the Equator) to allow for a computational expensive inundation modelling of many SLR increments and population changes, and to be consistent with many previous coastal flood risk studies (see Table S3). Subsidence and global glacial–isostatic adjustment are not included in the analysis because both processes are time-dependent and their inclusion is not compatible with our scenario-neutral approach, which uses a SLR fingerprint to relate GMSLR to regional SLR to derive flood risk change and is independent of the timing of SLR projections. As subsidence can have a major influence (Nicholls et al., 2021), for example in the Mekong delta (Minderhoud et al., 2017), we have assessed the possible effect of subsidence for this Delta, providing a possible template for many other densely populated river deltas with large subsidence rates. Further, the possible effect of climate change on storm surge statistics and wave set-up is not included in the SLR fingerprint but could locally add to flood risk change. Compound flood risk due to concurrent coastal, pluvial and/or fluvial flooding has also not been considered.

Inundation maps of flood depth per grid cell, D_n, are produced using a geographic information system-based inundation model that takes into account water level attenuation and is forced by SLi (Tiggeloven et al., 2020). Unlike a simple 'bathtub' model, which is regularly used in global scale studies (See Table S3) but typically overestimates inundated area in the coastal zone (Kirezci et al., 2020; Vafeidis et al., 2017), this model uses a maximum attenuation factor of 0.5 m km^{-1} consistent with other studies (Tiggeloven et al., 2020; Vafeidis et al., 2017; Haer et al., 2018). This factor is linearly scaled to account for spatial variation in roughness based on the proportion of permanent water features in a grid cell (Tiggeloven et al., 2020; Haer et al., 2018), where no attenuation is applied to cells with 100% permanent water. As global mean sea level rises, permanent water features change so that for each SLR scenario the permanent water map was updated with submerged cells.

2.1.2. Coastal flood protection

Coastal protection standards, defined as return periods for each sub-country unit (Tiggeloven et al., 2020) are based on the modelling approach proposed in the FLOod PROtection Standards (FLOPROS) database (Scussolini et al., 2016). Defences are assumed to be maintained and to protect against any inundation at or below the return period in FLOPROS. As we aim to assess the need for adaptation, we assume no further adjustments are made. We simulate flooding at return periods of 1, 2, 5, 10, 25, 50, 100, 250 and 500 years without flow attenuation. We then linearly interpolate the flood depths for the FLOPROS return period per grid cell, FP_n, which describes the maximum flood depth that protection can withstand in each grid cell *n*. At local scale, additional safety margins can exist on top of the protection standards (e.g. + 0.1 to + 0.5 m on a levee). As, to our knowledge, safety margins are unreported at global scale, they are not further included in our analysis. We assume a simple flood defense mechanism: inundation occurs where $D_n > FP_n$, i.e. sea levels exceed the height of the protection and the protection breaches. However, in practice protection may also fail and breach when the water is below the protection height and may also only overtop and not breach and thereby still reduce the flood extent and depth. We calculate inundation depths accounting for the current standard of flood protection in each grid call $D_{n,FP}$, and flood depths where there is no flood protection, $D_{n,0}$.

2.1.3. Impacts to population at risk

Impacts are calculated for GMSLR between 0 and 3 m (at 0.00 m, 0.10 m, 0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m, 1.50 m, 2.00 m, 2.50 m and 3.00 m) and for extreme water levels for return periods (RP) of 0, 10 and 100 years that account for tides and storms. We refer to this as the SLR-impact functions. We have used the mean sea level to derive a minimal adaptation commitment to permanent submergence, while in some regions the impacts of frequent flooding as a result of high tide could already be a strong reason to adapt. A global population database (WorldPop (CIESIN), 2018), gridded at ~ 30 arc-seconds (1 km resolution), is used to assign present day population to each DEM grid cell, both datasets use the WGS84 projection so no additional translation is required. For all grid cells with flood depth, $D > 0$, we evaluate: (i) the area of land and population affected, by locations that are permanently submerged; and (ii) area of land, and people inundated, by return period. Land is considered to be submerged if mean sea level at the shoreline exceeds both flood protection level and land elevation (z) i.e. $SL_i > \max(z, FP_i)$. We distinguish between people potentially exposed to flooding (not accounting for current protection) and people at risk due to the absence of coastal flood protection from flooding (where current protection standards are exceeded). The number of exposed people is thus always higher than the number of people at risk.

Impacts in terms of the number of people exposed/at risk are aggregated for sub-country units (https://gadm.org/), countries, World Bank regions (WorldBank regions), as well as globally. Small countries with a total area less than 25 km (Neumann et al., 2015) are not reported individually in the country assessment but are included in the aggregated regional and global analysis. To account for potential population dynamics a sensitivity analysis was done for population change on top of the SLR impacts.

2.2. Timing using sea level rise and socio-economic scenarios

We integrated the SLR-impact functions from the scenario-neutral analysis with time series of different SLR scenarios to calculate the timing and rate of impacts and to understand the implications thereof for adaptation. We use the median and likely range of SLR timeseries from the recent IPCC SROCC (Oppenheimer, 2019) scenarios from 2020 to 2150 for two Representative Concentration Pathways (RCP): RCP4.5 and RCP8.5 corresponding with a stabilization scenario and a high emission scenario (Table 1). We use 2150 as a time horizon, instead of 2100 that is used in many other SLR impact studies (Supplement Tables S2 and S3), to enable the assessment of consequences for adaptation decisions with a long legacy. For coastal adaptation decisions the (societal) lifetime ranges from decades to hundreds of years (Haasnoot et al., 2020). We linearly interpolate between our SLR-impact functions to calculate the time series of impacts to be expected under an IPCC SROCC SLR scenario. We set the GMSL to zero in 2020 so that no population or area may be exposed to permanent submergence when the population is mapped.

We also compute impacts and their timing for two high-end scenario from Bamber et al. (2019) (B19) and Kopp et al. (2017) (K17) that account for deeply uncertain but possible rapid SLR due to accelerated mass-loss from Antarctica based on (DeConto and Pollard,

Table 1
Sea level rise projections (m relative to 2020), median values and likely range (p17-p83).

	RCP4.5			RCP8.5		
	2050	2100	2150	2050	2100	2150
IPCC SROCC (Oppenheimer et al., 2019)	0.15 (0.08–0.21)	0.47 (0.30–0.64)	0.71 (0.47–0.97)	0.18 (0.11–0.26)	0.76 (0.52–1.02)	1.37 (0.89–1.93)
Kopp, 2017	0.19 (0.11–0.29)	0.84 (0.59–1.18)	1.65 (1.14–2.65)	0.24 (0.15–0.33)	1.39 (1.02–2.03)	4.02 (3.10–5.40)
Bamber et al., 2019	0.19 (0.11–0.29)	0.58 (0.38–0.87)	n.a.	0.25 (0.17–0.38)	1.02 (0.70–1.65)	n.a.

2016). Although B19 is a more recent projection it only goes up to 2100, while the K17 is available up to 2150. Other projections exist, including a further stabilization of the temperatures under RCP2.6, which would result in lower SLR compared to RCP4.5 in particular beyond 2100. We focus on RCP4.5 and RCP8.5 to allow for a comparison with the available SLR estimates that account for rapid mass-loss from Antarctica (referred as RCP4.5+ and RCP8.5+).

We assess the effectiveness of adaptation strategies that restrict development in the areas at risk (e.g. no-build zones), by determining the influence of future population change. We use projections for the coastal zone (under the Shared Socio-economic Pathways (SSP) 2 and 5 by Merkens et al. (2016). Similar to the SLR impacts, we first calculated impacts of population change as the stress-test in our scenario-neutral analysis and then derive the time dependent impacts for each sub-country region using a scaling factor relative to the population in 2020 based on the projected change in population per 5 years (Merkens et al., 2016). Supplement S3 presents the average scaling factors per World Bank region (Fig. S-2). We combine SSP2 with RCP4.5 and SSP5 with RCP8.5, following the Coupled Model Intercomparison Project (CMIP) 6 practice (O'Neill et al., 2016). Because no SSP scenarios for gridded population exist beyond

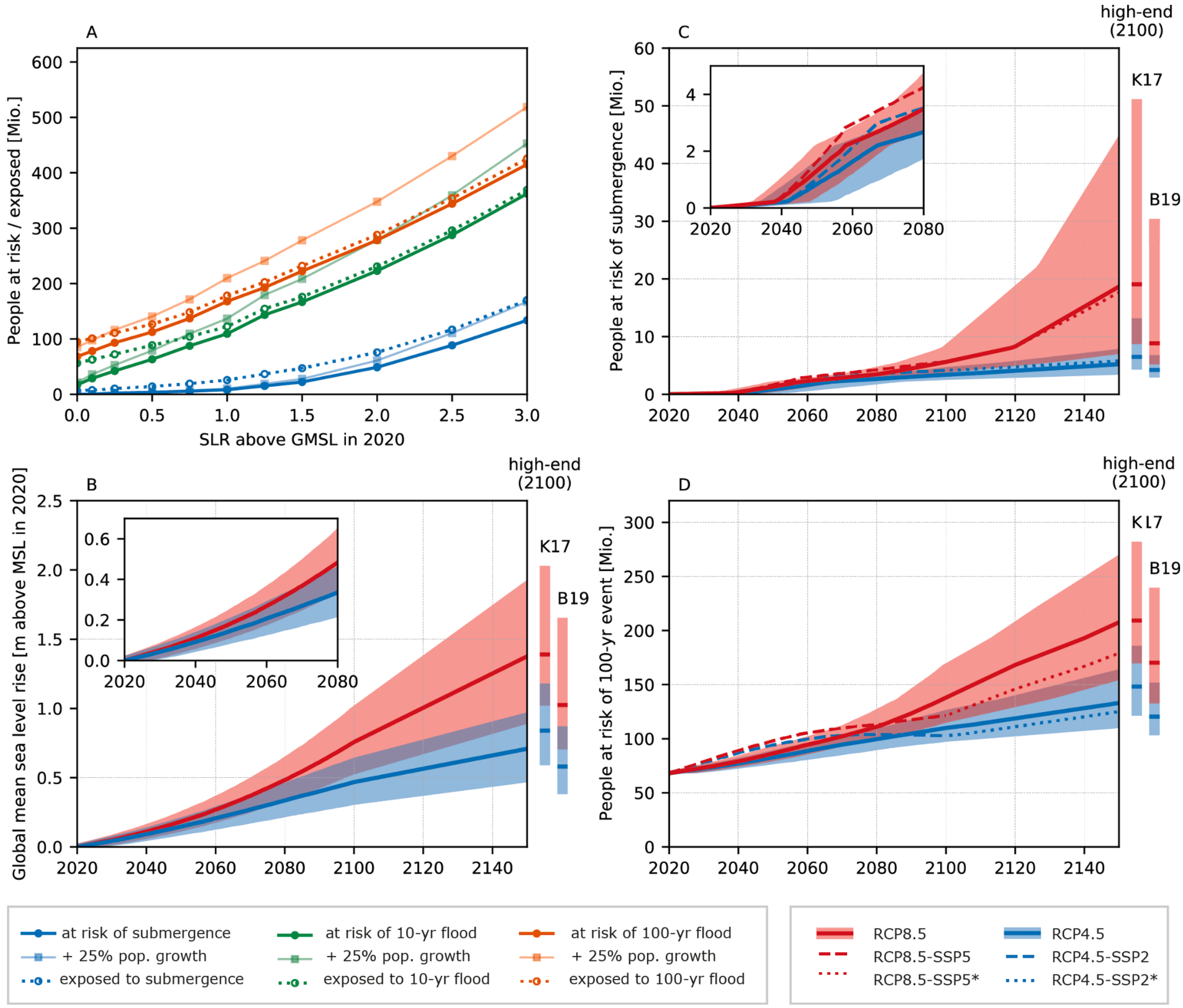

Fig. 1. Global impacts of sea-level rise (GMSLR) on people at risk of coastal flooding. Panel A: Projected impacts of GMSLR on the number of people exposed (assuming no protection, dashed lines) and people at risk (accounting for present day protection standards, solid lines) of permanent submergence, a 10-year flood event and a 100-year flood event, and people at risk combined with an increase of 25% of the population (transparent solid lines). Panel B: Regionalised IPCC SROCC projections (Oppenheimer et al., 2019) for GMSLR for RCP4.5 and RCP8.5 relative to 2020 for the likely range and median values (showing the 17th, 50th and 83th percentile, meaning there is 66% chance the results are within this range). Inset figure shows GMSLR to 2080. Panel C: The number of people at risk of permanent submergence (inset shows people at risk until 2080). Panel D: The number of people at risk of a 100-year flood event taking into account existing coastal protection standards. The bars on the side of panels B, C, and D reflect the likely range of SLR and range of impacts under high-end SLR scenarios from Bamber et al. (2019) (B19) and Kopp (2017) (K17) for RCP4.5 and RCP8.5 in 2100. The dashed lines in panel C and D show the impacts for a combination with population change according to median values of RCP4.5-SSP2 and RCP8.5-SSP5 accounting for gridded population change in the coastal zone derived from Merkens et al. (2016) until 2100 and assuming no change beyond 2100 (indicated with * and dotted lines).

2100, we assume the 2100 population does not change for post-2100 projections, similar to Brown et al. (2018).

To assess when adaptation to SLR is needed, we identify the timing of exceedance of different impact thresholds defined by the number of people at risk and assuming present day protection standards. As impact thresholds we use 0.1, 0.5, 1, 5 and 10 million people per country that will become at risk of a 100-year flood event, in addition to the number of people currently at risk to a 100-year flood event. We consider these impact thresholds as proxies for potential adaptation tipping points (Kwadijk et al., 2010) and thus as stimuli to adapt, simultaneously accepting that locally, these reasons to adapt vary. The timing of these impacts thus only gives a first

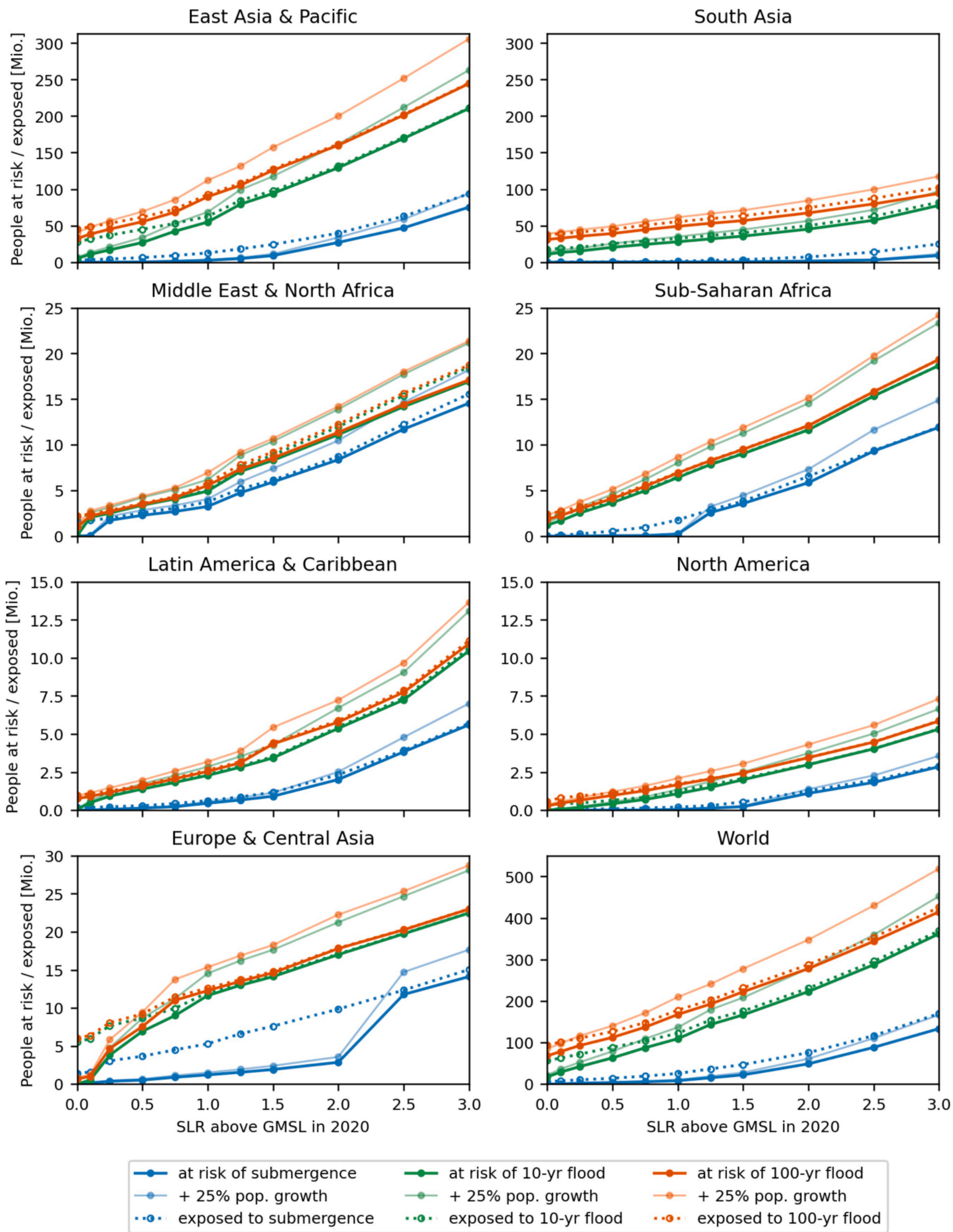

Fig. 2. Regional impacts of sea-level rise (GMSLR) on the people at risk of coastal flooding (scenario-neutral results). Projected number of people exposed (assuming no protection, dashed line) and at risk (accounting for present day protection, solid line) of permanent submergence (blue), and a 10-year flood event (green) and a 100-year flood event (orange), and people at risk combined with an increase of 25% of the population (transparent solid lines; for illustrative purposes) globally and per World Bank region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

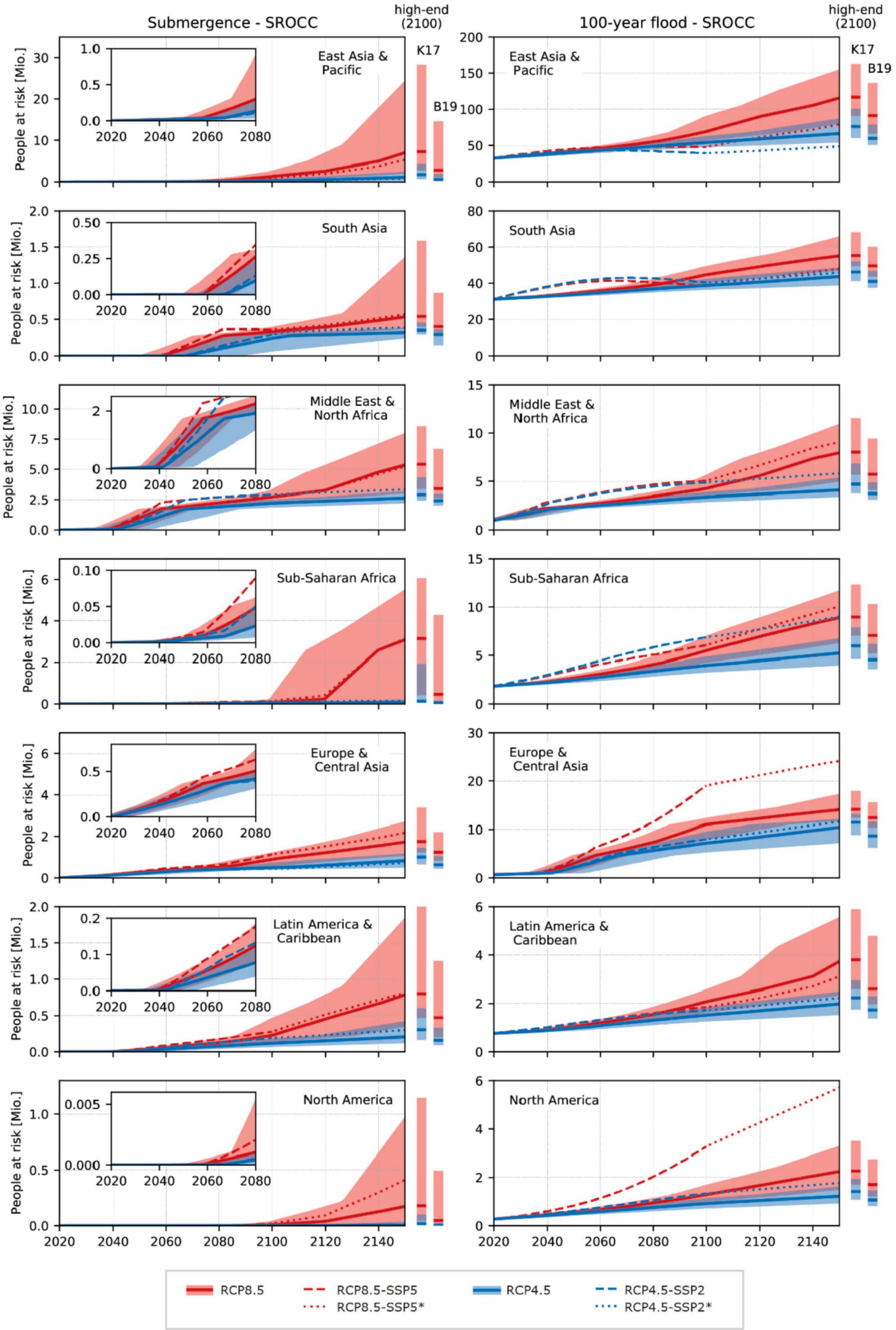

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Fig. 3. Regional impacts of GMSLR on the people at risk of permanent submergence (left) and a 100-year flood event (right) using regionalised IPCC SROCC (Oppenheimer et al., 2019) projections for GMSLR of RCP4.5 and RCP8.5 relative to 2020 for the likely range (p17-p83) and median values (lines) (showing the 17th, 50th and 83th percentile, meaning there is 66% chance the results are within this range). Inset figures present the impacts for until 2080. The bars on the side of the graphs reflect the median and likely range under high-end SLR scenarios from Bamber et al. (2019) (B19) and Kopp (2017) (K17) for RCP4.5 and RCP8.5 in 2100, which account for accelerated mass-loss from the Antarctic ice sheet. The dashed lines show the impacts for a combination with population change according to RCP4.5-SSP2 and RCP8.5-SSP5 accounting for gridded population change in the coastal zone derived from Merkens et al. (2016) until 2100 and assuming no change beyond 2100 (indicated with * and dotted lines).

order assessment of when and where impacts will occur first and/or rapidly, and adaptation may thus need to start earlier.

3. Results

3.1. Global adaptation commitment

Here, we present the number of people at risk of coastal flooding for global mean SLR (Fig. 1). Global population at risk increases with SLR if no further adaptation measures are taken (see Fig. 1A showing the scenario-neutral results). Globally, 4 million people will be at risk of permanent submergence at 0.5 m SLR, increasing to 8 million at 1 m SLR, and to 50 million at 2 m SLR, assuming present-day population and protection. The risk of submergence increases with accelerating pace: Below 1 m SLR, every 0.1 m SLR adds a further 0.8 million people at risk of submergence, this rises to on average 4 million between 1 and 2 m SLR and 8–12 million beyond 2 m SLR. Currently, 68 million people are at risk of a 100-year flood, which is projected to double with 0.75 m SLR, and triple with 1.4 m SLR.

To assess the efficacy of the current coastal protection standards we compare the population at risk (accounting for the level of current protection) to the population potentially exposed (assuming no protection) for mean sea level or the 10 or 100-year extreme water level (Fig. 1A). This shows that current flood protection protects 26 million people against a 100-year event, but becomes increasingly inadequate to protect against extreme sea levels in many locations, protecting just 14 million people after 0.5 m SLR, assuming that present protection is maintained but not further updated to SLR. However, existing flood protection reduces the number of people at risk of a 10-year event until 1 m SLR and the risk of submergence for SLR up to 3 m (Fig. 1A, compare dashed and solid lines).

Integrating the SLR-impact functions (Fig. 1A) with GMSLR (Fig. 1B) enables an assessment of when and how fast the population at risk increases (Fig. 1C and 1D). The rate of SLR amplifies the acceleration of the growth of risk, in particular beyond 2050. This is even greater beyond 2100 under RCP8.5, and under the high-end scenarios (bars on the side of Fig. 1C and D). Assuming risk should be kept at present levels, such an acceleration in the increase of risk will require more frequent adaptation of the scale typically implemented in the recent past, or fewer but larger scale adaptation interventions.

After the next 20–25 years, the number of people at risk of permanent submergence will start to increase rapidly (Fig. 1C). If no additional adaptation measures are taken, about 1 million people are projected to face permanent submergence within 30 years under both RCPs. The number of people at risk of a 100-year flood increases by 25% to 85 million people within the next 35 years under both RCP4.5 and RCP8.5 (median values), and doubles at 0.75 m SLR relative to 2020, which is projected to occur by 2100 (2085–2130) under RCP8.5 and by 2150 (2115-beyond 2150) under RCP4.5 (Fig. 1D). However, under the high-end scenarios RCP8.5+ and RCP4.5+ of K17 a doubling occurs decades earlier, leaving less time to adapt (~20 years for the median estimates RCP8.5+ compared to RCP8.5 and ~ 60 years for RCP4.5+ compared to RCP4.5). Under B19 this occurs ~ 15 years earlier under RCP8.5+ and has not yet occurred in 2100 under RCP4.5.

Beyond 2080**,** the population at risk diverges more between SLR scenarios; impacts occur earlier under higher amounts of SLR and are much larger in the long-term. For example, in 2120 the risk of submergence is half as much under RCP4.5 compared to RCP8.5, while in 2150 the RCP4.5 values are less than a third of what could happen under RCP8.5 (Fig. 1C). Under the high-end scenarios comparable impacts are projected to occur considerably earlier. The estimated flood risk for the median SLR values of SROCC in 2150 are comparable to the high-end projections of K17 in 2100; thus occurring 50 years earlier than in SROCC. The upper range of B19 also occurs 50 years earlier. For the median values of B19 there is a shift of 20 years; the median values of SROCC in 2120 are similar to the median values of B19 in 2100.

The rate and location of population growth affect how risk changes (Fig. 1C and D dashed lines). Immediate action (e.g. protection, floodproof development or no-build zones) would help to avoid increased impacts in the next 20–40 years, while by the end of the century impacts are delayed globally due to a decrease in population beyond 2060 under both SSPs. For example, 10 million more people are at risk of the 100-year flood ~ 10 years earlier (~2030 instead of ~ 2040) for the median estimates under both RCP-SSP combinations. A strategy of no-build zones in risky areas could reduce the population at risk of a 100-year flood up to 12 million people with an average of ~ 13% reduction in the next 20–40 years, both under RCP8.5-SSP5 and RCP4.5-SSP2. Under an accelerated SLR according to B19 and K17, these values are similar as there is not yet much difference in SLR.

3.2. Regional differences in adaptation commitment

Differences between global regions are caused by topography, coastal population density, and protection standards (Fig. 2 for the scenario-neutral results and Fig. 3 for time series). Without additional adaptation or population change, risk increases mostly in East and South Asia, but large increases are also projected for Europe and Africa. Abrupt changes mostly occur when (extreme) sea levels exceed the height of the protection in densely populated low-lying deltas and coastal zones, for example in the Nile, Niger, and Dutch delta.

The ‘Middle East & North Africa’ region is the first to experience an abrupt change in the population at risk of permanent submergence at mid-21st century (between 0.1 and 0.2 m SLR), mainly in the Nile delta. Next, the population at risk of submergence starts to increase in ‘East Asia & Pacific’ (between 0.2 and 0.5 m SLR) but at an accelerating pace, as more people are placed at risk in Vietnam, Japan, Indonesia, and the Philippines. By almost 2100, 1 (0.3–2.2) million people are projected to be affected by submergence under RCP8.5 (median value and likely range), which is delayed by ~ 40 years under RCP4.5 (median). Under RCP8.5 this increases further to 7 (2–24) million by 2150. Assuming present day protection standards and population, both the East and South Asia already have a large number of people at risk of a 100-year event (63 million) because many Asian regions (except in China and Malaysia) have comparatively low levels of flood protection. The effect of protection is apparent up to 1 m in ‘East Asia & Pacific’ for the 10-year flood (Fig. 2).

The ‘Sub Saharan Africa’ region shows a rapid increase in the people at risk of submergence by 2120 under RCP8.5, when SLR exceeds 1 m and much of the population that presently live Niger delta is at risk. Natural sedimentation could raise land levels, but not in urban areas. In ‘Latin America’ the population at risk of permanent submergence starts to increase in the mid-21st century (between

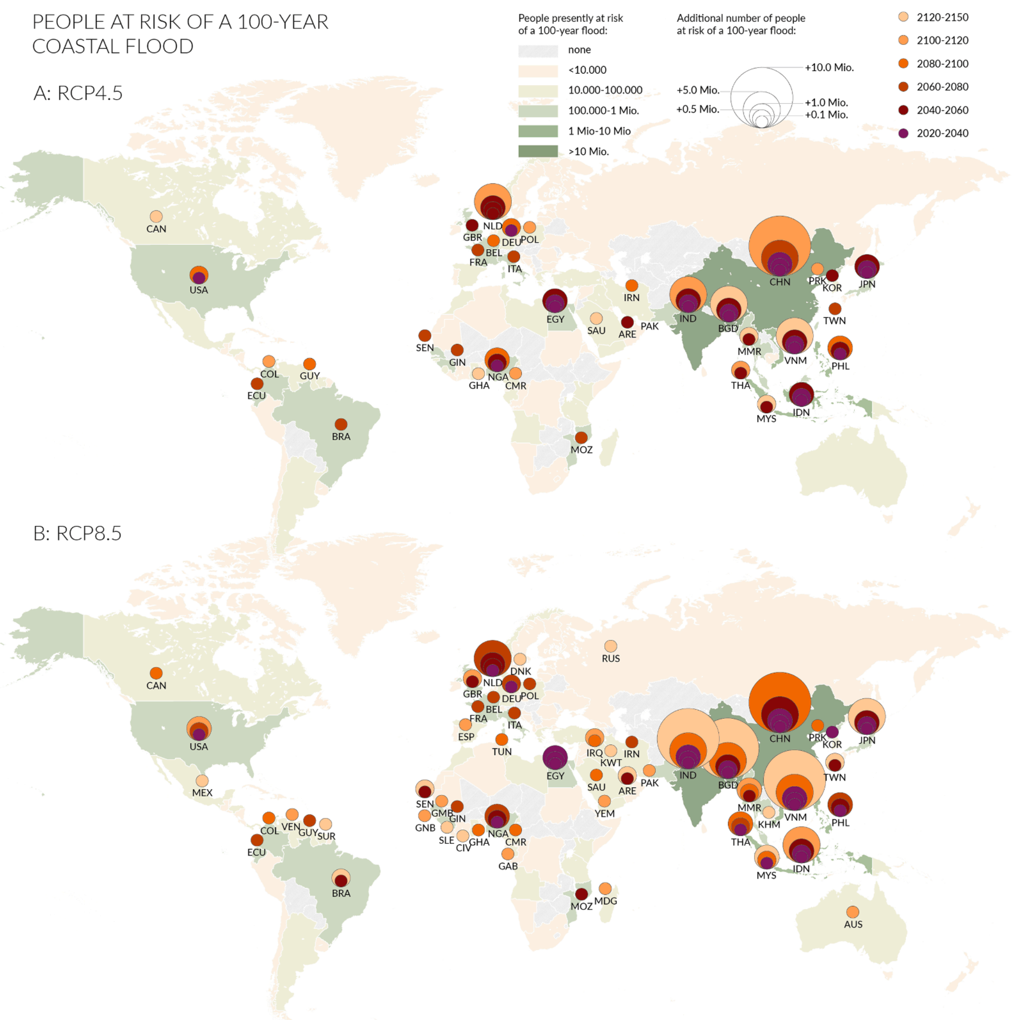

Fig. 4. Number of people at risk of 100-year coastal flood in 2020 (green shades; landlocked countries with grey stripes). The colour of the circles indicates when an impact threshold is exceeded for the median value of RCP4.5 (a) and RCP8.5 (b) according to IPCC SROCC (Oppenheimer et al., 2019) projections. Impact thresholds considered are 0.1, 0.5, 1, 5 and 10 million people per country that will become at risk of a 100-year flood event, in addition to the people currently at risk of a 100-year flood event, assuming present population and protection. The size of the circles indicates the additional number of people that become at risk compared to the current population at risk. Where circles have similar colours, risk increases rapidly. Countries with dark colours have an early increase of risk. Countries with small circles have lower risk until 2150. This information is provided for countries, in which the minimum threshold of 100,000 people additionally at risk will be exceeded by 2150. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.25 and 0.5 m of SLR), and in 'North America' this occurs in the mid-22nd century between 1 and 1.25 m; the rates of change for these two regions are similar.

'Europe & Central Asia' will experience a rapid increase of the population at risk to a 100-year event to 5 (3–6) million people over the next 40 years under RCP8.5 or 50 years under RCP4.5, and reaches between 7 (5–10) to –11 (8–12) million people by 2100 under RCP4.5 and RCP8.5, respectively. The large increase in the latter half of the century can be attributed to the growing population at risk of a 100-year flood in the Dutch delta and countries with large coastal cities (e.g. United Kingdom, Germany, France, Italy, Belgium). For this region there is a large impact of the present protection (Fig. 2).

Population dynamics differ substantially across the different regions (Fig. S2 in supplement), influencing risk accordingly (dashed lines in Fig. 3). In 'Europe & Central Asia' and 'North America' the projected population at risk of a 100-year flood is about twice as much under RCP8.5-SSP5 compared to RCP8.5, while there is little difference between SSP2 and RCP4.5-SSP2. For 'East Asia & Pacific', 'South Asia', 'Middle East & North Africa' both SSP2 and SSP5 project population increases in the low-lying coastal zone in the next 20–30 years, after which it decreases again to similar or lower amounts compared to 2020, which is reflected by the growth then fall in risk of compared to considering SLR alone.

3.3. Projected adaptation commitment at national scale

To derive a first order assessment of which countries may need to adapt earlier and/or faster, we assessed the year in which the number of people at risk to a 100-year flood exceeds certain thresholds ranging from an additional 0.1–10 million people assuming present-day protection. Fig. 4 shows all countries in which at least an additional 0.1 million people are projected to be at risk to a 100-year flood in the next 150 years (58 countries, Fig. 4) for the median values of RCP4.5 (A) and RCP8.5 (B) (See Supplement figures S-3 to S-16 for full range and RCP-SSP and high-end scenarios). The timing of the threshold exceedance for both RCPs is similar over the next 30 years but diverges beyond this.

Countries that receive continued or early additional adaptation stimuli because of people at risk of submergence include Egypt and Poland, while others, such as India, Indonesia, Italy, Japan, Poland, and Tunisia, are projected to experience this later, albeit the amounts remain mostly low (only low thresholds exceeded) (Figure S-3, S-4, S9, S11). Other regions that currently have some protection against extreme sea levels (e.g., Bangladesh, China, Thailand, Vietnam) will not be at risk of permanent submergence soon but will experience more frequent flooding even under low SLR, as indicated with the people at risk of a 10-year flood (see Supplement figure S-5 and S-6). China, Japan, Egypt, Vietnam, India, Bangladesh, Indonesia, USA, and Japan are amongst the countries that are projected to experience large and early increases in the number of people at risk to a 100-year event. Within the next 10 years, an additional 1 million people may be at risk of a 100-year event for both RCP4.5 and RCP8.5 in China (median values; Fig. 4). In Vietnam, Japan, Bangladesh, and India, this is projected to occur within 25 years. In the Philippines, Nigeria, USA, and Germany the rate of increase is less, but a lower threshold of 0.1 million people is exceeded in the next 20 years, surpassing 1 million people at risk just before or after 2100, under RCP8.5 (median values). Other countries in which an additional 0.1 million people are projected to be at risk within the next 50 years include the United Kingdom, France, Myanmar, Brazil, Mozambique, Taiwan, and Senegal. Rapid increases in risk continue in China reaching 10 million around 2080 or just beyond 2100 under RCP8.5 and RCP4.5. In the Netherlands rapid changes are projected for the next 30–40 years (median values) without additional adaptation.

Population changes affect the timing of threshold exceedance, although adaptations such as restricting development in places at risk of coastal flooding would delay or prevent this. Across all regions, thresholds exceeded in the next 40–60 years considering just SLR occur earlier when accounting for population change. Moreover, the uncertainty range in timing that these thresholds will be exceeded is reduced (see e.g. Supplement Figs. S7 and S8 for a 100-year flood event). Beyond 2080, the SSP scenarios lead to greater differentiation amongst regions. In parts of Asia (e.g. China, Vietnam, Indonesia) threshold exceedance is delayed when SSPs are considered. In contrast, in the USA and Europe (Netherlands, United Kingdom, Germany) thresholds are exceeded earlier, and higher thresholds are exceeded, in particular under RCP8.5-SSP5 (Figures S-4, S-6 and S-8). Under the high-end scenarios (Figs. S9–S16) threshold exceedance happens earlier and faster in succession.

4. Implications for adaptation decision making

Countries with areas projected to become permanently submerged have the greatest commitment to some form of coastal adaptation, such as defence construction and/or population migration. Many countries will need to increase adaptation efforts to avoid a substantial increase in the number of people at risk of 10-year and 100-year floods. The exact timing when adaptation needs to be in place is uncertain and dependent on global emissions and related SLR and risk tolerance to flooding. Over the next 40 years, uncertainties in timing and magnitude of the projected risks are lower across the scenarios (see e.g., Fig. 1 and Supplement Tables S11–S18), and many coastal regions would benefit from adaptation immediately to contain risk to present levels including protection measures as well as no-build zones in the areas at risk of coastal flooding.

Looking beyond 2100 illuminates the long-term adaptation commitment regardless of the rate of SLR. For example, a doubling of the population at risk of a 100-year flood occurs if no further adaptation actions are taken under the RCP and SSP scenarios considered, but under RCP4.5 with stabilized emissions this will happen later, allowing more time to adapt. Neglecting the long-term adaptation commitment resulting from impacts beyond 2100 or from potential high-end SLR could lead to different, possibly high-regret, decisions as coastal investments typically have a long lead- and lifetime, shaping subsequent coastal change, and can involve large transfer costs if course correction is needed (Sadoff et al., 2015; Haasnoot et al., 2020). Fig. 5 shows how a short time-horizon (e.g. until 2150) could result in an adaptation commitment gap, as the minimal adaptation needed by 2150 is higher than what is planned for when considering 2100 as a time horizon. Decision makers with a low risk tolerance to flooding (Hinkel et al., 2019) benefit from an adaptation commitment based upon high SLR scenarios. This does not mean they have to immediately implement measures, rather they could plan for this following an adaptive pathways strategy (Haasnoot et al., 2013).

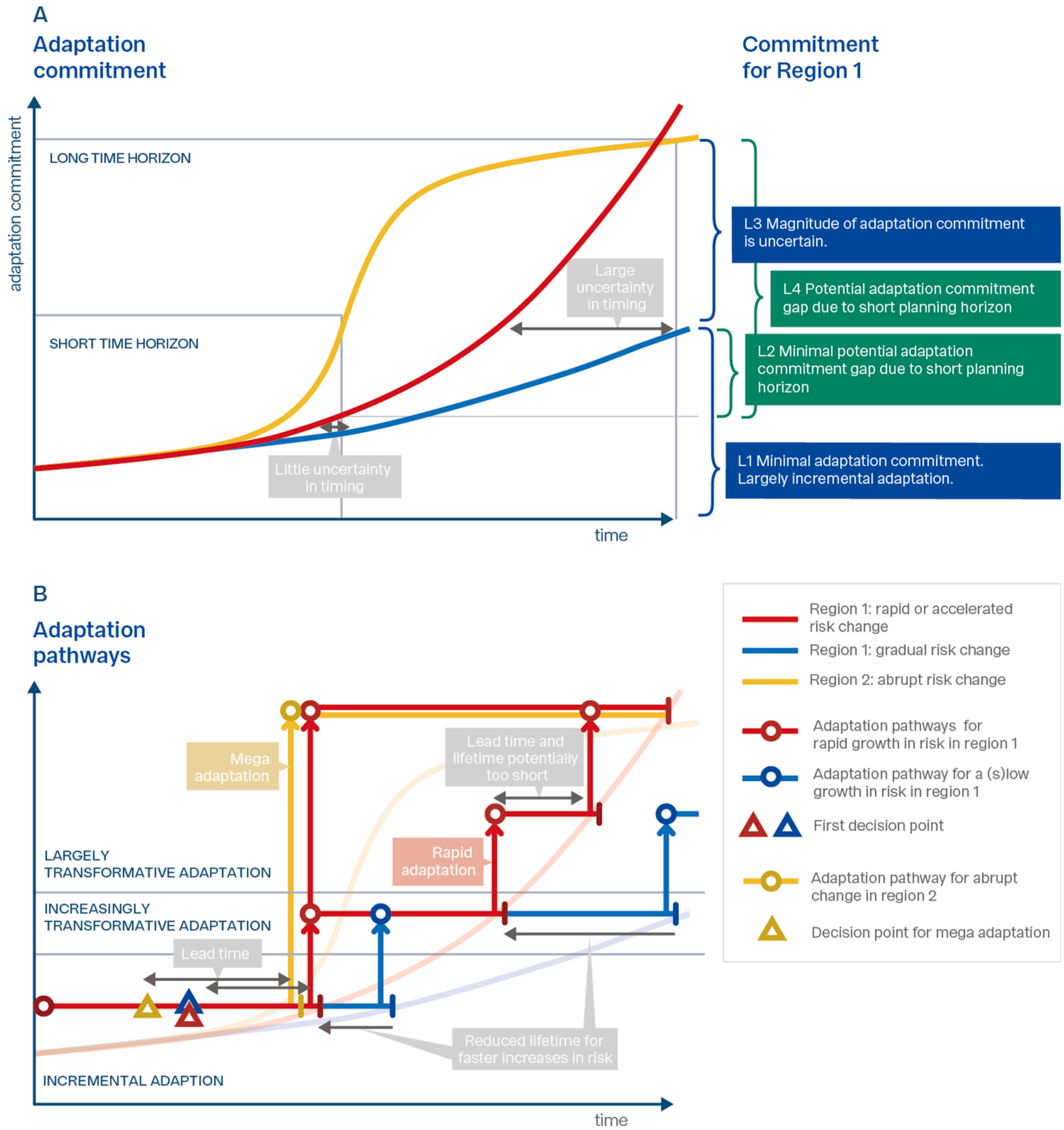

Fig. 5. Archetypes of adaptation commitment, uncertainties and consequences for adaptation pathways. Panel A: Three archetypes of changes in adaptation commitment. The blue and red line show the range of adaptation commitment (from gradual to rapid) for the same region (1, e.g. Sub Saharan Africa, Latin America), but with different RCP/SSP scenarios that mediate the rate of change in risk. The blue line is the minimal commitment over time, resulting in a minimal commitment (Level 1, L1) over the long time horizon (large rectangle). The black arrow shows the uncertainty in the timing of this minimal commitment. For decisions with a short time horizon (e.g. sand nourishment or pumping) there is much less uncertainty in the timing (small rectangle). However, for many interventions a focus on a short time horizon for planning instead of a long time horizon can result in a commitment gap as indicated by the difference in the minimal adaptation commitment for the different time horizons (L2) (e.g. for hard infrastructure). Above the blue line, the magnitude of the adaptation commitment is uncertain within the considered horizon (L3), part of it may still be needed beyond the long time horizon as sea levels continue to rise of hundreds of years, and could result in an even larger adaptation commitment when a short time horizon is use in planning (L4). In other regions abrupt changes in adaptation commitment can occur (yellow line, e.g. Europe). The timing and magnitude of the abrupt increase in adaptation commitment depends on the RCP/SSP scenario (not shown for clarity). Panel B: Adaptation pathways showing sequences of decisions to address the adaptation commitment over time. For region 1, the first two adaptation measures of the pathway could be similar, but the lifetime is reduced under the red line. Alternatively, a large step in adaptation can be taken in this region (red line). Such a mega adaptation pathway could also work for region 2 (yellow line) to address the abrupt changes but may need to be implemented more quickly to manage the increase in risk. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

An effective coastal adaptation strategy should consider not just absolute changes in risk, but also the timing and rate of change under multiple futures, and alternative pathways to manage those changes (Fig. 5). Our results show that in many regions of the world, adaptation will need to cope with an increasing growth in the population at risk beyond 2050, especially after 2100 under RCP8.5. This occurs sooner under high-end scenarios, or temporarily accelerates according to coastal development. A lower rate of risk change, which occurs more often under RCP4.5, allows policy makers to make incremental choices about adaptation in the next 100 years, such as the construction or heightening of dikes and seawalls. Faster rates of SLR and increase in adaptation commitment will reduce the functional lifetime of adaptation measures and other assets (Haasnoot et al., 2020). Measures will then need to be built faster or to higher amounts of SLR to address larger increases in adaptation commitment (Fig. 5, compare red and blue adaptation pathway). Where risk increases rapidly, incremental adaptation strategies, that are typically built for gradual risk change and low rates of SLR, will have a reduced lifetime, and need to be replaced, retrofitted or adapted earlier than envisioned (Haasnoot et al., 2020). Moreover, under these conditions, options would be limited to those which could be implemented with a short lead time. Large - possibly mega - adaptation efforts to address abrupt changes (Fig. 5, yellow adaptation pathway) likely require long lead time. However, implementing some choices when uncertainty is still large can lead to overinvesting if emissions and consequently SLR rates are reduced, while postponing measures may risk being too late (de Ruig et al., 2019). Ultimately, the chosen pathway depends on local conditions including risk tolerance, available material, knowledge and governance.

Our results show that coastwards migration or population growth is projected to increase the amount of people at risk in the next decades, requiring faster increases in flood protection, introducing a policy to limit coastal development, or only allow floodproof developments. Beyond 2060 projected population changes are highly uncertain. In some regions this can lead to similar, more, or fewer people at risk (see e.g., Fig. 3 Latin America where RCP8.5-SSP5 has a higher risk than RCP8.5 and under RCP4.5-SSP2 the risk is lower compared to RCP4.5. In 'Europe & Central Asia' risk increases substantially under RCP8.5-SSP5 compared to RCP8.5, but under RCP4.5-SSP2 there is little change compared to RCP4.5). Under large uncertainty, flexible strategies that keep options open and allow for learning and adaptation over time are favored (Marchau et al., 2019). However, established cities have large inertia and path-dependency of decisions, and require long lead times to adapt (Hallegatte et al., 2009) or to experiment with transformative measures (e.g., Oppenheimer et al., 2019) that may be needed in the long-term (Haasnoot et al., 2020) especially under high rates of SLR. Many coastal cities are already locked into a protection strategy and switching to alternative (transformative) options will be costly and have large societal impacts in the near-term, but can be beneficial when a longer time horizon is considered to evaluate decisions (see e.g. Fig. 5 or O'Neill et al., 2016).

An infrastructure-based protection strategy has its limits and will not be a solution along every coastline or affordable for every society. In some locations managed retreat can have a higher benefit-cost ratio (Lincke and Hinkel, 2021) and could enable cities and settlements to transform and align with social goals (Mach and Siders, 2021) if planned ahead (Haasnoot et al., 2021). Even if protection is raised fast enough, the number of people vulnerable to flooding continues to grow creating more residual risk (Mechler and Schinko, 2016) as protection may fail. Low-lying coasts will increasingly need pumps and storage capacity to drain and temporarily store (ground)water, and ultimately may require rivers to be entirely drained by pumping (Haasnoot et al., 2020; Hall et al., 2019). The longer a protect pathway that involves raising flood defences as sea levels rise is followed, the more costly and challenging it becomes to maintain protection levels. Ultimately faster, more costly, and potentially inequitable relocation of people and assets, may be required when flood risk becomes acute (Lawrence et al., 2020; Siders et al., 2019). Considering the long-term adaptation commitment and the adaptation options within the solution space (Haasnoot et al., 2020) can support timely adaptation aligned with societal goals which allows for managed retreat pathways to achieve positive outcomes (Mach and Siders, 2021; Haasnoot et al., 2021).

Projected adaptation commitment suggests that competition for global resources may be exasperated (e.g., sand Torres et al., 2017) needed for the construction of defences or for beach nourishment). Adaptation of coastal settlements will therefore benefit from international coordination and cooperation on disaster risk reduction management including early warning, evacuation, insurance and recovery, as well as sharing adaptation knowledge, techniques and material.

The approach followed in this paper has limitations and should therefore be considered as a first order assessment of how the adaptation commitment can unfold. Large uncertainties exist in the flood risk assessment that are not covered here including the elevation data (Hooijer and Vernimmen, 2021; Gesch, 2018), storm surge (change) (Wahl, 2017; Arns et al., 2017), population change (Merkens et al., 2016; Smith, 2019; MacManus et al., 2021), and human adaptation to SLR and socio-economic developments (Hinkel et al., 2021). For example, adding local subsidence (Nicholls et al., 2021) would accelerate the timing at which risk thresholds are exceeded, in particular in coastal cities in Asian deltas, where accounting for a continuation of the average subsidence rates in Vietnam brings a threshold of 5 million people at risk of a 100-year flood forward ~ 40 years under RCP8.5 and is not yet reached by 2150 under RCP4.5 (Supplement figure S-17). On the other hand, more accurate local data on existing coastal protection levels, such as the use of a freeboard of 0.5–1 m (e.g. in Germany, UK, USA https://www.fema.gov/glossary/freeboard; Wilby et al., 2011; http://www.overtopping-manual.com/) could delay impacts for decades.

At the national and regional level, decision makers can use our findings as a first order assessment to target and coordinate adaptation and development investments. However, adaptation is delivered at local scale. For this, decision makers can reapply the methodology to assess the rate and timing of impacts up to 2150 using best-available local data to assess the adaptation commitment over time and support robust and flexible adaptation decisions. This can inform coastal decision makers that are facing many impacts of climate change (e.g. windstorm, ocean warming, salinisation (Oppenheimer, 2019) compound flood events (Eilander et al., 2020) and socio-economic developments (e.g. growth or shrinkage of the population (Vousdoukas et al., 2018; Fang, 2020), land reclamation (Sengupta et al., 2020), cultural heritage (Reimann et al., 2018), critical infrastructure (Brown et al., 2013).

5. Conclusion

Regardless of future greenhouse gas emissions trajectories, some commitment to adaptation to SLR is inevitable to avoid displacement of people due to submergence and contain risk to present levels. Present coastal protection standards reduce the population at risk. At 0.5 m SLR they still provide protection from a 100-year flood to half of the people they currently protect. Adaptation policies that are able to restrict coastal migration and population growth could reduce risk in the next 20–40 years by 13% under both RCP4.5-SSP2 and RCP8.5-SSP5 if started now. Timing and rate of impacts varies regionally, with some regions project to experience considerable impacts in the next decades (e.g. Asia, North Africa), while others will experience impacts later this century, or experience rapid changes (e.g. parts of Europe and Asia). Where risk is projected to increase rapidly, adaptation is especially challenging given the narrow timeframe and scale of action needed to address the risk.

Difficult decisions are inevitable. Determining the long-term adaptation commitment helps to explore climate resilient development and adaptation pathways and identify necessary short-term actions and innovations. In many coastal geographies (e.g. atoll islands, tropical agricultural deltas, and even in some resource rich cities (Oppenheimer et al., 2019) continuing along a pathway of coastal flood protection may only buy time and reduce impacts in the short-term. A transformative approach, which includes limiting developments in high-risk areas, accommodating flood risk by modifying existing development, and relocating, allows society to plan a pathway that helps to prevent abrupt increases in impacts on the longer time horizon.

5. Data availability

Data developed in this study are available in the Supplementary Information and material.

6. Code availability

The code of the flood model that supported the findings of this study is available at: https://github.com/Deltares/aqueduct-coastal-flooding under the GPL license v3. The code for postprocessing and plotting the results from the flood model is available under https://doi.org/10.5281/zenodo.4267696.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

M.H. conceived the idea of the study, M.H. and G.W. designed the approach and prepared the figures. G.W. and D.E. performed the modelling. All authors performed parts of the analysis and co-wrote the paper. We thank A. Slangen and J. Bamber for providing their SLR projections and advice on their use.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2021.100355.

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