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Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities

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and surface water; and (vi) impeded drainage. This section discusses some of these hazards (flooding, erosion, salinisation) as well as observed and projected impacts on some critical marine ecosystems (marshes, mangroves, lagoons, coral reefs and seagrasses), ecosystem services (coastal protection) and human societies (people, assets, infrastructures, economic and subsistence activities, inequity and well-being, etc.). In many cases, the Chapter 4 assessment of impacts and responses uses results from literature based on values of SLR and ESL events prior to SROCC. However, the general findings reported here also carry forward with the new SROCC SLR and ESL values. Except in the case of submergence and flooding of coastal areas (Section 4.3.3.2), this section assumes no major additional adaptation efforts compared to today (i.e., neither significant intensification of ongoing action nor new types of action), thus reflecting the state of knowledge in the literature.

4.3.3.1 Attribution of Observed Physical Changes to Sea Level Rise

The AR5 concludes that attribution of coastal changes to SLR is difficult because 'the coastal sea level change signal is often small when compared to other processes' (Wong et al., 2014: 375). New literature, however, shows that extreme water levels at the coast are rising due to mean SLR (4.2.2.4 for observations, and 4.3.5 for projections), with observable impacts on chronic flooding in some regions (Sweet and Park, 2014; Strauss et al., 2016).

On coastal morphological changes for example, contemporary SLR currently acts as a 'background driver', with extreme events, changes in wave patterns, tides and human intervention often described as the prevailing drivers of observed changes (Grady et al., 2013; Albert et al., 2016). Morphological changes are also interacting with other impacts of SLR, such as coastal flooding (Pollard et al., 2018). Despite the complexity of the attribution issue (Romine et al., 2013; Le Cozannet et al., 2014), recent literature suggests possibly emerging signs of the direct influence of recent SLR on shoreline behaviour, for example on small highly-sensitive reef islands in New Caledonia (Garcin et al., 2016) and in the Solomon Islands (Albert et al., 2016). Early signs of the direct influence of SLR on estuaries' water salinity are also emerging, for example, in the Delaware, USA, where Ross et al. (2015) estimate a rate of salinity increase by as much as 4.4 psu (Practical Salinity Unit) per metre of SLR since the 1950s.

Overall, while the literature suggests that it is still too early to attribute coastal impacts to SLR in most of the world's coastal areas, there is *very high confidence* that as sea level continues to rise (Sections 4.2.3.2, 4.2.3.3), the frequency, severity and duration of hazards and related impacts increases (Woodruff et al., 2013; Lilai et al., 2016; Vitousek et al., 2017; Sections 4.2.3.4, 6.3.1.3). Detectable impacts and attributable impacts on shoreline behaviour are expected as soon as the second half of the 21st century (Nicholls and Cazenave, 2010; Storlazzi et al., 2018).

4.3.3.2 Submergence and Flooding of Coastal Areas

Since AR5, a number of continental and global scale coastal exposure studies have accounted for sub-national human dynamics such as coastward migration or coastal urbanisation. These studies project a population increase in the LECZ (coastal areas below 10 m of elevation) by 2100 of 85 to 239 million people as compared to only considering national dynamics (Merkens et al., 2016; Section 4.3.2). Under the five SSPs and without SLR, the population living in the LECZ increases from 640–700 million in 2000 to over one billion in 2050 under all SSPs, and then declines to 500–900 million in 2100 under all SSPs, except for SSP3 (i.e., a world in which countries will increasingly focus on domestic issues, or at best regional ones), for which the coastal population reaches 1.1–1.2 billion (Jones and O'Neill, 2016; Merkens et al., 2016).

The population exposed to mean and ESL events will grow significantly during the 21st century (*high confidence*) with socioeconomic development and SLR contributing roughly equally (*medium confidence*). Considering an average relative SLR of 0.7–0.9 m but no population growth, the number of people living below the hundred-year ESL in Latin America and the Caribbean will increase from 7.5 million in 2011 to 9 million by the end of the century (Reguero et al., 2015). Considering population growth and urbanisation, only 21 cm of global mean SLR by 2060 would increase the global population living below the hundred-year ESL from about 189 million in 2000 to 316–411 million in 2060, with the largest absolute changes in South and Southeast Asia and the largest relative changes in Africa (Neumann et al., 2015). Considering population growth, Hauer et al. (2016) estimate that 4.3 and 13.1 million people in the USA would live below the levels of 0.9 and 1.8 m SLR by 2100.

New coastal flood risk studies conducted since AR4 at global, continental and city scale, reinforce AR5 findings that if coastal societies do not adapt, flood risks will increase by 2–3 orders of magnitude reaching catastrophic levels by the end of the century, even under the lower end SLR expected under RCP2.6 (*high confidence*; Hinkel et al., 2014; Abadie et al., 2016; Diaz, 2016; Hunter et al., 2017; Lincke and Hinkel, 2018; Abadie, 2018; Brown et al., 2018a; Nicholls, 2018). In combination, these studies take into account a SLR scenario range wider than the *likely* range of AR5 but consistent with the range of projections assessed in this report (Section 4.2.3.2). For example, considering 25–123 cm of SLR in 2100, all SSPs and no adaptation, Hinkel et al. (2014) find that 0.2–4.6% of global population is expected to be flooded annually in 2100, with expected annual damages (EAD) amounting to 0.3–9.3% of global GDP. Assessing 120 cities globally, Abadie (2018) find that under a weighted combination of the probabilistic scenarios, New Orleans and Guangzhou Guangdong rank highest with EAD above 1 trillion USD (not discounted) in each city. For Europe, EAD are expected to rise from 1.25 billion EUR today to 93–960 billion EUR by the end of the century (Vousdoukas et al., 2018b). Already today, many small islands face large flood damages relative to their GDP specifically through TCs (Cashman and Nagdee, 2017) and under SLR EAD can reach up to several percent of GDP in 2100, as highlighted in

AR5 (Wong et al., 2014). Similar to the exposure studies, estimates of future flood risk without considering adaptation, as presented in this paragraph, do not provide a meaningful characterisation of coastal flood risks, because adaptation and specifically hard protection is expected to be widespread during the 21st century in urban areas and cities (*high confidence*; Section 4.4.3.2.2). Rather, these estimates need to be seen as illustrations of the scale of adaptation needed to offset risk.

Flood risk studies that have included adaptation find that hard coastal protection is generally very effective in reducing flood risks during the 21st century even under high SLR scenarios (*high confidence*; Hinkel et al., 2014; Diaz, 2016; Brown et al., 2018a; Hinkel et al., 2018; Lincke and Hinkel, 2018; Tamura et al., 2019) (Section 4.4.2.2.2). For example, Hinkel et al. (2014) find that under 25–123 cm of SLR in 2100 and all SSPs, hard coastal protection reduces the annual number of people affected by coastal floods and EAD by 2–3 orders of magnitude. Under high-end SLR and beyond the 21st century, effectiveness of coastal adaptation is expected to decline rapidly, but there is a lack of studies addressing this issue. Furthermore, there is a lack of studies taking into account responses beyond hard protection such as ecosystem-based adaptation, accommodation, advance and retreat (Sections 4.4.2).

Studies also confirm AR5 findings that the relative costs and benefits of coastal adaptation are distributed unequally across countries and regions (*high confidence*; Wong et al., 2014; Diaz, 2016; Lincke and Hinkel, 2018; Tamura et al., 2019). For example, while the median cost of protection and retreat under RCP8.5 in 2050 has been estimated to be under 0.09% of national GDP, large relative costs are found for small island states such as the Marshall Islands (7.6%), the Maldives (7.5%), Tuvalu (4.6%) and Kiribati (4.1%; Diaz, 2016). Furthermore, on a global average and for urban and densely populated regions, hard protection is highly cost efficient with benefit-cost ratios up to 10^4, but for poorer and less densely populated areas benefit-cost ratios are generally smaller than one (Lincke and Hinkel, 2018). Hence, without substantial transfer payments supporting poor areas, coastal flood risks will evolve unequally during this century, with richer and densely populated areas well protected behind hard structures and poorer less densely populated areas suffering losses and damages, and eventually retreating from the coast.

While continental to global scale flood exposure and risk studies have also explored a wider range of uncertainty as compared to AR5, much remains to be done. All of these studies rely on global elevation data, but few studies have explored the underlying bias. For example, for the Po delta in Italy, it was found that elevation data based on the widely used Shuttle Radar Topography Mission (SRTM), Reuter et al. (2007) overestimates the 100-year floodplain by about 50% as compared to local Lidar data (Wolff et al., 2016), while in the Ria Formosa region in Portugal SRTM underestimates EAD by up to 50% depending on the resampled resolution of the Lidar data (Vousdoukas et al., 2018a). For the USA, SRTM data systemically underestimates population exposure below 3 m by more than 60% as compared to coastal Lidar data (Kulp and Strauss, 2016). A global scale comparison of major contributors to flood risk uncertainty finds that uncertainty in digital elevation data is roughly at equal footing with uncertainties in socioeconomic development, emission scenarios, and SLR in determining the magnitude of flood risks in the 21st century (Hinkel et al., 2014). At a European level, the number of people living in the 100-year coastal floodplain can vary between 20–70% depending on the different inundation models used and the inclusion or exclusion of wave set up (Vousdoukas, 2016). Comparing damage functions attained in different studies for European cities, Prahl et al. (2018) find up to four-fold differences in damages for floods above 3 m. Another major source of uncertainty relates to uncertainties in present-day ESL events due to the application of different extreme value methods (Wahl et al., 2017; Section 4.2.3.4). While all of the uncertainties reported above affected the actual size of exposure and flood risk figures, they do not affect the overall conclusions drawn here.

4.3.3.3 Coastal Erosion and Projected Global Impacts of Enhanced Erosion on Human Systems

Recent global assessments of coastal erosion indicate that land losses currently dominate over land gains and that human interventions are a major driver of shoreline changes (Cazenave and Cozannet, 2014; Luijendijk et al., 2018; Mentaschi et al., 2018). Luijendijk et al. (2018) estimate that over the 1984–2016 period, about a quarter of the world's sandy beaches eroded at rates exceeding 0.5 m yr^{-1} while about 28% accreted. While such global results can be challenged due to the relatively large detection threshold used (±0.5 m yr^{-1}), there is growing literature indicating that coastal erosion is occurring or increasing, e.g. in the Arctic (Barnhart et al., 2014a; Farquharson et al., 2018; Irrgang et al., 2019), Brazil (Amaro et al., 2015), China (Yang et al., 2017), Colombia (Rangel-Buitrago et al., 2015), India (Kankara et al., 2018), and along a large number of deltaic systems worldwide (e.g., Section 4.2.2.4).

Since AR5, however, there is growing appreciation and understanding of the ability of coastal systems to respond dynamically to SLR (Passeri et al., 2015; Lentz et al., 2016; Deng et al., 2017). Most low-lying coastal systems exhibit important feedbacks between biological and physical processes (e.g., Wright and Nichols, 2018), that have allowed them to maintain a relatively stable morphology under moderate rates of SLR (<0.3 cm yr^{-1}) over the past few millennia (Woodruff et al., 2013; Cross-Chapter Box 5 in Chapter 1). In a global review on multi-decadal changes in the land area of 709 atoll islands, Duvat (2019) shows that in a context of more rapid SLR than the global mean (Becker et al., 2012; Palanisamy et al., 2014), 73.1% of islands were stable in area, while respectively 15.5% and 11.4% increased and decreased in size. While anthropogenic drivers played a major role, especially in urban islands (e.g., shoreline stabilisation by coastal defences, increase in island size as a result of reclamation works), this study and others (e.g., McLean and Kench, 2015) suggest that these islands have had the capacity to maintain their land area by naturally adjusting to SLR over the past decades (*high confidence*). However, it has been argued that this capacity could be reduced in the coming decades, due to the combination of higher rates of SLR, increased wave energy (Albert et al., 2016), changes in run-up (Shope et al., 2017) and storm wave direction (Harley et al., 2017), effects of ocean warming and acidification on critical ecosystems such as coral reefs (Section 4.3.3.5.2), and a continued increase in anthropogenic pressure.