Cross-Chapter Paper 2: Cities and Settlements by the Sea
Supplementary Material

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SMCCP2.1 Climate Change Risks to Cities and Settlements by the Sea

This section provides an extended review of risks to C&S by the sea to complement the summary in CCP2.2.

The dynamic interaction between climate drivers and varied coastal geographies influences a number of physical impacts, including many that are unique to C&S by the sea (Figure CCP2.2). Interactions between climate and non-climate drivers of coastal change are increasing the frequency and intensity of many coastal hazards, with settlement archetypes and the wider coastal zone subject to escalating risk (Figure CCP2.3; Table SMCCP2.1 for examples of selected coastal C&S).

SMCCP2.1.1 Risks to Land and People

Sea-level rise (SLR) will increase coastal squeeze (Pontee, 2013), permanently erode or submerge inadequately protected coastal settlements and the surrounding land providing C&S with ecosystem services, and reduce freshwater availability through salinisation (Ellison, 2015; Ha et al., 2018; Oppenheimer et al., 2019). Before being permanently eroded or submerged, a coastal C&S could be subject to increased risk of episodic flooding arising from SLR, increasing frequency and intensity of storm surge and waves (Vousdoukas et al., 2018) and, in estuary settings, increased rain and river flooding (Moftakhari et al., 2017; Ward et al., 2018). In the Arctic, warming imperils coastal settlements, and is increasing geohazard activity along circum-Arctic coasts which could increase the frequency of tsunamigenic landslides (Fritz et al., 2017; Strzelecki and Jaskólski, 2020), posing a significant threat to Arctic coastal communities and built infrastructure (e.g., (Hatcher and Forbes, 2015; Radosavljevic et al., 2016; Gauthier et al., 2018; Jaskólski et al., 2018)).

Currently between 76-310 million people, and assets worth US$6,500-US$11,000 billion are on land in the coastal 1-in-100-year floodplain in C&S of all sizes (Neumann et al., 2015; Muis et al., 2016; Brown et al., 2018; Kulp and Strauss, 2019; Kirezci et al., 2020; Haasnoot et al., 2021b). Across these studies, there is *high confidence* that without further action, by 2100, 158-510 million people and US$7,919-12,739 billion of assets under RCP4.5, and 176-880 million people and US$8,813-14,178 billion of assets under RCP8.5, would be in the 1-in-100 year floodplain. Recent improvements in digital elevation data indicate that exposure is likely to be at the higher end of these estimates (Kulp and Strauss, 2019). SLR driven changes in wave characteristics and tides could further amplify risk (Arns et al., 2017). Human-induced subsidence (e.g., through groundwater abstraction) increases relative SLR locally in deltaic coastal cities in deltas having impacts same order of magnitude as SLR but can in some cases be mitigated or even stopped with appropriate management (Esteban et al., 2020; Herrera-García et al., 2021; Nicholls et al., 2021). There is *limited evidence* but *high agreement* from long-term studies that the rate of increase of land at risk accelerates after 2100 (Brown et al., 2018), with risk doubling between 2020-2100 but is 1.5 times faster from 2100-2150 under RCP8.5 (Haasnoot et al., 2021b).

Nicholls et al. (2018) report a 26% and 38% reduction, relative to RCP8.5, in people experiencing flooding each year by 2095 if global temperatures stabilise at 2 or 1.5°C respectively. Most people exposed to coastal flooding live in coastal C&S in least developed countries (Edmonds et al., 2020; Haasnoot et al., 2021b). Currently, about 17 million people from middle-income countries are at risk of flooding by a 10-year event, and about 65 million by a 100-year event; just accounting for SLR (i.e., population and protection stays at 2020 levels) this is projected to increase rapidly to 27 and 74 million respectively (a rate of ~0.5 million/year). This accelerates after 2050, with the number of people in the 100-year floodplain increasing at a rate of ~0.55 million/year under RCP4.5 and ~1 million/year under RCP8.5 up to 2100, and ~1.4 million/year between 2100-2150 for RCP8.5 (Haasnoot et al., 2021b).

These impacts are concentrated in cities. For example Abadie et al. (2020) calculate USD1,600-3,200 bn in damages in 136 major coastal cities. Impacts vary between regions (Schinko et al., 2020), and are the far greatest in absolute terms in South and Southeast Asia, with large relative changes in Africa and Small Island Development States (SIDS) and considerable absolute changes as well in Europe (e.g., (Le, 2020; Haasnoot et al., 2021b; Hooijer and Vernimmen, 2021)). Furthermore, even small changes (10cm) in SLR above present can double the frequency of the 1-in-50 year flood event in many regions, especially in equatorial coastal settlements and Pacific islands (Vitousek et al., 2017).

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Worldwide, around a quarter of sandy beaches eroded at 0.5m yr^{-1} between 1984-2016 (Luijendijk et al., 2018), and as many as 70% of beaches experience erosion, which is expected to accelerate as global sea-level rises (Fitton et al., 2018). Between 1984-2015, the overall surface of eroded land is about 28,000 km^2, twice that of gained land; and is predominantly driven by construction of coastal or inland water management structures, exploitation of coastal resources or clearing of coastal ecosystems (Mentaschi et al., 2018). Improved understanding of biophysical feedbacks has reduced global estimates of wetland losses (including mangrove, fresh and saltwater marsh), and consequently, by 2100, under RCP8.5, these losses are estimated to be up to 30%, or 61,213 km^2, compared to present day (Schuerch et al., 2018).

Analysis of C&S and infrastructure at risk of coastal erosion are analysed at a local or regional scale. In England, for example, 8,900 properties, of which 1,200 do not have coastal protection, are in areas at risk from coastal erosion, and by the 2080s this could increase to over 100,000 properties (CCC, 2017). There are limited global analyses of future erosion rates, but Hinkel et al. (2013) estimate 6,000-17,000 km2 of land could be lost due to SLR driven erosion of sandy beaches, displacing 1.6-5.3 million people; with economic impacts between US$300-US$1,000 billion. More recent analysis by Vousdoukas et al. (2020b) calculates 13.6–15.2% of the world's sandy beaches could face severe erosion by 2050, increasing to 35.7–49.5% (95,061–131,745 km^2) by 2100 under RCP4.5 and RCP8.5 respectively. Where accommodation space exists (e.g., rural areas), migration of beaches may be possible (Cooper et al., 2020a).

Some observations and modelling of reef islands (including atolls) in the Pacific Ocean indicate they can adapt to SLR by sediment accretion (Kench et al., 2015; McLean and Kench, 2015; Kane and Fletcher, 2020; Masselink et al., 2020). Other studies suggest higher vulnerability to submergence due to SLR (Perry et al., 2018). For beaches and dunes, from 1984-2016, an estimated 24% of the world's sandy beaches eroded at rates exceeding 0.5 m yr^{-1}, while 28% are accreting and 48% are stable (Luijendijk et al., 2018). Direct impacts and responses to SLR are difficult to assess, as beach and dune erosion or accretion are affected by several other factors such as sediment availability, wind-wave climate, and anthropogenic actions on or near the shore (Perkins et al., 2015; Toimil et al., 2020). A study in the Mediterranean estimated SLR will cause about 25% increase in erosion volumes over this century (Enríquez et al., 2019).

SMCCP2.1.2 Risks to Livelihoods and Coastal Activities

There is *high confidence* about regionally differentiated but considerable and tangible climate change compounded impacts in coastal C&S, including damage and loss to lives and livelihoods (Tessler et al., 2015; Avelino et al., 2018), negative impacts on health and wellbeing (especially in extreme events) (McIver et al., 2016), and involuntary displacement and migration (Hauer et al., 2016; Hauer, 2017; Davis et al., 2018; Neef et al., 2018); as well as intangible impacts such as psychological impacts due to extreme events, heightened inequality based on gender/ethnicity/structural vulnerabilities, and loss of things of personal or cultural value, and sense of place or connection, including the existential risk of the demise of nations due to submergence (Allison and Bassett, 2015; Barnett, 2017; Weir et al., 2017).

Risks to key economic sectors: Key socio-economic sectors critical to coastal C&S - such as coastal tourism, fisheries and shipping - are already experiencing climate-related impacts and are projected to face escalating risk due to climate change (Weatherdon et al., 2016; Becker et al., 2018). Bindoff et al. (2019) noted with *high confidence* that fishery catches in many regions are already impacted by changes to the ocean and stated with *medium confidence* that further ocean changes are projected to reduce the maximum potential catches of fish stocks. Hoegh-Guldberg et al. (2018) notes coastal tourism risks, particularly in subtropical and tropical regions, will increase with climate change, or loss of beach and coral reef assets (*high confidence*). C&S reliant on coastal tourism are projected to experience reduced destination attractiveness as hazards intensify with climate change, with potential for negative effects on tourism demand and local economies (Seekamp et al., 2019; Arabadzhyan et al., 2020), as well as greater erosion and flood risk from coastal squeeze (Lithgow et al., 2019).

Livelihoods: SLR, land subsidence, and flooding are increasing the rate of change of expected losses in deltaic coastal systems (Nicholls et al., 2021), with current impacts highest in South Asia and future risk increases being greatest in the Rhine and Mississippi (4-8 times increase), and Chao Phraya and Yangtze deltas (1.5-4 times increase) depending on risk-reducing investments and strategies (Tessler et al., 2015). Critically, although risks are distributed across deltaic systems at all levels of economic development, global

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comparative studies show wealthier countries are more likely to limit current impacts through infrastructural coastal protection interventions (Tessler et al., 2015; Olazabal et al., 2019b), highlighting the uneven exposure and adaptive capacities in different coastal C&S archetypes. Ocean-dependent livelihoods of people living in coastal C&S are severely impacted by SLR, changing ocean temperatures, and shifts in the intensity and frequency of El Niño–Southern Oscillation (ENSO) events (Allison and Bassett, 2015; Barnett, 2017), with *high confidence* about the severity of coastal hazard risk in particular geographies such as the Arctic and small island states (Nunn, 2013; Schmutter et al., 2017; Weir et al., 2017). Ocean warming and acidification are projected to significantly affect communities dependent on fishing, aquaculture, and marine tourism through lowered incomes and disrupted livelihoods (Himes-Cornell and Kasperski, 2015; Avelino et al., 2018). Notably, these impacts will constrain coastal livelihoods in Africa, Oceania, and South and Southeast Asia more dramatically because of high exposure to climatic compounded coastal hazards, relatively lower levels of adaptive capacity, and higher dependence on fisheries for employment and livelihoods (Tessler et al., 2015; Ding et al., 2017).

The range of climate compounded hazards affecting coastal settlements also increases risks to livelihoods not directly dependent on the ocean (*medium confidence*). Increased soil salinity because of SLR threatens rice farming in low surface elevation deltas, with potential rice production decreasing substantially from 61% to 34% by 2100 with 1.8 m SLR (upper limit SLR for RCP8.5) in the Ebro Delta in the Mediterranean (Genua-Olmedo et al., 2016). Coastal erosion, cyclones, flooding, and drought drive vulnerability for agricultural livelihoods in coastal Bangladesh (Hoque et al., 2019), where insufficient adaptation constrains livelihood options available for the poorest (Islam et al., 2017; Ahmed et al., 2019).

Health and wellbeing impacts include trauma and fatalities from extreme weather events, increased heat-related illnesses and morbidity (Section 6.2.3.1), compromised water and food safety and security, the spread of vector-borne diseases and zoonoses, and psychosocial ill-health (McIver et al., 2016; Weir et al., 2017; Storlazzi et al., 2018; Pugatch, 2019). Without effective adaptation, increased intensity of extreme events, particularly tropical cyclones and flooding, are projected to result in increased human fatalities in coastal regions (*medium evidence, high agreement*) (Seo and Bakkensen, 2016; Yu et al., 2018a; Bakkensen and Mendelsohn, 2019; Pugatch, 2019). While there is *medium confidence* that climate change mediates exposure to and bioaccumulation of pollutants through the marine food chain (Bindoff et al., 2019) how this will cascade into impacts on human health and food systems remains less well understood (see Cross-Chapter Box ILLNESS in Chapter 2).

Human mobility: Decisions to migrate or not are mediated by climatic drivers (e.g., coastal flooding, cyclones) and non-climatic drivers (e.g., livelihood opportunities, conflict) (Cross-Chapter Box MIGRATE in Chapter 7; Boas et al., 2019). While ascertaining the projected numbers of migrants at different warming levels is constrained by attribution issues (how much movement is climate-driven) and the paucity of evidence on how multiple climatic risks interact (e.g., SLR, coastal flooding, and land subsidence) to drive mobility decisions and outcomes (Boas et al., 2019; Wrathall et al., 2019; McLeman et al., 2021), here, we present a summary of the current and projected evidence. While there is growing evidence on projected climate-driven migration in coastal settlements (Hauer et al., 2016; Rigaud et al., 2018; McMichael et al., 2020), there is *low agreement* on the actual numbers given the difficulties in attributing climate changes as a driver (Abubakar et al., 2018; Kelman, 2019) (Cross-Chapter Box MIGRATE in Chapter 7).

There is *high confidence* that climate change is already “reshaping the comparative advantages of regions, making some places less productive and liveable” (Adger et al., 2020), with impacts on observed migration (Cross-Chapter Box MIGRATE in Chapter 7 summarises this evidence). In coastal C&S, changing configurations of hazards, exposure, and vulnerability are already increasing human mobility necessitating a range of risk management strategies from involuntary displacement and forced migration, to planned relocation Oppenheimer et al. (2019) global; Maharjan et al. (2020) in South Asia; Koubi et al. (2016) in Vietnam.

There is *limited evidence* but *high agreement* that increased warming and hence accelerated SLR will increase future mobility-related risks in densely populated hazard-prone coastal settlements, in small islands and low-lying coastal zones, and among vulnerable populations increase (also see RKR H, Chapter 16; Hauer et al., 2020); Bell et al., 2021); Lincke and Hinkel, 2021);). Global SLR, which is typically framed as a coastal risk solely, is projected to have cascading risks through inland displacement and migratory effects

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(Hauer et al., 2016; Davis et al., 2018; Oppenheimer et al., 2019; Robinson et al., 2020). For example, SLR is projected to drive migration from low-lying coastal regions into inland areas with significant changes in regional population distribution (Aerts, 2017; Hauer, 2017). By 2050 in Bangladesh under RCP 8.5 (0.3m SLR), 0.82 million people are expected to migrate due to coastal inundation, and this figure is projected to increase to 2.1 million people by 2100 (Davis et al., 2018). This displacement will impact destination locations through additional demands on jobs (594,000 positions), housing (197,000 residences), and food (783×109 calories) by 2050 (ibid.). Without adaptation, in USA, SLR of 1.8m can potentially displace 13.1 million people, reconfiguring state populations (e.g., adding 1.5 million residents to Texas and displacing 2.5 million residents in Florida by 2100) (Hauer, 2017).

Critically, migration is not available or desirable to all (Assaduzzaman et al., 2020; Hoffmann et al., 2020; Bell et al., 2021) and does not necessarily reduce hazard exposure: there is *medium confidence* that people often move from one risk-prone locality into another, with mixed adaptation outcomes (e.g. Weber et al. (2019) in SIDS; Jain et al. (2017) in India; Dasgupta et al. (2016) in Bangladesh). There is *medium evidence* with *high agreement* that for communities with strong place attachment, relocation can often increase vulnerability e.g., as Farbotko et al. (2020) show in Fiji, Vietnam, Solomon Islands, and the USA. Most importantly, despite increasing risk, not all people can and will move, leading to involuntarily immobile populations (e.g., Zickgraf (2019) in Senegal and Vietnam; Laurice Jamero et al. (2017) in The Philippines).

Non-material impacts and losses: Climate risks in coastal C&S critically affect people through non-material impacts such as erosion of place-based social values, cultural practices, and 'lived values' that provide a sense of belonging, place attachment, esteem, and self-actualisation (*high confidence)* (Graham et al., 2013; Barnett, 2017; Ramm et al., 2017; Weir et al., 2017). In areas such as the SIDS, where entire communities and locations are directly and possibly irreversibly impacted by SLR, there is *high confidence* that climatic challenge peoples' cultural and national identities (Wyett, 2014; Weir et al., 2017). Additionally, there is increasing evidence of non-material impacts of climate change in other diverse geographical locations (e.g. Ramm et al. (2017) in Australia; Tschakert et al. (2017) in Alaska).

SMCCP2.1.3 Risks to the Built Environment

Many coastal C&S have densely built physical infrastructure and assets that are greatly exposed and vulnerable to climate change hazards, and hence a very high damage potential (*high confidence*) (Hinkel et al., 2014; Abadie et al., 2016; Diaz, 2016; Abadie, 2018; Abadie et al., 2020). Key sectors of the built environment include housing, transport and industry as well as other critical infrastructure such as for energy and communication systems (Section 16.5.2.3.4). Impacts to the built environment in coastal C&S therefore imply risks for societies and the global economy in general (Section 16.5.4).

SLR, land subsidence, continued infrastructure development in coastal flood plains, and the rise of asset values are major drivers of future risk in coastal C&S and, without adaptation, built environment risks in coastal C&S are expected to rise considerably in this century across all RCPs (*high confidence*) (Hinkel et al., 2014; Abadie et al., 2016; Abadie, 2018; Magnan et al., 2019; Oppenheimer et al., 2019). Estimating future flood losses in 136 of the largest coastal cities, (Hallegatte et al., 2013) find that average annual losses will increase from US$ 6 billion in 2005 to US $60-63 billion by 2050 due to SLR, land subsidence and socio-economic development even if current levels of flood probability are maintained through adaptation. Average annual losses could reach almost 1.5% of city-level GDP in Guangzhou and New Orleans (ibid.). Abadie (2018) finds, through an assessment of 120 coastal cities, that New Orleans and Guangzhou have the highest expected annual damage by 2100 under RCP 2.6, 4.5 and 8.5 projections, with around USD1.2 trillion in each city. Assessing 19 European cities, Abadie et al. (2016) find that under RCP8.5 average annual flood losses increase between four- and seven-fold by 2050 for the highest risk cities: Istanbul and Izmir (Turkey), Odessa (Ukraine), and Rotterdam (the Netherlands). Overall, the value of assets below the height of 100-year coastal flood events is US$ 17–180 trillion under RCP2.6, and US$ 21–210 trillion under RCP8.5 in 2100, the major fraction of which in cities (Hinkel et al., 2014).

Climate change already has, and is projected to have, increasingly severe impacts on ports, with major geopolitical and economic ramifications from the C&S to global scale (*very high confidence*) (Becker et al., 2018; Camus et al., 2019; Christodoulou et al., 2019; Walsh et al., 2019; Hanson and Nicholls, 2020; Yang and Ge, 2020; Izaguirre et al., 2021; León-Mateos et al., 2021; Ribeiro et al., 2021). Few ports have

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implemented actions addressing risks to assets and operations (*medium evidence, high confidence*) (Becker et al., 2018; Randrianarisoa and Zhang, 2019; Panahi et al., 2020). Port expansion may need to double or even quadruple by 2050, relative to a 2010 baseline, with total global investment of US$223-768 billion (Hanson and Nicholls, 2020). Beyond adapting existing ports to rising SLR, new port development presents opportunities to increase coastal C&S climate-resilience (Hanson and Nicholls, 2020). Port responses that go well beyond terminal and operational considerations, and benefit from engagement of stakeholders and governance actors as part of wider C&S adaptation pathways, show the greatest potential for CRD (*high confidence*) (Mat et al., 2016; Becker et al., 2018; León-Mateos et al., 2021). Port cities are thus critical focal points – functioning as enablers or barriers to adapt to climate change and transition towards low-carbon, CRD pathways (*high confidence*) (Mat et al., 2016; Randrianarisoa and Zhang, 2019; Panahi et al., 2020; León-Mateos et al., 2021).

In terms of risks to particular types of the built environment (residential buildings, industry, transportation infrastructure, informal settlements, cultural heritage sites), *limited evidence* is available at the global scale but individual case-study assessments predict with *high agreement* that overall risks will increase with climate change across the built environment of coastal C&S (Jim W. Hall et al., 2019). The number of seaports in Europe exposed to inundation levels higher than 1m under RCP8.5 is projected to increase by 80% from 2030 to 2080 (Christodoulou et al., 2019). Global annual damages to road and rail infrastructure from coastal flooding are currently US$ 0.4-6.2 billion (Koks et al., 2019), in Vietnam alone, 1m SLR would destroy 12% of the road network and cost US$ 2.1 billion to rebuild (Chinowsky et al., 2015). There are 269 airports at risk of coastal flooding, and this increases to 413 under RCP8.5 and the expected disruption to flights increases by a factor of 17-69 even if global temperature is stabilised at 1.5ºC or RCP8.5 respectively (Yesudian and Dawson, 2021). (Marzeion and Levermann, 2014; Reimann et al., 2018) suggest that at least 79–140 cultural and mixed world heritage sites are at risk of coastal flooding for global warming of 2ºC, with a significant proportion of these concentrated in the Mediterranean, although it is likely this is an underestimate especially for the African continent (Brooks et al., 2020).

Informal settlements and slums are, in many cities, over-proportionally exposed to flooding; in Mumbai, the flood exposure of slum settlements is 71% above the city average (Hallegatte et al., 2017). These settlements also have increased vulnerability to flooding and coastal storms due to the low building quality, mostly of a semi-permanent nature (Roy et al., 2016). Projections or scenario assessments for future risks trends in slums are *limited* to a few case studies. For Ho Chi Minh City (Vietnam), for example, the exposure differential of currently 10-20% between slums vs. non-slums is projected to increase with ongoing climate change (Bangalore et al., 2019).

Lastly, cultural heritage sites in coastal cities are vulnerable to coastal hazards because there is often little to no option for relocation or adaptation. Comprehensive global studies on climate risk to cultural heritage sites are still lacking. An analysis of 49 UNESCO World Heritage sites in the Mediterranean concludes that flooding risks might increase by 50% on average until 2100 under RCP8.5, with much larger increases possible for some sites (Reimann et al., 2018).

SMCCP2.1.4 Risks to Ecosystems and their Services

Coastal C&S depend to a variable extent on ecosystem services provided by nearby habitats and ecosystems, such as shallow lagoons and estuaries, intertidal flats and marshes, mangrove forests, seagrass beds, coral reefs, beaches and dunes. These services include provisioning of materials and food e.g., wood, fishery habitat (Kok et al., 2021; zu Ermgassen et al., 2021), mitigation of coastal hazards e.g., attenuation of storm surges, waves, and reducing erosion (CCP2.3.2.3; Godfroy et al., 2019; Zhu et al., 2020), climate change mitigation e.g., through carbon sequestration (Macreadie et al., 2017; Rovai et al., 2018; Ward, 2020), water quality regulation e.g., nutrient, pollutant and sediment retention and cycling (Wilson et al., 2018; Zhao et al., 2018), and recreation and tourism (Pueyo-Ros et al., 2018).

There is *high confidence* that loss of coastal ecosystem services will expose millions of people and associated property to increased coastal hazard risk; in particular, flood risk. There is *medium evidence* and *high agreement* that loss of coral reefs and mangroves are expected to contribute to loss of fisheries production in adjacent waters (Mehvar et al., 2019; Sandoval Londoño et al., 2020; Seraphim et al., 2020). The economic value of mangroves, tidal marshes, coral reefs, seagrass beds is typically estimated to

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be US$10,000-100,000/ha, higher than terrestrial or other marine ecosystems (Costanza et al., 2014; Macreadie et al., 2019). The value of services including art, food provision, amenity and recreation in Bangladesh and Indonesia are projected to decrease by 16-40% and 25%-90% respectively (Mehvar et al., 2018; Mehvar et al., 2019), in the USA benefits are as much as US$825 million in direct damage reduction and US$ 971 million indirect damage reduction (Storlazzi et al., 2019).

The impact of climate change on coastal ecosystems is significant, but depends on the ecosystem's natural capacity to adapt to change and sustain its functioning; these depend upon local biophysical settings like tidal range, water quality, and species composition (Balke et al., 2016; Kirwan et al., 2016; Edmonds et al., 2020; Wiberg et al., 2020). Other climate change factors, such as increasing CO_2 concentrations and temperature effects on plant productivity, may affect these ecosystem functioning (Manea et al., 2020).

In many places, marshes and mangroves can adapt to relative SLR rates of 3-10 mm yr^{-1} (Blankespoor et al., 2017; Horton et al., 2018b; Saintilan et al., 2020; Törnqvist et al., 2020), but fail to survive SLR rates of just a few mm yr^{-1} when suspended sediment concentrations are very low (1–10 mg l^{-1}) or where tidal range is <1m (Kirwan et al., 2016; Wiberg et al., 2020). Coastal ecosystem losses could be minor if warming stays below 1.7°C GWL, but at higher GWL or SLR above 0.5m expected to lead to large scale impacts and loss of ecosystem services including their ability to protect coastal C&S (Section 13.4; Key Risk 1; van der Spek, 2018; Jones et al., 2020; Triyanti et al., 2017).

Globally, coral reefs currently provide US$ 272 billion flood protection against 1-in-100 year storms (Beck et al., 2018). Yet, coral reefs are considered to be the marine ecosystem most at risk, even under an RCP2.6 scenario (Dasgupta et al., 2019; Díaz et al., 2019; Graham et al., 2020; Cornwall et al., 2021). Under RCP8.5, most coral reefs are predicted to experience mean water depth increases of more than 0.5 m by 2100, which will increase high wave-energy exposure accelerating sediment mobility, shoreline change, and island overtopping (Perry et al., 2018). There is *high confidence* that 2ºC or more GWL will lead to significant loss of coral cause by ocean warming and acidification, which induces coral bleaching and reduces coral calcification (Hoegh-Guldberg et al., 2018; Perry et al., 2018; Hughes et al., 2020; Cornwall et al., 2021). Cumulative impacts of SLR, acidification and anthropogenic damage reduce coral effectiveness of adapting to climate change (Hughes et al., 2017b; Perry and Morgan, 2017; Yates et al., 2017).

There is *high confidence* that anthropogenic interventions, such as river damming and coastal engineering interventions pose the greatest immediate risk to coastal ecosystems as they reduce sediment supply (Chapters 3 and 13; Cooper et al. (2020b); Sabour et al. (2020); Ranasinghe et al. (2019);Yang et al. (2020)), and limit lateral inland migration (e.g., blocked by dikes, buildings, roads). Up to 30% of the global marsh and mangrove area is at risk of disappearing by 2100 under RCP 8.5, with the Gulf of Mexico, Indonesia, and Mediterranean at greatest risk (Schuerch et al., 2018).

In summation, non-climatic anthropogenic drivers have already increased the exposure and vulnerability of coastal ecosystems and low-lying coastal C&S to climate change impacts and SLR and extreme sea level events in particular, and this is expected to continue into the distant future (*very high confidence*). To compound matters, coastal C&S are subject to both compound and cascading risks (see Section 6.2.5; Bevacqua et al., 2019; Lawrence et al., 2020; Zscheischler et al., 2018 for definitions).

SMCCP2.1.5 Cascading and Compound Risks

Most studies on C&S in this section have focused on adapting to a single, or limited set of risks, such as SLR, heat waves or water resources. Some (e.g., Nicholls et al., 2015; Estrada et al., 2017; Yin et al., 2020; Malagon Santos et al., 2017), but comparatively fewer studies, address the combined effects of multiple drivers, clustering of multiple events, or assess the consequences of having to adapt to multiple impacts and risks that cascade (Box 15.2).

Coastal C&S are particularly vulnerable to compound and cascading impacts due to severe storms (*high confidence*) that may be exacerbated by climate change. In late October 2012, Hurricane Sandy severely impacted the New York – New Jersey coast. Over 100 people were killed and damages incurred of approximately USD 65 billion in direct impacts due mainly to storm surge flooding (Rosenzweig and Solecki, 2014). In New York City, the event set off a series of cascading impacts with massive power

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outages causing extended disruptions of water, gasoline (for vehicles), communication (i.e., mobile phones), and HVAC (for heating) for hundreds of thousands of residents (Haraguchi and Kim, 2016).

In 2017, parts of the Caribbean and Florida, USA, were devastated by compound and cascading impacts from Hurricanes Irma and Maria, which caused devastation with compound and cascading impacts that included significant rainfall and inland/street flooding, extreme winds, and storm surge flooding that caused cumulative and compounded damage well beyond the storm surge zone (Kishore et al., 2018; Rey et al., 2019; So et al., 2019; Raymond et al., 2020). Severe cascading impacts affected Puerto Rico's settlements in the aftermath of Maria; a public health crisis continued to spread and impact the well-being of residents for over a year, resulting in thousands of excess deaths significantly greater than the official death toll of 64 (Kishore et al., 2018). Compound impacts from Hurricane Irma resulted in both Barbuda and Ragged Island, Bahamas, being declared uninhabitable, requiring the evacuation of all residents, and leaving these islands without human residents for the first time since being occupied (Look et al., 2019; Thomas and Benjamin, 2020).

The occurrence of compound risks from extreme events exacerbated by climate change can be further complicated by non-climate related drivers, such the COVID-19 pandemic, that threaten population health and hamper pandemic responses (Salas et al., 2020; Shultz et al., 2020a; Shultz et al., 2020b). In May 2020, Cyclone Amphan brought extensive wind, rain, and storm surge damage to Kolkata, India. Storm preparedness and response, including evacuation and sheltering, was considerably compromised by the pandemic crisis. Evacuation and sheltering had to simultaneously respond to the storm impacts and public health guidelines to prevent the further spread of the virus (Baidya et al., 2020; Ebrahim et al., 2020; Majumdar and DasGupta, 2020).

Either separately or individually, compound and cascading risks can significantly alter the climate risk profile and vulnerability of coastal C&S (Edmonds et al., 2020; Eilander et al., 2020; Ghanbari et al., 2021), and population mobility (CCP2.2.2). Better understanding the probability of these compound events, and the processes driving them, is essential to lessen, or adapt to these potentially high-impact risks; however, difficulties in predicting concurrent climate and non-climate risks will risk reduction and resilience building difficult (Ebrahim et al., 2020; Cross-Chapter Box COVID in Chapter 7). Individual coastal C&S, and regional case studies (particularly for Europe, Australia, and the U.S.), illustrate an increasing likelihood of compound risks with accelerating climate change (*likely, medium confidence*) (Wahl et al., 2015; Xu et al., 2019; Kirezci et al., 2020).

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Table SMCCP2.1: Illustrative examples of 31 coastal cities and settlements detailing risks (as a function of hazard, exposure, and vulnerability) and adaptation actions. *Population estimates are for the entire metropolitan region population.

Geomorphology	**City, country, population (2020, in millions)**	**Section CCP2.2 – Risks to coastal cities and settlements**			**Section CCP2.3 – Solution space**
		Hazard	**Exposure**	**Vulnerability**	**Adaptation options**
Estuary	Monkey River Village, Belize (0.0002) *200 people*	Coastal erosion Tropical cyclones Fluvial flooding Sea level rise	Entire village exposed to hurricanes (90% of built structures destroyed by Hurricane Iris in 2001) (Karlsson and Hovelsrud, 2015; Karlsson et al., 2015)	Remote, small village; few livelihood opportunities; outmigration; at risk Creole culture; emotional and spiritual connections to place at risk due to erosion Weak political voice; expensive to transport goods to village; no local health services; destructive practices upstream negatively impact village life; tensions about options for future (Karlsson et al., 2015)	*Protect:* Ad hoc measures over time; 2000-2010 temporary sea defence with tires and wooden stakes built; but not addressed erosion due to upstream practices starving river of sediment to prevent erosion. *Accommodate:* For hurricanes, early warning, evacuation, and post-disaster recovery.
	Belém, Brazil (1.5)	Urban heat island Sea level rise, Flooding	40% of urban area is sited in low lying areas below mean sea level (Mansur et al., 2016)	Coastal mangrove contraction due to sea level rise (Mansur et al., 2016) Large proportion of informal settlements in flood prone areas and inadequate peripheral areas for housing (Szlafsztein and de Araújo, 2021)	*EbA:* Conservation and restoration of mangrove forests along Para River to reduce coastal erosion (Borges et al., 2017) *Accommodate:* Enhance urban storm water drainage systems to reduce pluvial flood risk; raising of domestic bathroom and shower thresholds to reduce household flooding (Mansur et al., 2018)
	Perth, Australia (2.1)*	Urban heat island Sea level rise Drought Flooding	Exposure to sea level rise due to low elevation of densely populated metropolitan area Strong urban heat island effects (Rogers et al., 2019), heatwaves and air quality (Patel et al., 2019), and exposure to more frequent	Elderly population in urban area; extensive coastal property and key infrastructure along coastline that potentially leads to conflict if coastal retreat from sea level rise is implemented (Grace and Thompson, 2020)	The Western Australian Coastal Planning Policy allows for flexible coastal adaptation for sea level rise utilising a variety of approaches along a time frame (Grace and Thompson, 2020), including: *Protect:* sea walls, groynes, levees and offshore breakwaters *Accommodate:* Sand nourishment and dune stabilisation for coastal erosion; desalination for drought (Morgan, 2020)

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			and intense drought (Radcliffe, 2015)		*Retreat:* Long term planned retreat and expansion of coastal foreshore reserve
	Shanghai, China (27)*	Fluvial, pluvial floods Urban heat island Sea level rise Land subsidence	SLR-linked exposure to coastal inundation is very high, exacerbated by land subsidence and socioeconomic development (Du et al., 2020). Expected damages due to SLR - $16-212 billion (RCP 8.5, 2100) (Abadie et al., 2020).	High intra-city inequality among neighbourhoods especially based on population age, built infrastructure, and migrant status (Gu et al., 2018)	*Protect:* Sea walls with 200-year coastal flood return level, seawalls with a 100-year coastal flood return level, flood walls with 1000-year riverine flood return level along the Huangpu River *EbA:* Lingang Sponge City with green roofs, RWH wetlands, permeable pavements to store excess runoff (Temmerman et al., 2013; Yu et al., 2018b; Filho et al., 2019; Du et al., 2020)
	Greater London, United Kingdom (8.9)*	Fluvial, pluvial floods Storm surge Sea level rise Urban heat island Drought		London includes some of the poorest areas in the UK Considerable amount of ageing infrastructure (Caparros-Midwood et al., 2017)	*Protect:* Maintain current assets, and raise existing flood defences when needed. Longer term (from 2050), decide and construct the best option for the future of the Thames Barrier and adapt other assets *Accommodate (from 2035):* Reshape riverside through development, to improve flood defences, create habitat and improve access to the river; Thames tideway large sewer tunnel to manage sewage and surface water *EbA:* green infrastructure within the city to manage surface water flooding and UHI (Dawson et al., 2011; Pelling et al., 2016; Hall et al., 2019)
	Venice, Italy (0.637)	Sea level rise Subsidence Air Pollution	Without adaptation, potential economic damages of USD$5.5-16 billion for the 21st century. Flood duration expected to increase from 2-3 weeks to 2-6 months/yr for RMSL rises of 30, 50 and 75cm, respectively	UNESCO World Heritage Site that is most at risk in Mediterranean >90% city is vulnerable to flooding High dependence on tourism	*Protect:* System of mobile barriers (MoSE, Modulo Sperimentale Elettromeccanico), which close lagoon inlets during storm surges only. *Accommodate:* Locally: Wet and dry flood proofing of buildings. *EbA:* Present salt marshes also reduce flood risk, but protection is needed. (Ch13 Box 13.1)
	Esmeraldas, Ecuador (0.16)	Flooding Sea level rise Landslides Drought	8.4% to 14% of the current population, and airport, at risk of permanent/periodic flooding by 2100	Poverty, informal housing, and limited-service provision Majority of town informal settlement Inadequate financial, human or political resources (Gutierrez et al., 2020)	*Accommodate:* Spatial planning to limit urban expansion in at risk areas. *Retreat:* Relocation of high-risk communities *EbA:* Green infrastructure for UHI Improvements of sewer systems and water efficiency measures (UN-Habitat, 2012; Tiepolo, 2016)

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	Istanbul, Turkey (15.214)	Flooding Sea level rise Salinization Subsidence Drought	Nearly 15 million people exposed to flood risk Damages projected to be $10bn/year from SLR and flooding by 2100 (Abadie et al., 2016; Istanbul, 2018; Reimann et al., 2018)	Rapid population growth Important Port Fisheries World Heritage Site	*Protect:* Flood protection *Accommodate:* Spatial planning, urban green spaces, building resilience measures Improvements in sewer systems and water efficiency measures (van Leeuwen and Sjerps, 2016)
	Bangkok, Thailand (10.6)	Sea level rise Land subsidence Flooding Urban heat island Air pollution	High exposure to SLR; expected SLR damage in 2100 ~ USD$312.5 billion (Abadie et al., 2020) Additional exposure from groundwater extraction for municipal use leading to land subsidence (Jevrejeva et al., 2016) (Berquist et al., 2015)	Rapid urbanisation and population growth with large proportion of informal settlements Most population and key infrastructure contributing to economy are vulnerable to flooding and most of Bangkok is <1.5 m asl (Thanvisitthpon et al., 2018).	*Protect:* Flood control infrastructure (canals, drainage pipes) as well as a polder system integrated with drainage tunnels
	New York City, USA (23.5)*	Flooding Urban heat island Sea level rise Land subsidence Salinization	Approximately 10% of metropolitan region's population lives in the coastal zone	High inequality, poverty Aging infrastructure	*Protect, accommodate:* Rebuild by Design integrated protection for high value sites like lower Manhattan; flood proofing and bulkheading, street level raising; minor overflow retention and detention efforts; shutting down salinized wells *EbA:* For heat mitigation, passive cooling solutions along with NbS
Deltaic	Dhaka, Bangladesh (21)	Tropical cyclones Sea level rise Fluvial, pluvial floods Heatwaves Drought	By 2050, 0.9 and by 2100 2.1 million people could be displaced by direct inundation due to SLR in the country (Davis et al., 2018)	Poor public infrastructure Unplanned urbanisation ~40% population lives in informal settlements, high in-migration and livelihood precarity (Araos et al., 2017; Rahman and Islam, 2019)	*Protect:* bunds, embankments (Rahman and Islam, 2019; Lázár et al., 2020) *Accommodate:* Autonomous strategies by households such as raising floor height; urban land zoning away from low-lying areas (Araos et al., 2017); improving stormwater drainage infrastructure (Rahman and Islam, 2019) Bangladesh Delta Plan 2100
	Rotterdam, Netherlands (0.651)	Sea level rise Fluvial flooding Subsidence Salinization Water scarcity Urban heat island	~60% of The Netherlands is susceptible to large scale coastal and river flooding, of which 26% is below present msl.	Majority of the region lives below sea level	*Protect:* maintaining coastline with (mega)sand nourishment and flood defences (levees and storm surge barriers). Alternative solutions are explored for high SLR, including advance and a combination of protect city centers and accommodate/retreat.

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					Flushing polders with fresh water. Locally experiment with air barriers to reduce salt intrusion. Water storage and water efficiency measure to address drought. *EbA:* Retention and greening in cities to avoid pluvial flooding (Kwadijk et al., 2010; Van Alphen, 2016)
	Can Tho City, Viet Nam (0.4)	Tidal flooding Pluvial flooding Extreme rain Flash floods		High poverty and limited adaptive capacity, small shop-owners are particularly vulnerable (Huong and Pathirana, 2013)	*Accommodate:* Elevation of housing, canal dredging. Upgrading of drainage system to cope with heavy rains and flesh floods. (Sudmeier-Rieux et al., 2015; Radhakrishnan et al., 2018)
	Jakarta, Indonesia (10.8)	Sea Level Rise Land subsidence Pluvial flooding	Exposure from mean SLR compounded by relatively large land subsidence from groundwater extraction (3.3m in 2040) (Abadie et al., 2020). Up to 1/6th additional land area will be subject to 1m floods from extreme rain by 2050 (Takagi et al., 2016)	Vast majority of population and key infrastructure reside in low-lying areas, with high vulnerability to commercial/business, industrial, and governmental land use areas (Budiyono et al., 2016)	*Protect:* Engineered sea walls and dikes e.g., Giant Sea Wall project – (Garschagen et al., 2018) *Retreat:* moving of new capital city of Indonesia to Borneo Island
Open coast	Accra, Ghana (2.5)	Sea Level Rise Extreme rainfall Pluvial, fluvial floods Coastal erosion Storm surge		Poor drainage infrastructure 90% flood-prone communities are in informal settlements with poor physical and socio-economic living conditions (Amoako and Inkoom, 2017)	*Protect (SLR):* Reactive measures to reduce the erosion impacts through building sea defence structures on Ghana's coast (e.g., Ada Sea Defense System in Kewunor fishing village). Includes seawalls, land reclamation technology such as groins, and revetments and roads to protect a coastline. *Protect (pluvial flooding):* Levees to redirect floodwaters *Accommodate/retreat:* Upgrading storm drains; reinforcement of houses, clearing of gutters, sandbagging and relocation by households (Twerefou et al., 2019)
	Alexandria, Egypt (5.2)	Sea Level Rise Storm surge Water scarcity Tsunami	Regional SLR up to 20cm (RCP8.5, 2100)	High poverty and socio-economic disparity High geomorphological vulnerability as large parts of the city are below mean sea level. Hence, even a 10cm SLR has significant damage potential.	*Protect*: elevated ridges and sea walls, particularly around the depressed areas east of the city Rainwater harvesting

	Lagos, Nigeria (14)*	Sea Level Rise Urban heat island Extreme rain Flash floods	Expected SLR 0.9m (RCP8.5, 2100) Increasing exposure due to climate change and new settlements in floodplains	High percentage of population living in slums with informal status and particularly high vulnerability in terms of health impacts, damage to assets as well as economic impacts. High evidence that women have higher vulnerability. (Adelekan, 2010; Ajibade et al., 2013; Ajibade and McBean, 2014; Jevrejeva et al., 2016; Abiodun et al., 2017; Ajibade, 2017)	*Accommodate*: neighbourhood scale adaptation; Advance (of the maladaptive type): Further advance through the development of new coastal estates, partly through nourishment, particularly in Eko Atlantic. (Adelekan, 2010; Ajibade et al., 2013; Ajibade and McBean, 2014; Jevrejeva et al., 2016; Abiodun et al., 2017; Ajibade, 2017)
	Napier City (0.065), Hawkes Bay (0.1786), New Zealand	Tsunami Coastal erosion Storm surge Sea Level Rise Flooding Land subsidence after earthquake	Critical infrastructure on low-lying shoreline exposed to SLR, including airport, port infrastructure, and small communities in the Hawkes Bay.	Low cost of living but generally high standard of living Low-lying coastal areas prone to coastal hazard risk Coastal flooding during long-period swell events occurs more often, along with continued erosion in these areas. Peri-urban and holiday settlements built along the coast. Community concern over perceived inaction to ongoing damage at the coast to properties	*Protect:* for assets immediately at risk *Accommodate:* Land use planning restrictions *Retreat:* managed retreat, withdrawal of insurance cover in the most exposed coastal areas. *Protect:* infrastructural interventions *EbA*: beach nourishment and wetlands management, realignment
	Happisburgh, United Kingdom (0.009)	Coastal erosion		Small population limits economic benefits of protection	*Retreat:* Purchase and removal of dwellings at risk; relocation of caravan site and village hall *Accommodate:* Realignment of coastal footpath; business support
	St Georges, Grenada (0.036)	Flooding Sea level rise Urban heat island Tropical cyclones Tsunami Land subsidence Drought		Lack of infrastructure, limited financial, human resource capacity. City centre and Grenadian national identity is coastal and subject to SLR related flooding.	*Accommodate, protect:* National planning documents to protect, and accommodate SLR *Protect:* Earthquake and tsunami warning system.
	Miami-Dade, USA (6.2)*	Flooding Urban heat island Sea level rise	Most of the region is at low elevation, increasingly subject to flooding	Extreme income inequality	*Accommodate:* Buy out programs, elevating buildings and roads to reduce risk to coastal flooding; draining

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		Tropical cyclones Land subsidence Salinization		Inadequate infrastructure to respond to highly dynamic climate risks and urbanization	and pumps, and elevating buildings to address pluvial flooding. *Protect* is considered, but is limited. Pathways considered include drainage and pumps to buy time to elevate roads and buildings, and relocate in some locations.
	Utqiagvik (formerly Barrow), Alaska, USA (0.005)	Storm surge Coastal erosion Thawing permafrost Sea ice melt Subsidence	$1bn of infrastructure at risk	Poverty and inequality; migration and demographic change Isolation Disruption to food and fisheries; failing ice cellars	*Protect:* Erosion, flood protection, including beach nourishment. *Accommodate:* Sea ice and weather information system; identify and map watersheds, wetlands, and traditional trails important to subsistence; changing hunting and fishing practices; use Local Environmental Observers *Retreat:* New sites for construction, and zoning; creating new ecological areas and/or restoring, enhancing existing ones.
	Nassau, Bahamas (0.275)	Tropical cyclones Sea level rise Flooding Salinization Ocean acidification and warming	60% tourism infrastructure within 100 m of the coastline and exposed to flooding and SLR. (Pathak et al., 2020)	Tourism is > 50% city's GDP; 83% tourism infrastructure is at risk to storm surge and flooding associated with Category 5 tropical cyclone (Pathak et al., 2020)	*Protect:* small-scale seawalls, dykes, groynes with some beach nourishment by communities, individuals and businesses experiencing coastal erosion
	Kingston, Jamaica (1.2)	Tropical cyclones Sea level rise Flooding Salinization Ocean acidification and warming	Concentration of settlements in flood-prone low elevation areas (Burgess et al., 2015) Critical transportation infrastructure located in low-lying areas (Monioudi et al., 2018)	At 1.5°C above pre-industrial levels, critical transport infrastructure faces disruptions due to higher temperatures, rainfall and wind changes, inundation (Monioudi et al., 2018) Vector-borne diseases more prevalent in urban areas where human and vector populations are high (Henry and Mendonça, 2020)	*Protect:* raising and fortifying roads (Monioudi et al., 2018)
	Seychelles (0.1)	Sea level rise Rainfall variability Ocean warming	Densely populated settlements concentrated in low-lying and narrow	Reliance on coastal tourism and fishing (Khan and Amelia, 2014)	*Protect:* rock armouring; timber piling; sea walls; boardwalks and bollards to prevent removal of beach sediments; shoreline stabilization

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		and acidification Coastal flooding Extreme weather events	coastal zones. (Khan and Amelie, 2015)		*EbA:* sand dune restoration and management, replanting native coastal vegetation; beach nourishment; mangrove restoration; coral reef restoration
	Singapore, Singapore (5.6)	Urban heat island Sea level rise Flash flooding	SLR-linked exposure is high; mean SLR - 0.9 m (RCP4.5, 2100) to 1.5m (RCP8.5, 2100) (Horton et al., 2018a) Vast majority of population reside in low-lying areas	Key infrastructure contributes to economy (e.g., rail, airport, ports) located <2 m above sea level and vulnerable to future SLR (Cannaby et al., 2016)	*Protect*: sea walls, polders *Accommodate* (coastal land reclamation) (Chou et al., 2019; Sengupta et al., 2020) *EbA* via connected urban parks for Urban Heat Island and urban flash flood events (Chow, 2018) Large technological solutions e.g., desalination of seawater, recycled sewage to reduce drought exposure (Chuah et al., 2018)
	Manila, Philippines (14)	Sea level rise Land subsidence Flooding Tropical cyclones	Exposure from severe tropical cyclones and SLR. Land subsidence from groundwater extraction leads to additional SLR in Manila by 2025 (Jevrejeva et al., 2016). Risk from more intense tropical cyclones in West pacific at 2C warming (Oppenheimer et al., 2019)	Low elevation, large proportion of informal settlements lining waterways, groundwater extraction for municipal use (Doberstein et al., 2020) Most population and key infrastructure vulnerable to flooding and storm surges from tropical cyclones (e.g. Haiyan in 2013).	*Protect:* Breakwaters to protect seaport from TC storm surges (Lam et al., 2017) *Managed Retreat* through small-scale resettlement (Doberstein et al., 2020)
Mixed	Maputo-Matola, Mozambique (3)*	Fluvial flooding Sea level rise Tropical cyclones	Population at risk due to climate compounded flooding and other perils ~50,000 people (2016-17) (Rodrigues, 2019)	Rapid urbanization, largely unregulated and chiefly informal settlements with high levels of poverty and absence of basic services (Rodrigues, 2019). Urban sprawl spreading into low-lying coastal areas causing environmental degradation that increases exposure to hazards compounded by climate change (Beja da Costa and Ribeiro, 2019)	*Protect:* for port related facilities *Accommodate:* Numerous autonomous adaptation actions taken by vulnerable people - collective action to specific measures in face of flooding (Rodrigues, 2019)
	Florianopolis, Santa Catarina Island, Brazil (1.2)	Storm surges Coastal erosion Flooding Sea level rise	West coast of the island assessed as highly variable, with 'nodes' of high exposure (da Silveira and Bonetti, 2019).	City HDI of 0.847, one of the most liveable and safest places to live in Brazil.	*Protect:* ad hoc protect measures to for at-risk property from coastal storms and storm surges.

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			~13.4% exposed to SLR by 2100 (Montanari et al., 2020)	High inequality; in informal settlements (favelas) HDI is 0.390). Rapid urbanization, poor sanitation and water supply; major raw sewage contamination in coastal environment, extensive unregulated land occupation.	
	Cape Town, South Africa (4.6)*	Sea level rise Coastal erosion Extreme waves Storm surges Salinization of aquifers Urban heat island Drought Flooding	88,000 informal households prone to flooding (Desportes et al., 2016) 19 sites on open coastlines exposed to impacts of SLR. ~125,000 people displaced by SLR by 2100	Apartheid legacy Gini coefficient 0.59 (the lowest for a SA metropolitan area) High inequity, unemployment, crime, violence Inadequate public infrastructure, and poverty	*Protect:* infrastructure measures to contain flooding. Chiefly infrastructure provisions for reducing drought risk - proved inadequate in recent years. *Accommodate:* Emergency management provisions like early warnings for flood and erosion/storm/wave damage
	Mumbai, India (20.4)*	Sea level rise Extreme precipitation Pluvial flooding	By 2100, at 1m SLR, submergence of ~ 86.22 km^2 land ~43 km^2 built-up area exposed to flooding (Murali et al., 2020) Expected damages due to SLR - $112-735 billion (Abadie et al., 2020)	Poor public infrastructure Highest informal settlement population in Asia (42%) Built on reclaimed land prone to flooding; high environmental degradation (e.g., of urban mangroves that provided mitigated flood risk) (Singh et al., 2021) Certain social groups (e.g., fishers) highly marginalized	*Advance:* Building new road infrastructure on reclaimed land *Accommodate:* Vulnerable communities are adapting autonomously (e.g., urban fishing villages spread risk by using insurance, diversifying their livelihoods in the face of growing coastal erosion. In flood-affected informal settlements, households are increasing floor height and extending the wall to increase ceiling height and storing valuables on elevated platforms. Micro Small and Medium Enterprises building temporary barriers, constructing platforms to elevate machinery, and using dewatering pumps to drain floodwater (Schaer and Pantakar, 2018)

Table SMCCP2.2: Constraints and enablers to adaptation in coastal C&S: illustrative examples from 25 coastal cities and settlements. Constraints are categorised as **economic** (existing livelihoods, economic structures, and economic mobility); **social/cultural** (social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support); **human capacity** (individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, and skill development**; governance, institutions & policy** (existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity); **financial** (lack of financial resources); **information/awareness/technology** (lack of awareness or access to information or technology; **physical** (presence of physical barriers); and **biological** (temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind) (categorization based on Ch 16.4).

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Geomorphology	**City, country, population (2020, in millions)**	**Adaptation constraints**							**Enablers**
		Economic	**Social/ cultural**	**Human capacity**	**Governance, institutions & policy**	**Financial**	**Information/ awareness/ technology**	**Physical/Biological**	
Estuary	Monkey River Village, Belize (0.0002) *200 people*	Constrained livelihood opportunities	Tensions about development pathways	Limited adaptive capacity or resource to address erosion	Villagers disconnected from political power; self-reliant	Very limited	Limited	Remote, isolated	– Erosion perceived by all to be a threat to collective interests. – Intervention by journalists, researchers and local NGOS (bridging organizations) to secure media attention - especially after hurricane - and use window of opportunity to attract government investment in temporary protective works. – Choices about future tourism development will reconfigure constraints and enablers.
	Shanghai, China (27)*		High income inequality, can exacerbate differential vulnerability					Physical location makes it a high-risk city	– Long-term planning up to 2100 – Access to technical expertise – Strong national and municipal focus on climate change
	Greater London,							Long term legacy of	– Long term Thames Estuary 2100 planning

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	United Kingdom (8.9)*							development of the city	– Strategic leadership with climate change embedded through the Greater London Spatial Development Plan, and London Climate Change Partnership – Access to technical expertise
	Esmeraldas, Ecuador (0.16)				Institutional capacity and incongruent coordination and planning between multi-level governments Political resistance to implement and enforce zoning regulations				–
	Istanbul, Turkey (15.214)				Ineffective coordination between institutions. Local and regional implementation plans do not adequately address climate change impacts and adaptation		Data limited as climate change research relatively new		– Potential for citizen involvement in urban green space adaptation – Develop institutional capacity, including need for training, building inter institution cooperation, awareness raising, and monitoring and evaluation system
	Bangkok, Thailand (10.6)			High vulnerability due to difficulties in	poor implementation and communication				–

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				building adaptive capacity, especially in informal settlements	of policies; lack of accounting or climate change Flood risks from pluvial and SLR/land subsidence factors are not coordinated and policies often fail to account for climate change (Saito, 2014)				
	New York City, USA (23.5)*		Underlying social and environmental inequity that encourage distrust and lack of support of planning efforts, and worldview that argues for remaining in high-risk locations and resisting conditions of retreat		Lack of governance structures to deal with inter jurisdictional issues Assorted adaptation approaches without any centralized approach across three US states and hundreds of municipalities in the NY metropolitan region		Lack of financial resources		– Municipal and state governments have attempted to increase the amount of public outreach and community engagement to increase support for resiliency and adaptation efforts.
Deltaic	Dhaka, Bangladesh (21)		High inequality can lead to inequitable risk management	Low human capacity for long-term adaptation	Reactive governance (earlier), somewhat fragmented approach to climate risks		Inadequate funding (vis a vis exposure)	Low-lying deltaic city with very high exposure and high population density	– Proactive governance with current plans going up to 2100 – Strong focus on technology transfer (E.g., with The

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									Netherlands) to develop long-term delta plans – Climate change is a key national priority
	Rotterdam, Netherlands (0.651)								– Delta program developed adaptive plan to anticipate (uncertain) climate change. The programme has its legislative foundation in the Delta Act, and has a Delta Fund with a budget of € 1 billion per year. This yearly budget is reserved until 2029 (Bloemen et al., 2019b; Haasnoot et al., 2020) – Present plan is able to address 1m in 2100
	Can Tho City, Viet Nam (0.4)	Poor households have limited resources to adapt (mostly upgrade and lift their houses).			Land use planning is met with such high pressure to grow the city, that precautionary adaptation (e.g., flood retention areas) is difficult to implement. (Garschagen, 2015)				– Growing domestic policy attention to climate change adaptation and high attention by international donors and research organizations. (Radhakrishnan et al., 2018)
	Jakarta, Indonesia (10.8)				Reactive risk management that hinders adaptation (Neise et al., 2017)				– Cultural enablers in the community e.g., mutual assistance, social structures from self-organisation, networking for social-

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									economic support (Surtiari et al., 2017)
Open coast	Accra, Ghana (2.5)	Poorer households and migrant status shapes adaptation action	People are continually reclaiming lagoons and mining sand leading to more inundation and poor drainage)		Poor waste disposal practices and drainage systems, silting and choking of drains, land-use change and informal urbanization (Twerefou et al., 2019)	Inadequate money to undertake flood mitigation at HH level (Twerefou et al., 2019)	Access to information for preparing for flood needs to be improved in all the localities (Yankson et al., 2017)	Inadequate drainage infrastructure	– Locality and government approaches to flood mitigation mediate household adaptation: "households living in communities in which houses built on waterways had been demolished appear less likely to adopt some protective action against flood damage". – Better early warnings for floods can reduce flood impacts. – Behavioural change to avoid clogging stormwater drains can mitigate flood risk.
	Lagos, Nigeria (14)*	Low resource base for households to do undertake accommodate adaptations.				Widespread lack of housing rights Lack of integrated, risk-sensitive and forward-looking planning			–
	Napier City (0.065), Hawkes Bay (0.1786), New Zealand				Vested interests challenge provisions for public safety and sustainability			Eroding coastline	– Relatively strong information / technical capacity. – Political will, governance capacity and resources available to implement adaptation pathways logic in face of coastal hazard risk

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									– Robust institutional provisions supported by national legislation and guidance – Robust social capital and institutionalised commitment to Maori. – Strong environmental ethic
	Happisburgh, United Kingdom (0.009)		Undervalued coastal cultures and icons		Unclear goals of adaptation			Uncertainty about coastal change	–
	Utqiagvik (formerly Barrow), Alaska, USA (0.005)				Absence of a lead entity for adaptation and lack of clear jurisdiction or protocols Focus of disaster response on rebuilding as opposed to risk-prevention activities Resource management regimes often ad hoc and fragmented Lack of integrated strategy and actions often short term /				– Leverage local knowledge, and historical precedent of transformative change in the past – Better integration of community and scientific information e.g., real time sea ice analysis

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					piecemeal and not anticipatory				
	Nassau, Bahamas (0.275)				Government places responsibility for coastal protection with private sector and individuals while individuals expect government to be responsible for long-term projects	Very limited national funding provided for adaptation	Inadequate data on climatic risks inhibits vulnerability assessments Low perception of climate change risk among population and policymakers, (Petzold et al., 2018; Thomas and Benjamin, 2018)		- Increasing knowledge of climate change risks through evidence-based studies - Improving governance systems to identify responsibilities and plans for adaptation and gaining access to funding to supplement limited national budget.
	Kingston, Jamaica (1.2)					Costs of adaptation critical infrastructure is high (Monioudi et al., 2018)			
	Seychelles (0.1)		Customary practices such as parking cars in dune areas reduces adaptation effectiveness and increases costs (had to construct bollards to prevent parking)	Limited decision-makers and technical staff with climate change adaptation expertise	Fragile institutions and inadequate governance related to climate change; climate change not integrated into development planning	Lack of national funding to support adaptation strategies; limited financial support from international agencies	Limited scientific knowledge that is useful for decision making; limited understanding of climate change risks; little investment in adaptation research; lack of quality data on impacts; data gaps at the sub-national scale,	Land use patterns inhibit rainwater drainage and lead to flash flooding	- Promote individual behavior change through constructive and punative measures - Promote synergies between adaptation and mitigation by connecting EbA projects with community-based adaptation; promote cross-sectoral and institutional collaboration to avoid duplication of projects; ensure that climate

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							particularly for more rural areas		change policies are coherent with national development strategies – Form direct partnerships between climate scientists and decision-makers to co-produce usable information for decision-making, draw on local knowledge to identify local indicators of climate change impacts; technology transfer from successful adaptation responses in other similar locales – Cross-sectoral and institutional collaboration to improve efficient use of limited financial resources
	Singapore, Singapore (5.6)							Small land area with no space for retreat from SLR	- Integrated whole of government approach across ministries committing to long-term climate adaptation (and mitigation) goals by 2030 (Angiello, 2021)
	Manila, Philippines (14)		Social and Livelihood risks		Jurisdictional conflicts between municipalities, lack of political will and corruption (Meerow, 2017; Doberstein et al., 2020) Uncoordinated top-down			lack of land availability	– Bottom-up community-based actions that improve adaptive capacity exist and can be strengthened (Porio, 2014) – Institutional reorientation towards metro-wide planning and infrastructure transformations that are climate-resilient and

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					municipal action				equitable (Meerow, 2017)
Mixed	Maputo-Matola, Mozambique (3)*			Deep poverty and precarity with minimal access to basic services	Weak government capacity; self-help is predominant coping mechanism for majority of urban poor	Weak and inadequate adaptation finance	Limited capacity, and key role played by international donor community	Mangrove ecosystems and coastal ecosystems in decline compounding CC risk	– Port city provides foundation for livelihoods. Community DIY coping mechanisms.
	Florianopolis, Santa Catarina Island, Brazil (1.2)	Strong economy, undermined by environmental degradation; rapid unregulated urbanization	Inequity but strong tradition of cultural heritage	Low access to good research capability	Inadequate government capacity and coordination to regulate development and land-use practices; poor leadership at federal level; no evidence of preparation for long-term SLR			'Pinchpoint' connection to the mainland where there is densely populated habitation; Ongoing environmentally destructive practices	– Knowledge hub; robust economy; partnerships between private sector-municipality and active civil society – Physical exposure to coastal risks limited to two main areas on east and NE coast (Mussi et al., 2018) – Need to attend to short-term basic services and infrastructure and long-term climate goals (e.g., (Bonatti et al., 2019).
	Cape Town, South Africa (4.6)*	Marked inequity; reliance on key sectors impacted by climate change and Covid-19 e.g., tourism	Diverse and divergent socio-cultural realities fractured along wealth and racial lines Legacy of apartheid - poverty and inequity;	Health, education, crime, housing, etc. highly differentiated driving vulnerability to climate change Rapid spread of informal settlements	Well-governed metro; but impacted by political turf-battles from local to national level; coordination challenges between sectoral agencies within and between spheres of	Access to significant finances but unevenly spread; infrastructure and human development needs exceed available resources	High capacity, unequally distributed and institutional capacity mismatched with needs.	Variable climate compounded hazard exposure; high energy coast with some areas at high risk of SLR Fragility of water infrastructure	– Capable leaders; effective interactions between municipal authority and researchers; experience in community-based initiatives.

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			divided city - spatial layout distributes climate risks to poor	and population growth	government, and inadequate leadership from central government; disconnect between municipal authority and people in informal settlements; underlying challenge of meeting present pressing needs and preparing for future climate realities.			Legacy development exposed to climate change impacts Distinctive coastal ecosystems adversely impacted by CC	
	Mumbai, India (20.4)*			Low human capacity to undertake long-term adaptation to floods Rapid spread of informal settlements and population growth	Political inertia, reactive risk management; lack of urban adaptation plan (Araos et al., 2016; Weinstein et al., 2019; Singh et al., 2021)			Low lying areas, with city built on reclaimed land Legacy development exposed to CC impacts	–

Table SMCCP2.3. Adaptation options assessed for three selected coastal archetypes. Their soft (surpassable) and hard (unsurpassable) limits indicate reasons for adding more adaptation options or switching to alternative options. For each option the potential effectiveness to reduce risk to coastal flooding and erosion is assessed in terms of a relative sea-level rise: low (e.g., less than 0.3m), medium (e.g., 0.3–0.8m) and high (e.g., more than 0.8m). Trade-offs include synergies and conflicts with social goals, climate mitigation, and other hazards.

Geomorphology Small islands with open coasts. **Illustrative cities:** Kingston (Jamaica), Seychelles, Nassau (Bahamas), Singapore, South Tarawa (Kiribati), Funafuti (Tuvalu), Male (Maldives).					
Strategy	**Option**	**Soft/hard limits**	**Potentially effective to low/medium/high SLR**	**Trade-offs and co-benefits**	**References**

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Protect	Seawall, with possibly a drainage system	- Is already not sufficient to prevent flooding and erosion in several places - In higher places it could delay flooding.	Low	Trade-offs: potential for negative ecological impacts and loss of ecosystem services; induced long-term loss of beaches has negative implications for neighbouring sediment cells, but also for coastal tourism and access to beaches for recreational and spiritual uses; has potential to be maladaptive as it could provide false sense of security that attracts developments in risky places and triggers a self-reinforcing protect pathway	SMCCP2.1, Chapter 16, (Logan et al., 2018; Brown et al., 2020)
Protect/-NBS	Wetland, mangrove (restoration)		Low	Co-benefits: provides new livelihood opportunities; supports healthy ecosystems and reliant livelihoods such as fisheries	CCP2.3, Chapter 2, (Oppenheimer et al., 2019)
Protect-NBS	Coral reef, (restoration)	- Coral reefs can keep up with 0.5 cm/year, constrained at 1.5C and lost at 2C in many places.	Medium	Co-benefits: provides new livelihood opportunities; supports healthy ecosystems and reliant livelihoods such as fisheries	CCP2.3, Chapter 2, (Oppenheimer et al., 2019)
Retreat/avoid	No-build zones		Low		
Retreat	Relocate landwards (national)	- Hard limit for SIDS sited on topographically challenged regions	Low in highly urbanized regions.	Trade-offs: increased population density in inland areas may lead to strain on resources (e.g., water availability reduced	

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				as freshwater lens are salinized due to SLR)	
Retreat	Relocate international	- Requires receiving location - Long lead time	High	Trade-offs: loss of sovereignty, significant non-economic loss and damage including loss of community, sense of place, traditional livelihoods, locations of cultural and spiritual significance.	(Laurice Jamero et al., 2017; Magnan and Duvat, 2020)
Accommodate	Elevate infrastructure	- Option for household level - Raising floor and ground of houses and roads has limited height and becomes increasingly unacceptable with higher frequency of flooding	Low	Trade-offs: does not prevent loss of ecosystem services (e.g., salinization of freshwater lenses); loss of land suitable for farming	(Laurice Jamero et al., 2017)
Protect	Land raising	- Requires space to temporarily relocate to - Material to raise land. - Costs	Low		(Magnan and Duvat, 2020)
Advance	Land reclamation with ground elevation	- Costs, but can pay back through real-estate revenues - Strong subsidence after construction - Material to build land - Potentially long lead time - High costs, less feasible with large water depth > 30m	Low	Trade-offs: negative effects on ecosystems and biodiversity	SMCCP2.1, (Hinkel et al., 2018; Sengupta et al., 2018; Brown et al., 2020; Wang and Wang, 2020)
Advance	Floating	- Experimental stage, implemented within a city in calm waters - Provides opportunities for developments in land scarce cities	High		(Penning-Rowsell, 2020; Wang and Wang, 2020)

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Geomorphology Resource rich megacities in deltas, open coasts and estuaries **Illustrative cities:** New York (USA), Greater London (UK), Shanghai (China), Bangkok (Thailand)					
Strategy	**Option**	**Soft/hard limits**	**Potential effectiveness**	**Trade-offs and co-benefits**	**References**
Protect	Seawall and drainage/pump system	- With increasing SLR is becomes more difficult to drain excess water, in particular in regions with heavy monsoons or in river deltas - High benefit cost ratio in urbanized regions, but not affordable for every community	Medium		Chapter 13, (Esteban et al., 2020; Vousdoukas et al., 2020a)
Protect	Levees and dunes		High		
Protect	Storm surge barrier (for estuaries, and bays)	Residual risk. Long lead time for planning and implementation. Increasingly closes with higher SLR until permanently closed, hampering connection with hinterland	Medium - high		SMCCP2.1, Chapter 10, Chapter 13, (Scussolini et al., 2017; Du et al., 2020; Haasnoot et al., 2020; Yin et al., 2020)
Protect-EbA	Wetland, mangrove restoration	- Mangroves can keep up with 0.5-1 cm/yr, decreased effectiveness at 2C GWL. - Space: coastal squeeze. - Higher benefit cost ratio than protect and less residual risk. - Time: require time to establish/grow	Low-medium	livelihood and ecosystem benefits (e.g., fish populations)	SMCCP2.1, Chapter 2, Chapter 10, (Oppenheimer et al., 2019; Du et al., 2020; Morris et al., 2020)
Accommodate	Wet-proofing Dry-proofing of infrastructure and buildings	Can be implemented faster and with less costs compared protect.	Medium		(Scussolini et al., 2017; Du et al., 2020)

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Retreat	No-build zones		Medium		Chapter 13, (Du et al., 2020; Lincke et al., 2020)
Retreat	Relocate (internal)	Space, sunk costs, lack of planning, time and public and political support. Can help to transform cities	High	Negative impacts on poor, marginalised groups in terms of exposure to new risks and reduced livelihood opportunities	(Ajibade, 2019; Haasnoot et al., 2021a; Jain et al., 2021; Lincke and Hinkel, 2021; Mach and Siders, 2021)
Protect	Land raising	Difficult in existing regions, easier in rebuild or newly build areas. Long lead time	High		(Scussolini et al., 2017; Storbjörk and Hjerpe, 2021)
Advance	Land reclamation with ground elevation	Costs, material, potentially long lead time. Lifetime can be extended with levees. Can experience large subsidence	High		(Brown et al., 2019; Sengupta et al., 2020)
Advance	Floating seawards	Within a city, experiments occur in calm waters	Uncertain		(Penning-Rowsell, 2020)

Table SMCCP2.4: Governance challenges, enablers and lessons learned in the face of escalating coastal hazard risk: [This assessment builds upon and extends Oppenheimer, et al., 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, H.-O. Pörtner, et al., (eds.) and integrates CCP2 assessment of archetypal cities and settlements by the sea (Table SMCCP2.1; Table SMCCP2.2)]

Key governance challenges	**Critical enablers and lessons**	**Illustrative lessons from around the world**	**Illustrative archetypal cities and settlements**
<u>Complexity:</u> Climate change compounds non-climatic hazard risks facing coastal cities and settlements (C&S) in interconnected, dynamic and emergent ways for which there are no simple solutions - Complexity grows as change unfolds and intersecting coastal hazards cause cascading	**Draw on multiple knowledge systems to co-design and co-produce more acceptable, effective and enduring responses** (Dannevig and Aall, 2015; Dutra et al., 2015; Sovacool et al., 2015; Desportes and Colenbrander, 2016; Ziervogel et al., 2016; Adger et al., 2017;	Lessons learned in C&S from Australia, the Comoros, Arctic, Canada, Portugal, Brazil, and New Zealand to Norway and the USA (Costas et al., 2015; Dannevig and Aall, 2015; Betzold and Mohamed, 2017; Chouinard et al., 2017; Elrick-Barr et al., 2017; Carter, 2018; Flynn et al., 2018; Lawrence et al., 2018; Huntington et al., 2019; Marengo et al., 2019; St. John III and Yusuf, 2019) - Reveal dynamic complexity by drawing on multiple sources of locally relevant evidence - Use and integrate local, indigenous and scientific knowledges - Create shared knowledge and understanding through storytelling	Seychelles (0.1mill): Partnerships being created between science and policy, with local knowledge, to co-produce usable information for decision-making but major awareness and information constraints to overcome. Dhaka (21mill), Bangladesh: Climate change is national priority. Partnering with the Netherlands to develop long-term data plans, but challenge to overcome governance and institutional constraints, marked inequity and differential risk, and low human capacity for long-term adaptation given severe escalating risk.

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and compounding impacts and risks, with responses at times deepening risk - SLR introduces novel compound problems, with complex connections between biophysical and socio-economic, cultural and political aspects that challenge conventional science and public planning, decision-making and implementation - The rapid pace, complexity and novelty of SLR is already challenging conventional decision-making in some localities, e.g., some Arctic and Pacific Island communities	Betzold and Mohamed, 2017; Onat et al., 2018; Warner et al., 2018; St. John III and Yusuf, 2019; Fayombo, 2020)	- Bridge gaps between science, policy and practice by experimenting with novel approaches supported by governance actors and stakeholders working across organisational, sectoral and institutional boundaries	Jakarta (10.8mill), Indonesia: Community-based efforts foster mutual assistance and self-organisation, but reactive measures predominate, and severe adaptation constraints.
	Build governance capacity to tackle complex problems (Moser et al., 2012; Head and Alford, 2013; Head, 2014; Dewulf and Termeer, 2015; Kwakkel et al., 2016; Termeer et al., 2016; Alford and Head, 2017; Chu et al., 2017; Daviter, 2017; Cinner et al., 2018; McConnell, 2018; Valdivieso and Andersson, 2018; Fink, 2019; Head, 2019; Ndebele-Murisa et al., 2020; Wijaya et al., 2020; Angiello, 2021)	Lessons learned in the Dutch Delta Programme to future-proof the Netherlands (Dewulf and Termeer, 2015; Bloemen et al., 2018; Bloemen et al., 2019a): - Joined up visionary leadership is key, e.g., make Cabinet- and city-level commitments to long-term policy implementation - Translate political will into substantial dedicated budgets to build government capacity to tackle complex problems - Use flexible approaches that build resilience, e.g., create an independent agency alongside traditional administrative body - Use an adaptation pathways approach to make short-term decisions consistent with long-term goals, given future uncertainty - Translate national requirements into local action by having enabling provisions for tailored local-level policy and practice - Tackle emergent problems by setting up enduring monitoring and lesson-learning processes - Governance arrangements reconcile competing demands in an inclusive, timely and legitimate manner - Counter policy deadlocks due to short-term priorities and vested interests with a long-term perspective (e.g., 100 years), considering plausible scenarios, and incentivising novel solutions	Singapore (5.6 mill), Singapore: Integrated whole of government approach across ministries committing to long-term climate adaptation (and mitigation) goals by 2030 (Angiello, 2021) Rotterdam (0.65mill), Netherlands: Delta Programme, supported by law, administrative arrangements, and €1bill pa budget to 2029. Florianopolis, Santa Catarina Island (1.2mill), Brazil: Building a knowledge hub through public-private-civil society partnerships, but constrained by inequity and challenge of unregulated development, and need to reconcile short-term infrastructure and service imperatives with long-term climate goals. Nassau, (0.275mill) Bahamas: Identifying responsibilities, accessing funding, and preparing adaptation plans drawing on evidence-based studies to overcome constraints of limited funding, inadequate data, and low governance capacity. Shanghai (27mill), China: Combination of long-term planning, political will and national and municipal provisions to address climate change, and strong technical capability, has contained risk in short- to medium-term. But longer-term prospects daunting, given no room to retreat. Can Tho City (0.4 mill), Vietnam: Emerging focus on adaptation, engaging international donors and research community, but immense urban growth pressure, and poor households have limited capacity to take long-term actions.

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<u>Time horizon and uncertainty:</u> The future is uncertain but climate change will continue for generations and cannot be addressed by short-term (e.g., 1-10 years) responses - Coastal C&S face a dilemma: Delayed action imposes a huge burden on future generations but there is a fine line between under- and over-investing in risk reduction, especially for at-risk C&S - SLR is certain to continue for many centuries, with deep uncertainty about the magnitude and timing of SLR beyond 2050 - SLR and coastal hazard risk challenges standard planning and decision-making practices, which strive for certainty and predictability - Coastal hazard risk goes beyond short-term bureaucratic, political, electoral and budget cycles - SLR and coastal hazard risk is dynamic and difficult to address in an adaptive manner given the inflexibility of laws and institutions like private property rights - Given its long time horizon, it is hard to	**Adopt a long-term view but take action now and keep options open to adjust responses as sea level rises and circumstances change** (Haasnoot et al., 2013; Hurlimann et al., 2014; Dewulf and Termeer, 2015; Stephens et al., 2018; OECD, 2019; Fu, 2020)	Lessons learned in diverse C&S from Nigeria to Bangladesh, Brazil, the Arctic, Indonesia, China, Netherlands and New Zealand (Termeer et al., 2013; Broto et al., 2015; Tuts et al., 2015; Ajibade et al., 2016; Brown et al., 2016; Butler et al., 2016b; Francesch-Huidobro et al., 2017; Ahmed et al., 2018; Cradock-Henry et al., 2018; Flood et al., 2018; Flynn et al., 2018; Bloemen et al., 2019a; Lawrence et al., 2019; Marengo et al., 2019; OECD, 2019): - Establish national policies and guidance that takes a long-term view (e.g., 100 years) but compels action now - Seek buy-in from key stakeholders in government, the private sector and civil society - Develop a shared medium- (10-50 years) to long-term vision (100+ years) - Meaningfully involve stakeholders in adaptation planning, e.g., by involving representatives in decision-making - Reconcile divergent perspectives through tailored responses - Address power imbalances and human development needs, e.g., in goal-setting and process design - Draw on local, indigenous and scientific knowledges	Napier (0.065 mill), Hawkes Bay, (0.178 mill) New Zealand: National law compels local authorities to take 100-year perspective, and local 2100 Strategy to address coastal hazard risk explicitly accounts for dynamic complexity and uncertain future through adaptation pathways logic. Shanghai (27mill), China: Plans up to 2100, strong national and municipal focus on climate change, and access to technical expertise, helps to address escalating risk, despite high income inequality and differential exposure and vulnerability. Dhaka (21mill), Bangladesh: Long term adaptation plans in place through to 2100, but challenge to translate national prioritisation of climate change into local reality.
	Avoid new development commitments in high-risk locations (Hurlimann and March, 2012; Glavovic and Smith, 2014; Hurlimann et al., 2014; Tuts et al., 2015; Berke and Stevens, 2016; Butler et al., 2016b; OECD, 2019)	Lessons learned in diverse C&S from Australia to the USA (Dyckman et al., 2014; Hurlimann et al., 2014; Kousky, 2014; Tuts et al., 2015; Butler et al., 2016a; Gibbs, 2016; Vella et al., 2016; Koslov, 2019; OECD, 2019; Siders, 2019): - Use spatial planning to regulate coastal development in exposed localities - Take advantage of the window of opportunity created by extreme events - Adopt tailored risk reduction and resilience building measures post-disaster - Understand and address political risks and local opposition to enable managed retreat when risk is intolerable and inundation is unacceptable	Rotterdam (0.65mill), Netherlands: Delta Programme promotes 'living with water', which simultaneously allows for and manages urban flooding. Napier (0.065 mill), Hawkes Bay, (0.178 mill), New Zealand: Regulatory provisions discourage new development in high-risk locations, and addressed through coastal hazard strategy that provides for sequenced adaptation interventions in the face of unfolding climate change impacts. Florianopolis, Santa Catarina Island (1.2mill), Brazil: Unregulated ad hoc development in at-risk locations hampers effective adaptation.

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mobilise visionary action through today's business, civic and political leaders			
Cross-scale and cross-domain coordination: Decisions bound by jurisdictional and sectoral boundaries fail to address linkages within and between coastal ecosystems and C&S facing interconnected climate change compounded impacts and risk - SLR impacts extend across scales and levels of governance - SLR and coastal hazard impacts extend across sectors, policy domains and functional areas of governance (e.g., planning, emergency services, asset management, etc.) - Tackling coastal hazard risk exceeds the capacity of many local governments, communities and property owners - A 'joined-up' response to coastal hazard risk is vital, especially coherence between national policy and local competency	**Develop networks and linkages within and between different governance scales and levels, and across policy domains and sectors, to improve coordination, build trust and legitimise decisions** (Glavovic and Smith, 2014; Colenbrander and Sowman, 2015; Dutra et al., 2015; Sowman et al., 2016; Chu et al., 2018b; Forino et al., 2018; Lund, 2018; Pinto et al., 2018; Clar, 2019; Pittman and Armitage, 2019; Reiblich et al., 2019; Kim et al., 2020)	Lessons learned in diverse C&S from the Caribbean to Ireland, Vietnam, Uruguay and England (Flannery et al., 2015; Gopalakrishnan et al., 2017; Carro et al., 2018; Chu et al., 2018b; Den Uyl and Russel, 2018; Gopalakrishnan et al., 2018; Huynh and Stringer, 2018; Olazabal et al., 2019a) (Pittman and Armitage, 2019; Reiblich et al., 2019; Berman et al., 2020; Kim et al., 2020): - Collaborative projects involve state and non-state actors - Use multi-lateral agreements, e.g., between neighbouring countries (or between coastal regions and C&S) - Connect people, organizations and communities through boundary spanning organizations – within and between governance levels and scales - Leadership by central actors with capable teams is key - Mobilise the capabilities of communities and non-state actors - Address policy inconsistencies and clarify roles and responsibilities - Secure national and regional resources to support local efforts - Use measures to promote interaction, deliberation and coordination to avoid spill-over effects - Strengthen linkages between formal (e.g., regulatory) and informal (e.g., traditions and rituals) institutions, e.g., through information sharing - Use spatial coordination mechanisms, e.g., land-use planning, to translate national and regional provisions into local competencies	Seychelles (0.1mill): Cross-sectoral and institutional collaboration being explored to improve effective and efficient use of limited financial resources and community-based adaptation and EbA explored to bridge adaptation and mitigation and improve coordination. But governance constraints are severe and climate change not well integrated into development planning. Florianopolis, Santa Catarina Island (1.2mill), Brazil: Effective local climate action hampered by governance constraints and weak federal leadership. Cape Town (4.6mill), South Africa: Enabling multi-level climate governance is advanced at the local-provincial level, but political turf-battles hamper national-provincial-local progress. Enabling effective municipal-informal settlement action is challenging given the apartheid legacy and scale of poverty and inequity.
	Build shared understanding and enable locally appropriate responses through experimentation, innovation and social learning (Dyckman et al., 2014; Glavovic and Smith, 2014; Lassa and	Lessons learned in diverse C&S from India to Brazil, USA, Europe and east Asia (Blok and Tschötschel, 2016; Chu, 2016; Hughes et al., 2017a; Chu et al., 2018a; Bellinson and Chu, 2019; Duvat and Magnan, 2019; Fink, 2019; Marengo et al., 2019; Wolfram et al., 2019): - Take account of local history, culture and politics through engagement, experimentation and innovation - Prioritise social learning and shared understanding, e.g., make information accessible to all irrespective of level of education, language, etc.	Utqiagvik (formerly Barrow), Alaska, USA (0.04 mill): Leveraging local knowledge and historical precedent of transformative change, and better integrating local and scientific knowledge. But severe governance and institutional capacity constraints, with ad hoc actions focused on short-term, and lack of clarity about responsibilities. Cape Town (4.6mill), South Africa: Capable local leaders together with effective collaboration between

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	Nugraha, 2014; Dutra et al., 2015; Ensor and Harvey, 2015; Chu et al., 2018a; McFadgen and Huitema, 2018; Mazeka et al., 2019; Wolfram et al., 2019)	- Generate socio-economic, livelihood and climate-development co-benefits - Take advantage of national and trans-national community and local authority networks	climate researchers and municipal authority have initiated range of community-based adaptation initiatives. Translating plans into action is challenging given scope of poverty and inequity, and 'everyday' vulnerability challenges, exacerbated by climate change. New York City (23.5mill), USA: State and city government reaching out to communities to build adaptive capacity and resilience, and draw on strong technical capabilities but challenge given available financial resources and challenges of multi-level governance together with marked inequity and differential exposure and vulnerability, and private property rights prioritization.
Equity and social vulnerability: Climate change compounds everyday inequity and vulnerability in coastal C&S, making it difficult to disentangle and address social drivers of risk - Coastal hazard impacts and responses affect people in diverse ways, with costs and benefits unevenly spread - These responses can compound vulnerability and inequity - SLR and coastal hazards can undermine societal aspirations, like SDGs - Private responses can cause public harm - Responses can deepen vulnerability, risk and marginalisation through elite capture of coastal resources and assets	**Recognise political realities and address vulnerability and equity concerns to achieve just, impactful and enduring outcomes** (Eriksen et al., 2015; Sovacool et al., 2015; Tuts et al., 2015; Adger et al., 2017; Hardy et al., 2017; Holland, 2017; Dolšak and Prakash, 2018; Finkbeiner et al., 2018; Sovacool, 2018; Warner et al., 2018; OECD, 2019)	Lessons learned in diverse C&S from Mozambique to Australia, Cambodia, India, Thailand, Pacific Islands, the Arctic and the USA (Archer and Dodman, 2015) (Broto et al., 2015) (Hardy et al., 2017) (Nunn et al., 2017) (Siriporananon and Visuthismajarn, 2018) (Romero Manrique et al., 2018) (Torabi et al., 2018): - Expose the drivers and root causes of injustice, structural inequity and vulnerability - Link human development concerns, risk reduction, resilience and adaptation - Raise awareness and public support for actions that are just and equitable - Address discriminatory drivers (e.g., on racial grounds) of coastal land-use patterns and risk - Address the barriers marginalised groups face in participating in risk reduction and adaptation planning - Use inclusive planning, decision-making and implementation processes to give voice to marginalised people	Cape Town (4.6mill), South Africa: Adaptation efforts framed by legacy of apartheid and focus on reducing vulnerability, public safety and securing critical infrastructure and community assets. Scale of challenge is daunting. Maputo-Matola (3mill), Mozambique: Port-city provides coastal livelihood opportunities but compromised by environmental degradation compounded by climate change compelling community DIY coping mechanisms in face of severe poverty and vulnerability and weak governance and institutional capacity, and reliance on donor support. New York City (23.5mill), USA: Climate change risk and plight of exposed and vulnerable people brought to public attention after Hurricane Sandy (2012), catalysing adaptation action.
	Strengthen community capabilities to respond to SLR and coastal hazard risk, drawing on external assistance and government	Lessons learned in diverse C&S from Belize to small island states in the Pacific and Caribbean, and rural coastal communities in the USA (Karlsson and Hovelsrud, 2015; Joseph, 2017; Robinson, 2017; Warrick et al., 2017; Weir et al., 2017; Jurjonas and Seekamp, 2018; Kelman, 2018; Petzold and Magnan, 2019):	Monkey River village (200 people), Belize: Remote indigenous community capacity to tackle erosion enabled by interventions by researchers, journalists and local NGOs to secure media and political attention after hurricane damage. Enduring action hampered by severe adaptation constraints, limited

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	support where necessary (Schlosberg, 2012; Musa et al., 2016; Vedeld et al., 2016; Elrick-Barr et al., 2017; Warrick et al., 2017; Dolšak and Prakash, 2018)	- Raise vulnerability and risk awareness and understanding, build community capability and leverage external support by working with professionals, academics, local NGOs, journalists and activists - Where necessary, the rights of vulnerable groups can be secured through court action - Integrate traditional community responses with local government efforts - Ensure gender equity, e.g., through representation on planning and decision-making bodies	livelihood opportunities and contested future development pathways based on tourism. Accra (2.5mill), Ghana: Household adaptation mediated by local government approaches to flood mitigation, with need for better early warning system and measures to maintain local stormwater and related infrastructure to prevent flooding. Severe adaptation constraints. Lagos, Nigeria: Building adaptive capacity to overcome 'everyday' vulnerability and poverty is severely challenging.
<u>Social conflict:</u> Coastal C&S will be the locus of contending views about appropriate climate responses; and face the challenge of avoiding destructive conflict and realising its productive potential - As coastal hazard risk gets progressively worse, social conflict (i.e., non-violent struggles over values, interests, resources and influence) could escalate - In addition to exacerbating difficult trade-offs between private and public interests, ecological, social, cultural and economic considerations, and short- and long-term concerns, SLR could increase social tensions over impacted critical infrastructure, cultural connections to the coast,	**Design and facilitate tailor-made participation processes, involving stakeholders early and consistently through to implementation of agreed responses and subsequent adjustments** (Burton and Mustelin, 2013; Berke and Stevens, 2016; Gorddard et al., 2016; Webler et al., 2016; Schlosberg et al., 2017; Chu et al., 2018a; Lawrence et al., 2018; Mehring et al., 2018; Nkoana et al., 2018; Schernewski et al., 2018; Yusuf et al., 2018; Uittenbroek et al., 2019; Kim et al., 2020)	Lessons learned in diverse C&S from South Africa to Reunion Island and Australia (Sowman and Gawith, 1994; Celliers et al., 2013; Pasquini et al., 2013; Colenbrander and Sowman, 2015; Leck and Roberts, 2015; Pasquini et al., 2015; Chu et al., 2016; Desportes and Colenbrander, 2016; Ziervogel et al., 2016; Colenbrander and Bavinck, 2017; Glavovic et al., 2018; Magnan and Duvat, 2018; Torabi et al., 2018; Colenbrander, 2019): - Create opportunities for integrative solutions by involving key interests and affected parties in adaptation planning - Use conflict resolution mechanisms in participatory processes - Appoint independent facilitators/mediators and involve officials as 'bureaucratic activists' to improve inclusivity and iterative and reflexive engagement - Align informal participatory processes with statutory processes and government practices - Sustain engagement by securing resources for local use, and aligning activities with political and bureaucratic cycles - Involve historically disadvantaged and socially vulnerable groups, e.g., using accessible meeting locations / venues, local languages and culturally appropriate meeting protocols - Involve local leaders who will champion risk reduction and adaptation and help mainstream findings into C&S decision-making - Inclusive processes help address conflict and drivers of vulnerability, and promote just adaptation	Napier (0.065 mill), Hawkes Bay, (0.178 mill), New Zealand: Enabling national regulatory and non-regulatory provisions, together with collaboration between local authorities and indigenous people, involving stakeholders, led to co-designed long-term strategy with commitment to implementation. Translating plans into action is challenging given contending interests. Manila (14mill), Philippines: Metro-wide planning and infrastructure provisions for climate change foster climate justice and resilience being explored; with community-based actions. But severe challenges with extent of exposure and vulnerability, and limited political will, corruption and uncoordinated top-down municipal actions.

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and key livelihood, public health, identity, security and sovereignty concerns - SLR could compound socio-political stressors and challenge prevailing legal provisions and processes	**Create safe settings for inclusive, informed and meaningful deliberation and collaborative problem-solving** (Susskind et al., 1999; Laws et al., 2014; Hiwasaki et al., 2015; Susskind et al., 2015) (Glavovic, 2016; Ung et al., 2016; Nursey-Bray, 2017; Sultana and Thompson, 2017; Magnan and Duvat, 2018; Fayombo, 2020)	Lessons learned in diverse C&S in villages from Bangladesh to communities in South Africa, Australia, and Louisiana and New England, USA, (Rumore; Susskind et al., 2015; Glavovic, 2016; Nursey-Bray, 2017; Sultana and Thompson, 2017; Fayombo, 2020): - Use flexible and enabling processes based in local institutions judged to be robust and fair, supported by governing authorities - Pay attention to local social dynamics and reduce elite domination - Use local and indigenous knowledges and science to inform responses - Encourage institutional improvisation to address local concerns - Use trusted independent facilitators - Incentivise participation of disadvantaged groups - Focus on improving risk literacy, optimism and capacity for joint problem-solving - Use joint fact-finding, scenario planning, negotiate trade-offs, facilitate public dialogue, and secure institutional support for action - Enable ongoing public deliberation and social learning - Commit to continual adjustments as circumstances change over time, e.g., build shared understanding about locally relevant thresholds beyond which alternative courses of action need to be actioned	Napier (0.065 mill), Hawkes Bay, (0.178 mill), New Zealand: Active involvement of local communities, Indigenous People (Māori) and research community to co-produce fit-for-purpose long-term coastal hazard risk strategy. Rotterdam (0.65mill), Netherlands: Delta Programme, has institutionalised multi-level adaptation governance approach with strong accountability mechanisms. London (8.9mill), United Kingdom: Long term provisions for at-risk Thames Estuary, including major protective works, are embedded in Greater London Spatial Development Plan and London Climate Change Partnership that is championed by strategic leadership, and supported by the public and strong technical capability

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