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Cross-Chapter Box 9: Integrative Cross-Chapter Box on Low-lying Islands and Coasts

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Executive Summary

Ocean and cryosphere changes already impact Low-Lying Islands and Coasts (LLIC), including Small Island Developing States (SIDS), with cascading and compounding risks. Disproportionately higher risks are expected in the course of the 21st century. Reinforcing the findings of the IPCC Special Report on Global Warming of 1.5ºC, vulnerable human communities, especially those in coral reef environments and polar regions, may exceed adaptation limits well before the end of this century and even in a low greenhouse gas emission pathway (*high confidence*[1]). Depending on the effectiveness of 21st century mitigation and adaptation pathways under all emission scenarios, most of the low-lying regions around the world may face adaptation limits beyond 2100, due to the long-term commitment of sea level rise (*medium confidence*). LLIC host around 11% of the global population, generate about 14% of the global Gross Domestic Product and comprise many world cultural heritage sites. LLIC already experience climate-related ocean and cryosphere changes (*high confidence*), and they share both commonalities in their exposure and vulnerability to climate change (e.g., low elevation, human disturbances to terrestrial and marine ecosystems), and context-specificities (e.g., variable ecosystem climate sensitivities and risk perceptions by populations). Options to adapt to rising seas, e.g., range from hard engineering to ecosystem-based measures, and from securing current settings to relocating people, built assets and activities. Effective combinations of measures vary across geographies (cities and megacities, small islands, deltas and Arctic coasts), and reflect the scale of observed and projected impacts, ecosystems' and societies' adaptive capacity, and the existence of transformational governance (*high confidence*) {Sections 3.5.3, 4.4.2 to 4.4.5, 5.5.2, 6.8, 6.9, Cross-Chapter Box 2 in Chapter 1}.

Introduction

LLIC are already experiencing the impacts of climate-related changes to the ocean and cryosphere, for both extreme events and slow onset changes (Sections 4.3.3, 5.3.1 to 5.3.6, 6.2, 6.8, 6.9), due to their low elevation, narrow ecological zonation, climate sensitive ecosystems and natural resources, as well as increasing anthropogenic pressures (Sections 1.5, 4.3.2). High levels of impacts to coastal morphology, ecosystems and dependent human communities are detectable today and disproportionately higher risks are expected in the course of the 21st century (*medium evidence, high agreement*) (Sections 4.3.4, 5.3.7), even under a low emission pathway compatible with a 1.5ºC global warming (Hoegh-Guldberg et al., 2018; IPCC, 2018). The magnitude of projected impacts (i.e., risks; Cross-Chapter Box 2 in Chapter 1) will depend on future greenhouse gas emissions and the associated climate changes, as well as on other drivers such as population movement into risk-prone areas and societal efforts to adapt.

LLIC include a wide diversity of systems (Figure CB9.1). Relevant regions occur on both islands and continents from the tropics to the poles, and support urban and rural societies from across the development spectrum (including SIDS and Least Developed Countries (LDCs)). LLIC host around 11% of the global population (Neumann et al., 2015), and generate about 14% of the global Gross Domestic Product (GDP) (Kummu et al., 2016). This integrative Cross-Chapter Box focuses on the array of challenges created by the melting of the cryosphere and the changing ocean, described throughout the report, to address societal risks, adaptation and the future habitability of LLIC.

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[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see Section 1.9.2 and Figure 1.4 for more details).

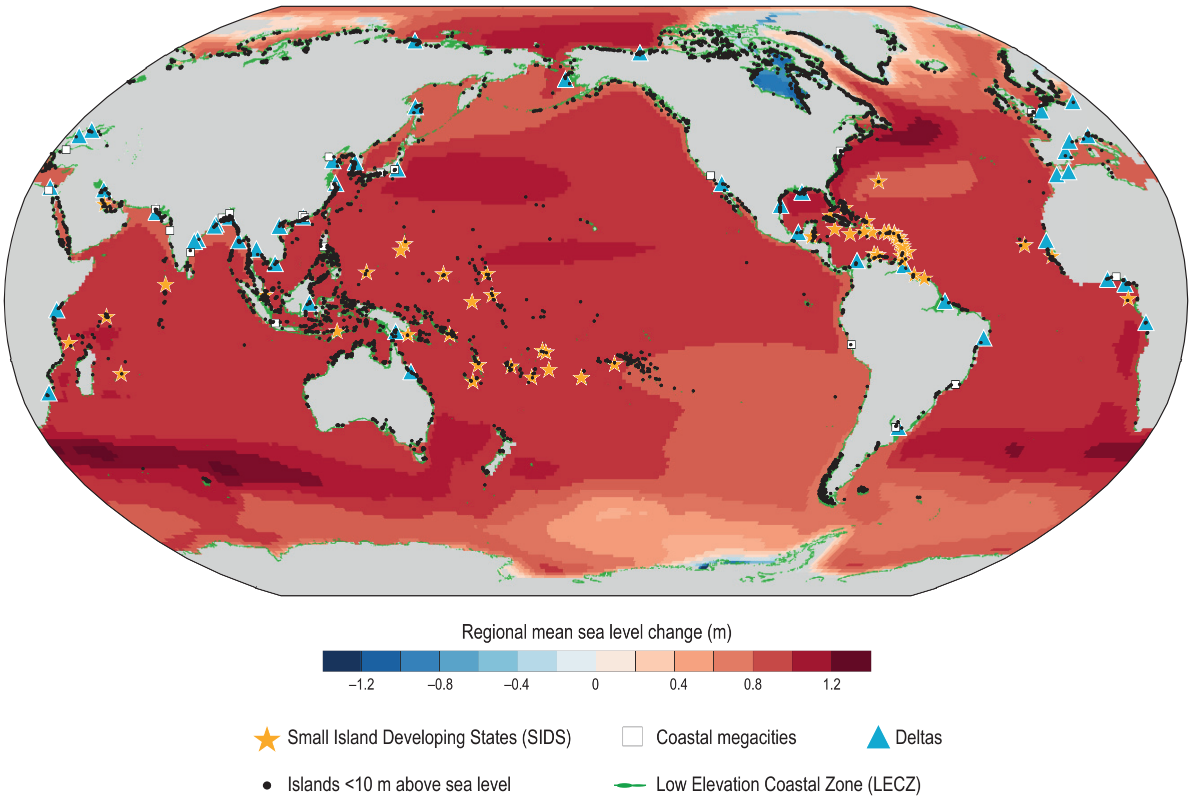

Figure CB9.1 | The global distribution of low-lying islands and coasts (LLIC) particularly at risk from sea level rise. This map considers the Low Elevation Coastal Zone (elevation data from National Geophysical Data Center, 1999; LECZ, defined by McGranahan et al., 2007), islands with a maximum elevation of 10 m above sea level (Weigelt et al., 2013), Small Island Developing States (SIDS; UN-OHRLLS, n.d.), coastal megacities (cities with more than 10 million inhabitants, within 100 km from coast, and maximum 50 m above sea level; Pelling and Blackburn, 2013; UN-DESA, 2018) and deltas (Tessler et al., 2015). Regional sea level changes refer to projections under Representative Concentration Pathway (RCP)8.5 (2081–2100) (see Figure 4.8).

Drivers of Impacts and Risks

Climate-related hazards – LLIC are subject to the same climate-related hazards as other islands and coasts (overview in Wong et al., 2014), for both extreme events, for example, marine heat waves, tropical and extratropical storms, associated storm surges, and heavy precipitation; and slow onset changes, for example, retreat of glaciers and ice sheets, sea ice and permafrost thaw, sea level rise, and ocean warming and acidification (Sections 1.4, 2.2, 3.2 to 3.4, 4.2, 5.2, 6.2 to 6.6, Box 6.1). Table CB9.1 summarises the SROCC updates of these hazards, which often combine to explain part of observed climate impacts and projected risks. For example, accelerating sea level rise will combine with storm surges, tides and waves to generate to extreme sea level events that affect flooding (Section 4.3.3.2), shoreline changes (Section 4.3.3.3) and salinisation of soils, groundwater and surface waters (Section 4.3.3.4). Sea level rise will also combine with ocean warming to accelerate permafrost thawing in the Arctic (Sections 3.4.1.2, 3.4.2.2). Ocean acidification will combine with ocean warming and deoxygenation to impact benthic and pelagic organisms, associated ecosystems (e.g., coral reefs, oyster beds) and top predators, with subsequent impacts on species' abundance and distribution, and the ecosystem services benefiting human societies (Sections 4.3.3.5, 5.2.2, 5.3.1 to 5.3.6, 5.4.1, 6.4.2, 6.5.2, 6.6.2, 6.7.2, 6.8.2). Importantly, LLIC are at risk for multi-metre sea level rise projected post-2100 under Representative Concentration Pathway (RCP)8.5 and restricted to 1–2 m in 2300 under RCP2.6 (Section 4.2.3.5).

Table CB9.1 | Summary information on the critical climate-related drivers for low-lying islands and coasts, their trends due to climate change, and their main physical and ecosystem effects. Based on SROCC chapters and IPCC 5th Assessment Report (AR5). MSL is mean sea level, RCP is Representative Concentration Pathway, TC is tropical cyclone, ETC is extratropical cyclone, SLR is sea level rise, SST is sea surface temperature.

Climate-related driver	Physical/chemical effects	Observed trends	Projections	SROCC section
Global mean sea level (MSL)	Submergence, flood damage, erosion; saltwater intrusion; rising water tables/ impeded drainage; ecosystem loss (and change)	Tide gauge records: *very likely* increase of 1.5 (1.1–1.9) mm yr^{-1} (1902–2010) and a total sea level rise of 0.16 (0.12–0.21) m Acceleration: with *high confidence* (–0.002–0.019) mm yr^{-2} over (1902–2010) Satellite altimetry: Global MSL of 3.0 mm yr^{-1} (2.4–3.6) over (1993–2015) Acceleration: with *high confidence* 0.084 (0.059–0.090) mm yr^{-2} over (1993–2015)	RCP2.6 (2046–2065): 0.24 (0.17–0.32) m RCP2.6 (2081–2100): 0.39 (0.26–0.53) m RCP2.6 (2100): 0.43 (0.29–0.59) m Rate of sea level rise (SLR) 4 (2–6) mm yr^{-1} in 2100 RCP4.5 (2046–2065): 0.26 (0.19–0.34) m RCP4.5 (2081–2100): 0.49 (0.34–0.64) m RCP4.5. (2100): 0.55 (0.39–0.72) m Rate of SLR 7 (4–9) mm yr^{-1} in 2100 RCP8.5 (2046–2065): 0.32 (0.23–0.40) m RCP8.5 (2081–2100): 0.71 (0.51–0.92) m RCP8.5 (2100): 0.84 (0.61–1.10) m Rate of SLR 15 (10–20) mm yr^{-1} in 2100	4.2.2.2 4.2.3.2
Regional sea level		Substantial regional variability at decadal at multi-decadal time scales due to changing winds, air-sea heat and freshwater fluxes and altered ocean circulation	Increased regional relative sea level with respect to AR5 nearly everywhere for RCP8.5 because of the increased Antarctic contribution (Figure 4.8)	4.2.2.4 4.2.3.2
Extreme sea levels		It is *very likely* that flood return period in low-lying areas has decreased over the past 20th century	*High confidence* in more frequently or yearly extreme sea level events which are currently rare (e.g., return period of 100 years) as a consequence of sea level rise at many locations for RCP8.5 by the end of the century (Figure 4.10) Even earlier and for RCP2.6 in locations where historical sea level variability (tides and storm surges) is small compared to projected sea level rise	4.2.3.4.1 4.2.3.4.3
Storms: tropical cyclones (TCs), extratropical cyclones (ETCs)	Storm surges and storm waves, coastal flooding, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change); coastal infrastructure damage and flood defense failure	TCs: Decreasing frequency of severe TCs in eastern Australia since the late 1800s; increase in frequency of moderately large US storm surge events since 1923; recent increase of extremely severe cyclonic storms over the Arabian Sea and intense TCs that make landfall in East and Southeast Asia in recent decades; increase in annual global proportion of hurricanes reaching Category 4 or 5 intensity in recent decades ETCs: *likely* poleward movement of circulation features but *low confidence* in intensity changes (AR5)	TCs: SLR will lead to higher storm surge levels for the TCs that do occur, assuming all other factors are unchanged (*high confidence*). *Medium confidence* that the proportion of TCs that reach Category 4 or 5 levels will increase, that the average intensity of TCs will increase (by roughly 1–10%, assuming a 2°C global temperature rise), and that average tropical cyclone precipitation rates (for a given storm) will increase by at least 7% per degree Celsius (SST) warming. *Low confidence* in how global TC frequency will change, although most studies project some decrease in global TC frequency ETCs: *Low confidence* in future changes in blocking and storm tracks in the northern hemisphere. The storm track projections for the southern hemisphere indicate an observed poleward contraction and a continued strengthening and southward contraction of storm tracks in the future (*medium confidence*)	6.3.1.1 6.3.1.2

Climate-related driver	Physical/chemical effects	Observed trends	Projections	SROCC section
Waves	Coastal erosion, overtopping and coastal flooding	Small increases in significant wave height globally and larger increases (5%) in extreme wave height, especially in the Southern Ocean (*medium confidence*). Global wave power has increased over the last six decades with marked spatial changes by oceans and long-term correlations with sea surface temperature (*low confidence*)	*High confidence* for projected increase of the mean significant wave height across the Southern Ocean, tropical eastern Pacific and Baltic Sea and for projected decrease of significant wave height over the North Atlantic and Mediterranean Sea. *Low confidence* in projections of significant wave height over the eastern north Pacific and Southern Indian and Atlantic Oceans. *Low confidence* in projected extreme significant wave height everywhere, except for the Southern Ocean (increase) and North Atlantic (decrease) (*high confidence*). Limited knowledge on projected wave period and direction	4.2.3.4.2 6.3.1.3
Sea surface temperature (SST)	Changes to stratification and circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality, poleward species migration; increased algal blooms	The ocean has warmed unabated, continuing the clear multi-decadal ocean warming trends documented in AR5. The 0–700 m layer of the ocean has warmed at rate of 5.31 ZJ yr^{-1} from 2005 to 2017. The long-term trend for 0–700 m layer has warmed 4.35 ZJ yr^{-1} from 1970 to 2017	For RCP8.5, the 0–2000 m layers of the ocean are projected to warm by a further 2150 ZJ (*very likely* range 1710 to 2790 ZJ) between 2017 and 2100 For RCP2.6, the 0–2000 m layers are projected to warm by 900 ZJ (*very likely* range 650 to 1340 ZJ) by 2100 (*) ZJ is Zettajoule	5.2.2.2.1
Marine heat waves		Have *very likely* doubled since 1980s	*Very likely* increase in frequency, duration, spatial extent and intensity, even under future low levels of warming	6.4.1
Freshwater inputs	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply	*Medium confidence* in a net declining trend in annual volume of freshwater input	*Medium confidence* for general increase in high latitude and wet tropics and decrease in other tropical regions	AR5
Ocean acidity	Increased CO_2 fertilization; decreased seawater pH and carbonate ion concentration (or 'ocean acidification')	*Virtually certain* that ocean surface water pH is declining by a *very likely* range 0.017 to 0.027 pH units per decade, since 1980, everywhere individual time-series observations exist	*High confidence* that the ocean will experience pH drops of between 0.1 (RCP2.6) or 0.3 (RCP8.5) pH units by 2100, with regional and local variability, exacerbated in polar regions	5.2.2.3
Sea ice and permafrost thaw	More storm surges, increasing ocean swells, coastal erosion	Permafrost temperatures have continued to increase to record high levels (*very high confidence*) Between 2007 and 2016, permafrost temperatures here increased 0.39°C ± 0.15°C in cold continuous zone permafrost and 0.20°C ± 0.10°C in warmer discontinuous zone permafrost It is *very likely* that Arctic sea ice extent continues to decline in all months of the year; the strongest reductions in September (–12.8% ± 2.3% per decade; 1979–2018) are *likely* unprecedented in at least 1000 years. It is *virtually certain* that Arctic sea ice has thinned concurrent with a shift to younger ice: since 1979, the areal proportion of thick ice at least 5 years old has declined by approximately 90%	For stabilised global warming of 1.5°C, an approximately 1% chance of a given September being sea ice free at the end of century is projected; for stabilised warming at a 2°C increase, this rises to 10–35% (*high confidence*). The potential for reduced (further 5–10%) but stabilised Arctic autumn and spring snow extent by mid-century for RCP2.6 contrasts with continued loss under RCP8.5 (a further 15–25% reduction to end of century) (*high confidence*) Widespread disappearance of Arctic near-surface permafrost is projected to occur this century as a result of warming (*high confidence*). Near-surface permafrost area is projected to be reduced by 2–66% for RCP2.6 and 30–99% by 2100 under RCP8.5	3.2.1.1 Box 3.2 3.2.2 3.3.2 3.4.1 3.4.2

Anthropogenic drivers – Human factors play a major role in shaping exposure and vulnerability to climate-related changes in the Arctic, in temperate and tropical small islands, and in coastal urban areas (Sections 2.5.2, 4.3.2, Cross-Chapter Box 2 in Chapter 1). In the absence of major additional adaptation efforts compared to today (i.e., neither further significant action nor new types of actions), the anthropogenic drivers' contribution to climate change related risk will substantially increase (*high confidence*) (Section 4.3.4.2).

Highly context-specific territorial and societal dynamics have resulted in major changes at the coast, for instance the growing concentration of people and assets in risk prone coastal areas (Section 4.3.2.2), and the degradation of coastal ecosystem services such as coastal protection and healthy conditions for coastal fisheries and aquaculture (Section 4.3.2.3, 5.4.1.3, 5.4.2.2.2). Local drivers of exposure and vulnerability include, for example, coastal squeeze, inadequate land use planning, changes in construction modes, sand mining and unsustainable resource extraction (e.g., in the Comoros; Betzold and Mohamed, 2016; Ratter et al., 2016), as well as loss of Indigenous Knowledge and Local Knowledge (IK and LK; Cross-Chapter Box 4 in Chapter 1). For example, the loss of IK and LK-based practices and associated cultural heritage limits both the ability to recognise and respond to ocean and cryosphere related risk and the empowerment of local communities (*high confidence*) (Section 4.3.2.4.2). Population growth in medium-to-mega coastal cities is also of concern. For the year 2000, the Low Elevation Coastal Zones (LECZ, highest elevation up to 10 m above sea level) were estimated to host around 625 million people (Lichter et al., 2011; Neumann et al., 2015), with the vast majority (517 million) living in non-developed contexts. By 2100, the LECZ population may increase to as much as 1.14 billion under a Shared Socioeconomic Pathway (SSP) where countries focus on domestic, or even regional issues (SSP3; Jones and O'Neill, 2016). Poor planning can combine with coastal population growth and climate-related ocean change to create maladaptation (Juhola et al., 2016; Magnan et al., 2016).

Local factors drive – as well as are driven by – more regional processes such as extensive coastal urbanisation, human-induced sediment starvation (and implications on subsidence), degradation of vegetated coastal ecosystems (e.g., mangroves, coral reefs and salt-marshes), lack of long-term integrated planning, changing consumption modes, conflicting resource use and socioeconomic inequalities (*high confidence*), among others. These are vehicles of increasing exposure and vulnerability at multiple scales.

Observed and Projected Impacts on Geographies and Major Sectors

Coastal cities and megacities – Coastal cities, especially megacities with over 10 million inhabitants, are at serious risk from climate-related ocean and cryosphere changes (Abadie, 2018). Over half of today's global population lives in cities and megacities, many of which are located in LLIC, including New York City, Tokyo, Jakarta, Mumbai, Shanghai, Lagos and Cairo (Figure CB9.1). Without substantial adaptation interventions, and based on the compounding effects of future growth in population and assets, sea level rise and continued subsidence, future flood losses in the 136 largest coastal cities are projected to rise from 6 billion USD yr^{-1} at present to 1 trillion USD yr^{-1} in 2050 (Hallegatte et al., 2013; Sections 4.3.3.2 and 6.3.3). In addition to important impacts on coastal megacities and large port cities, small and mid-sized cities are also considered highly vulnerable because of fast growth rates and low political, human and financial capacities for risk reduction compared to larger cities (Birkmann et al., 2016; Box 4.2).

At a more local scale, and regardless of the size of the city, coastal property values and development will be affected by sea level changes, storms and other weather and climate-related hazards. Real estate values, and the cost and availability of insurance, will be impacted by actual and perceived flood risks (McNamara and Keeler, 2013; Section 5.4.2.3.1; Putra et al., 2015). Properties are also at risk of losing value due to coastal landscape degradation (McNamara and Keeler, 2013; Fu et al., 2016) and increasing risk aversion. The economic consequences manifest in declining rental incomes, business activities and local employment (Rubin and Hilton, 1996).

Coastal megacities are especially critical nodes for transboundary risks (Atteridge and Remling, 2018; Miller et al., 2018) as they contribute substantially to national economies and serve as a hub for global trade and transportation networks. The 2011 floods in Bangkok, for example, not only resulted in direct losses of 46.5 billion USD (World Bank, 2012; Haraguchi and Lall, 2015), but also in important effects on supply chains across the globe (Abe and Ye, 2013). Urbanisation could, however, also provide opportunities for risk reduction, given that cities are centres of innovation, political attention and private sector investments (Garschagen and Romero-Lankao, 2015).

Small islands – The extreme events occurring today, such as storms, tropical cyclones (TC), droughts, floods and marine heat waves (Herring et al., 2017), provide striking illustrations of the vulnerability of small island systems (*high confidence*) (Section 6.8.5, Box 4.2, Box 6.1). Societal dimensions can combine with climate changes, e.g., sea level rise, to amplify the impact of TCs, storm surge and ocean acidification in small islands contributing to loss and damage (Moser and Hart, 2015; Noy and Edmonds, 2016). For example, Category 5 TC Pam devastated Vanuatu in 2015 with 449.4 million USD in losses for an economy with a GDP of 758 million USD (Government of Vanuatu, 2015; Handmer and Iveson, 2017). Kiribati, Papua New Guinea, Solomon Islands and Tuvalu were all impacted by the TC Pam system (IFRC, 2018). In 2016, TC Winston caused 43 deaths in Fiji and losses of more than one third of the GDP (Government of Fiji, 2016; Cox et al., 2018). In 2017, Hurricanes Maria and Irma swept through 15 Caribbean countries, causing major damages and casualties across numerous islands. Rebuilding in three countries alone – Dominica, Barbuda and the British Virgin Islands – will cost an estimated 5 billion USD (UNDP, 2017). The Post-Disaster Needs Assessment for Dominica concluded that hurricane Maria resulted in total damages amounting to 226% of 2016 GDP (The Government of the Commonwealth of Dominica, 2017). In 2018, Category 4 TC Gita struck the Pacific islands of Eua and Tongatapu, impacting 80% of the population of Tonga through destruction of buildings, crops and infrastructure, and resulting in 165 million USD of losses with a national GDP of 461 million USD (Government of Tonga, 2018). Effective early warning systems, in some Caribbean islands, have reduced the impact (WMO, 2018). Projected changes in extreme weather include increased intensity of TCs with increased wind speed and rainfall, together with reduced translational speed creating greater destruction from individual storms and counteracting the decreased frequency of occurrence (Sections 6.3 and 6.8).

SIDS are home to 65 million people (UN-OHRLLS, 2015). More than 80% of small island residents live near the coast where flooding and coastal erosion already pose serious problems (Nurse et al., 2014) and since the IPCC 5th Assessment Report (AR5) and the Special Report on Global Warming of 1.5°C (SR1.5), there is consensus on the increasing threats to island sustainability in terms of land, soils and freshwater availability. As a result, there is growing concern that some island nations as a whole may become uninhabitable due to rising sea levels and climate change, with implications for relocation, sovereignty and statehood (Burkett, 2011; Gerrard and Wannier, 2013; Yamamoto and Esteban, 2014; Donner, 2015). For example, at the island scale, recent studies (e.g., on Roi-Namur Island, Marshall Islands; Storlazzi et al., 2018) estimate some atoll islands to become uninhabitable before the middle of the 21st century due to the exacerbation of wave-driven flooding by sea level rise, compromising soil fertility and the integrity of freshwater lenses (Cheriton et al., 2016). The literature also discusses the future of atoll island shoreline. Atoll islands are not 'static landforms' (*high confidence*) and they experience both erosion (Section 4.3.3.3) and accretion of land. In the Solomon Islands, where rates of sea level rise exceed the global average at 7–10 mm yr^{-1} (Becker et al., 2012), a study of 33 reef islands showed five vegetated islands had disappeared and six islands were concerned with severe shoreline erosion (Albert et al., 2016). In Micronesia, a study showed the disappearance of several reef islands, severe erosion in leeward reef edge islands and coastal expansion in mangrove areas (Nunn et al., 2017). In Tuvalu, with sea level rise of ~15 cm between 1971 and 2014, small islands decreased in land area while larger populated islands maintained or increased land area with the exception of the remote island of Nanumea (Kench et al., 2018). Positive shoreline and surface area changes over the recent decades to century have been observed for atoll islands in the Pacific and Indian oceans (McLean and Kench, 2015; Albert et al., 2016; Kench et al., 2018; Duvat, 2019). Out of 709 islands studied, 73.1% had stable surface area, 15.5% increased and 11.4% decreased in size over the last 40–70 years (Duvat, 2019). It has, however, been argued that the capacity of some atoll islands to maintain their land area by naturally adjusting to sea level rise could be reduced in the coming decades (*low evidence*, *high agreement*). Indeed, the projected combination of higher rates of sea level rise (Sections 4.2.3.2, 4.2.3.3 and 4.2.3.5), increased wave energy (Albert et al., 2016; see also Section 6.3), changes in storm wave direction (Harley et al., 2017), as well as the impacts of ocean warming and acidification on the reef system (Quataert et al., 2015; Hoegh-Guldberg et al., 2018), is expected to shift the balance towards more frequent flooding and increased erosion (Sections 4.3.3, 5.3.3).

Deltas – In a context of natural subsidence exacerbated by high human disturbances to sediment supply, for example, due to fresh water exploitation or damming and land use change upstream from the coast (Kondolf et al., 2014), marine flooding is already affecting deltas around the world (Brown et al., 2018; Section 4.3.3.4, Box 4.1). An estimated 260,000 km^2 of delta area have been temporarily submerged over the 1990s–2000s (Syvitski et al., 2009; Wong et al., 2014). The recurrence of El Niño associated floods in the San Juan River delta, Colombia, led to the relocation of several villages, including El Choncho, San Juan de la Costa, Charambira and Togoroma (Correa and Gonzalez, 2000). The intrusion of saline or brackish water due to relative sea level rise in combination with storm surges and natural and human-induced subsidence, results in increasing residual salinity, as already reported in the Delaware Estuary, USA (Ross et al., 2015), in the Ebro Delta, Spain (Genua-Olmedo et al., 2016) and in the Mekong Delta, Vietnam (Smajgl et al., 2015; Gugliotta et al., 2017). This affects livelihoods, for example., freshwater fish habitat in Bangladesh (Dasgupta et al., 2017; Section 4.3.3.4.2). Increased salinity limits drinking water supply (Wilbers et al., 2014), with associated repercussions for the abundance and toxicity of cholera vibrio (*Vibrio cholerae*) as shown in the Ganges Delta (Batabyal et al., 2014). Local agriculture is also at risk. Oilseed, sugarcane and jute cultivation have already ceased due to high salinity levels in coastal Bangladesh (Khanom, 2016) and dry-season crops are projected to decline over the next 15 to 45 years, especially in the Southwest (Kabir et al., 2018). In the Ebro delta, Spain, Genua-Olmedo et al. (2016) anticipate a decrease of the rice production index from 61.2% in 2010 to 33.8% by 2100 for a 1.8 m sea level rise scenario, far above the upper end of the RCP8.5 *likely*[2] range (Section 4.2.3.2, Table 4.3).

Arctic coasts – Climate-related ocean and cryosphere changes combine to negatively impact not only the economy and life-styles of the Arctic coastal communities, but also the local cultural identity, self-sufficiency, IK and LK and related skills (Lacher, 2015; Sections 3.4.3, 4.3.2.4.2). Changes in fish and seabird populations amplified by climate change have an impact on ecosystems and livelihoods in Arctic island communities such as in Norway's Lofoten archipelago (Dannevig and Hovelsrud, 2016; Kaltenborn et al., 2017). Another concern relates to coastal erosion, for example triggered by permafrost thaw (Günther et al., 2013; Jones et al., 2018), and which already affects 178 Alaskan communities, with 26 in a very critical situation, such as Newtok, Shishmaref, Kivilina and northwestern coastal communities on the Chukchi Sea (Bronen and Chapin III, 2013). Noteworthy, erosion does not affect all Arctic coastlines: many of them are located in areas that experience rapid glacial-isostatic adjustment (GIA) uplift (James et al., 2015; Forbes et al., 2018) and have low sensitivity to extreme sea levels and sea level rise. An additional factor unique to the Arctic coasts compared to other LLIC is the decrease in seasonal sea ice extent (Section 3.2.1, 4.3.4.2.1), that both reduces the physical protection of the land (Overeem et al., 2011; Fang et al., 2018), for example, from wave action, and allows for greater open water fetch producing stronger wind-generated waves in the open water (Lantuit et al., 2011). In combination with a decreased stability of permafrost – another specificity of polar regions (Romanovsky et al., 2010) – and sea level rise, seasonal sea ice extent reduction results in shoreline erosion (Gibbs and Richmond, 2017; Jones et al., 2018), with associated impacts on coastal settlements (Table 3.4). However, as mentioned above, local geomorphology and geology in the Arctic is as important as permafrost and sea ice extent for determining current and future erosion (Lantuit et al., 2011).

Risks to Arctic coasts will be reinforced by anthropogenic drivers originating in the recent decades of history (e.g., socioeconomic adjustments after government policies requiring children to attend school) which resulted in the construction of infrastructure in near-shore areas. While risk levels vary by village, in several cases infrastructure has been lost and subsistence use areas modified (Gorokhovich et al., 2013; Marino, 2015). More broadly, in the Arctic, 'indigenous peoples (…) have been pushed into marginalised territories that are more sensitive to climate impacts' (Ford et al., 2016: 350), with consequences in terms of undermining aspects of socio-cultural resilience.

Impacts on critical sectors and livelihoods – Economic impacts for LLIC are expected to be significant in the course of the century due to the convergence of the anticipated increase in the number of LECZ inhabitants (Jones and O'Neill, 2016; Merkens et al., 2016), the high dependency of societies on ocean and marine ecosystems and services (Section 5.4.1, 5.4.2), and increased detrimental effects of climate-related ocean and cryosphere changes on natural and human systems (*medium evidence*, *high agreement*) (Hsiang et al., 2017; United Nations, 2017). However, the degree of impacts on the economy and related dimensions – for example, on employment, livelihood, poverty, health (Kim et al., 2014; Weatherdon et al., 2016), well-being and food security (Sections 1.1 and 5.4.2, FAQ 1.2 in Chapter 1) and public budgets and investments – will vary across context-specific physical settings and exposure and vulnerability levels.

Considering a sea level rise scenario range of 25–123 cm – all RCPs; wider range of sea level rise scenarios than the *likely* range of AR5 but relatively consistent with the range of projections assessed in this report (Section 4.2.3.2) – and no adaptation, Hinkel et al. (2014) estimated annual losses from future marine flooding to amount to 0.3–9.3% of global GDP in 2100. Noteworthy, coastal protection will inevitably have economic costs (DiSegni and Shechter, 2013), whether it involves hard coastal protection (Hinkel et al., 2018), ecosystem-based approaches (Narayan et al., 2016; Pontee et al., 2016) or a combination of both (Schoonees et al., 2019). Coastal agriculture (e.g., rice crops; Smajgl et al., 2015; Genua-Olmedo et al., 2016), and fisheries and aquaculture will also be seriously impacted (Sections 4.3.3.6.1, 4.3.3.6.3, 5.4.1). For example, it is expected that the marine fisheries revenues of 89% of the world's fishing countries will be negatively affected by mid-century under RCP8.5 (Hilmi et al., 2015). The fact that more than 90% of the world's rural poor are located in the LECZ of 15 developing countries (Barbier, 2015) and that these regions are highly dependent on fish for their dietary consumption, raises a serious concern about future food security (FAO et al., 2017; Section 5.4.2.1.2). But not all regions are equally threatened,

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[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Section 1.9.2 and Figure 1.4 for more details). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range.

with Lam et al. (2016) estimating that the impacts on fisheries will be more important in SIDS, Africa and Southeast Asia. Cascading effects are also expected from risks to coral reefs and associated living resources, both on direct consumption by local communities and through disturbances to the broader food web chains (Sections 5.4.2, 6.5 and Box 6.1).

Coastal tourism could be affected in various ways by ocean- and cryosphere-related changes (Hoegh-Guldberg et al., 2018; Sections 4.3.3.6.2, 5.4.2.1.3). Coastal infrastructure and facilities, such as harbours and resorts (e.g., in Ghana; Sagoe-Addy and Appeaning Addo, 2013), are prone to storm waves. For coral reefs for recreational activities and tourism (especially diving and snorkelling), Chen et al. (2015) estimated that the global economic impact of the expected decline in reef coverage (between 6.6 and 27.6% under RCPs 2.6 and 8.5, respectively) will range from 1.9 to 12.0 billion USD yr^{-1}. The future appeal of tourism destinations will partly depend on sea surface temperature, including induced effects such as an increase in invasive species, e.g., jellyfishes (Burge et al., 2014; Weatherdon et al., 2016) and lion fish in the Northwest Atlantic, the Gulf of Mexico and the Caribbean (Albins, 2015; Johnston et al., 2015; Holdschlag and Ratter, 2016). It will also depend on how tourists and tourism developers perceive the risks induced by ocean-related changes (e.g., Shakeela et al., 2013; Davidson and Sahli, 2015). This will combine with the influence of changes in climatic conditions in tourists' areas of origin (Bujosa and Rosselló, 2013; Amelung and Nicholls, 2014; Hoegh-Guldberg et al., 2018) and of non-climatic components such as accommodation and travel prices. Importantly, estimating the effects on global-to-local tourism flows remains challenging (Rosselló-Nadal, 2014; Wong et al., 2014).

Recent studies provide further empirical evidence that people are rarely moving exclusively due to changes in ocean- and cryosphere-based conditions, and that migration as a result of disasters and increasing hazards strongly interact with other drivers, especially economic and political motivations (*high confidence*) (Kelman, 2015; Marino and Lazrus, 2015; Hamilton et al., 2016; Bettini, 2017; Stojanov et al., 2017; Perumal, 2018). While significantly higher risks of human displacement are expected in low-income LLIC, for example in Guatemala (Milan and Ruano, 2014) and Myanmar (Brakenridge et al., 2017), the issue also concerns developed countries. For example, Logan et al. (2016) show that people temporarily or permanently displaced by hurricanes in the Gulf Coast, USA, create a significant economic burden to tourism-dependent coastal cities and harbours.

Responses: Adaptation Strategies in Practice

A wide range of coastal adaptation measures are currently implemented in LLIC worldwide (Sections 1.6.2, 2.3.7, 3.5.2, 3.5.3, 4.4.3, 5.5.2, 6.9, Figure 1.2, Box 5.4), including the installation of major infrastructure such as armouring of coasts (e.g., seawalls, groynes, revetments and rip-raps), soft engineering (e.g., beach nourishment and dune restoration), reclamation works to build new lands seaward and upwards, ecosystem-based measures (e.g., vegetation planting and coral farming), community-based approaches (e.g., social networks, education campaigns and economic diversification) and institutional innovations (e.g., marine protected areas and evacuation plans). The effectiveness of the measures to reduce risks depends on both local context-specificities (Gattuso et al., 2018) and the magnitude and timing of local climate impacts. However, there is still a gap in on-the-ground evidence, good practices and guidelines to evaluate the observed and projected benefits of each type of measures applied in various contexts, for example, to decide whether nature-based options represent low- to no-regret solutions, or not a solution at all.

Protection with hard coastal defences is commonly used to prevent inundation from extreme water levels and wave overtopping (Section 4.4.2.2). In environments such as megacities, adequately engineered hard coastal defences are considered to be successful options and an efficient adaptation option in the long run (Hinkel et al., 2018). However, such measures can also lead to detrimental effects, such as erosion exacerbation by seawalls reflecting wave energy and jetties disrupting cross-shore sediment transport. Adaptation labelled measures 'may [thus] lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare' (Noble et al., 2014: 857) and therefore be maladaptive (Barnett and O'Neill, 2013; Juhola et al., 2016; Magnan et al., 2016). As a result, alternatives have emerged, such as ecosystem-based design measures including coconut fibre blankets (David et al., 2016), plantations of seagrass (Paul and Gillis, 2015), artificial reefs made from bio-rock materials (Beetham et al., 2017; Goreau and Prong, 2017) and bamboo breakwaters (David et al., 2016). While restoration operations are often rather associated to conservation practices, they can have co-benefits in terms of coastal protection services (Section 4.3.2.3). For example, soft protection systems used in 69 studies were found to exhibit effectiveness in reducing wave heights at 70% for coral reefs, 62–79% for salt marshes, 36% for seagrass meadows and 31% for mangroves (Narayan et al., 2016). Arguing that coral reefs can provide comparably higher wave attenuation benefits to artificial defences such as breakwaters, Ferrario et al. (2014) conclude that reef defences for reducing coastal hazards can be enhanced cost effectively on the order of 1/10th. Coral reefs are, however, at very high risk from climate change (Hoegh-Guldberg et al., 2018; Section 5.3.4), which challenges the duration of such benefits.

Ecosystem-based measures, if applied place specific and adequate – for example, use of indigenous rather than exotic species (e.g., Duvat et al., 2016) – , are usually considered low-regret in that they can stabilise the coastal vegetation and protect against coastal hazards, while at the same time enhancing the adaptive capacity of natural ecosystems (*medium evidence, high agreement*) (Schoonees et al., 2019; Sections 2.3.3.4, 5.5.2, 6.9).

While human migration and relocation are expected to be a growing challenge for LLIC (*medium evidence*, *high agreement*) (Adger et al., 2014; Birk and Rasmussen, 2014; Milan and Ruano, 2014; Thomas, 2015; Sections 3.5.3.5, 4.4.2.4, 6.3.4, Table 3.4; Hajra et al., 2017; Stojanov et al., 2017), recent studies advocate for considering these options as adaptation to climate-related changes in the ocean and cryosphere (Shayegh et al., 2016; Allgood and McNamara, 2017; Hauer, 2017; Morrison, 2017; Perumal, 2018; Section 4.4.2.4). Such a view is, however, convoyed by discussions on related costs and impacts on the wellbeing of the people who are relocated (Null and Herzer Risi, 2016). Coastal retreat is underway in various LLIC around the world, for example, in Alaska and the US (Bronen, 2015; Ford et al., 2015; Logan et al., 2016; Hino et al., 2017), Guatemala (Milan and Ruano, 2014), Western Colombia (Correa and Gonzalez, 2000), the Caribbean (Apgar et al., 2015; Rivera-Collazo et al., 2015) and Vietnam (Collins et al., 2017). Noteworthy, environmentally-induced relocation is not necessarily new, for example, in the Pacific (Nunn, 2014; Boege, 2016). The Gilbertese people from Kiribati moved to the Solomon Islands during the 1950s–1960s, as a result of long periodic droughts and subsequent environmental degradation (Birk and Rasmussen, 2014; Albert et al., 2016; Tabe, 2016; Weber, 2016). In the Solomon Islands, the relocation of the Taro Township (Choiseul Province) as a result of rising sea level and coastal erosion is already underway (Haines and McGuire, 2014; Haines, 2016). In Fiji, the relocation of Vunidogoloa village as a result of sea level rise and coastal erosion was successfully carried out in 2014 (McNamara and Des Combes, 2015). In Alaska, some communities (e.g., Newtok) responded to changing environmental and livelihood conditions due to permafrost thaw with self-initiated relocation efforts. Subsequently, Alaska state funding has been allocated to assist them (Bronen, 2015; Hamilton et al., 2016). Conflict escalation is a serious concern in the resettlement areas, between newcomers and locals, or between different groups of newcomers, particularly under conditions of land scarcity, high population density and (perceived) inequality (Connell and Lutkehaus, 2017; Boege, 2018). The obstacles thus extend well beyond the cost of relocation itself because of the multi-dimensional impacts on people's lives. Relocation also concerns economic activities, as illustrated with shellfish aquaculture relocation in the west coast of the US due to ocean acidification-driven crises (Cooley et al., 2016).

For all interventions, adaptation is fully recognised as being a societal challenge, and not merely a question of technological solutions (*medium evidence, high agreement*) (Jones and Clark, 2014; McCubbin et al., 2015; Gerkensmeier and Ratter, 2018). Enhancing adaptation implies various sociopolitical and economic framings, coping capacities and cross-scale social and economic impacts (Sections 4.4.3, 4.4.5, Cross-Chapter Box 3 in Chapter 1). As a result, community-based decision making, sustainable spatial planning and new institutional arrangements gain increasing attention (Sections 4.4.4). Such approaches can involve working with local informal and formal institutions (Barron et al., 2012), enhancing risk ownership by communities through participative approaches (McEwen et al., 2017), establishing collaborative community networks (Hernández-González et al., 2016), and better integrating LLIC communities' IK and LK (see McMillen et al., 2014; Cross-Chapter Box 4 in Chapter 1). Small island communities, in particular, can strengthen their adaptive capacities by building on relatively high degrees of social capital, that is, dense social networks, collective action, reciprocity and relations of trust (Petzold and Ratter, 2015; Barnett and Waters, 2016; Petzold, 2016; Kelman, 2017; Section 4.3.2.4.3). The aim of all these approaches is both to facilitate the effective implementation of adaptive action, and create widespread acceptance of adaptation policies by stakeholders and local populations.

Participatory scenario building processes, collaborative landscape planning and co-design of ecosystem-based management for LLIC resilience are underway along with promising approaches to actively engage all levels of society in the exploration of future adaptation scenarios. Experiences are reported for the German North Sea coast (Karrasch et al., 2017), Tenerife Island in the Atlantic Ocean (Hernández-González et al., 2016) and Pacific island communities (Burnside-Lawry et al., 2017). While adaptation labelled measures currently applied 'on the ground' are mainly reactive and short-term, long-term approaches are emerging (Noble et al., 2014; Wong et al., 2014), as illustrated by the development of 'adaptation pathways' – that is, long-term adaptation strategies based upon decision cycles that, over time, explore and sequence a set of possible actions based on alternative external, uncertain developments (Haasnoot et al., 2013; Barnett et al., 2014; Wise et al., 2014; Werners et al., 2015; Hermans et al., 2017; Section 4.4.4.3.4). Key expected benefits are an improved consideration of both the evolving nature of vulnerability (Denton et al., 2014; Dilling et al., 2015; Duvat et al., 2017; Fawcett et al., 2017) and climate change uncertainty (O'Brien et al., 2012; Brown et al., 2014; Noble et al., 2014), as well as better anticipation of the risks of maladaptation (Magnan et al., 2016). Practical applications of adaptation pathways in LLIC are occurring, for example, in the Netherlands (Haasnoot et al., 2013), Indonesia (Butler et al., 2014), New York City (Rosenzweig and Solecki, 2014) and Singapore (Buurman and Babovic, 2017).

Conclusions

LLIC are particularly at risk from climate-related changes to the ocean and the cryosphere, whether they are urban or rural, continental or island, at any latitude and regardless of level of development (*high confidence*). Over the course of the 21st century, they are expected to experience both increasing risks (*high confidence*) and limits to ecological and societal adaptation (de Coninck et al., 2018; Djalante et al., 2018; Section 4.3.4.2, Figure 6.2, Figure CB9.2; Hoegh-Guldberg et al., 2018), which has the potential to significantly increase the level of loss and damage experienced by local coastal livelihoods (e.g., fishing, logistics or tourism) (Djalante et al., 2018). However, there are still important research gaps on residual risks and adaptation limits, given that these limits can be reached due to the intensity of the hazards and/or to the high vulnerability of a given system, and can be ecological, technological, economic, social, cultural, political or institutional. In addition, ocean and cryosphere changes have the potential to accumulate in compound events and cause cascades of impacts through economic, environmental and social processes (*medium evidence, high agreement*) (Sections 6.8.2 to 6.8.3, Box 6.1). This is the case when coastal flooding and riverine inundation occur together, for example, during the 2012 Superstorm Sandy in New York City, USA (Rosenzweig and Solecki, 2014); the 2014 cyclone Bejisa in Reunion Island, France (Duvat et al., 2016), and the 2017 Hurricane Harvey in Houston, USA (Emanuel, 2017). Cascade effects far beyond the extent of the original impacts bring the risk in LLIC of slowing down and reversing overall development achievements, particularly on poverty reduction (*low evidence*, *medium agreement*) (Hallegatte et al., 2016). Global time series analysis of risk and vulnerability trends show that many Pacific island states have fallen behind the global average in terms of progress made in the reduction of social vulnerability towards natural hazards over the past years (Feldmeyer et al., 2017). These findings may well be indicative of the situation for other LLIC (*medium confidence*) (Hay et al., 2019).

In addition, LLIC provide relevant illustrations of some of the IPCC Reasons for Concern (RFC) that describe potentially dangerous anthropogenic interference with the climate system (IPCC, 2014; IPCC, 2018). LLIC especially illustrate the risks to unique and threatened systems (RFC1), and risks associated with extreme weather and compound events (RFC2), and the uneven distribution of impacts (RFC3). Using this frame, O'Neill et al. (2017) estimate, for example, that the potential for coastal

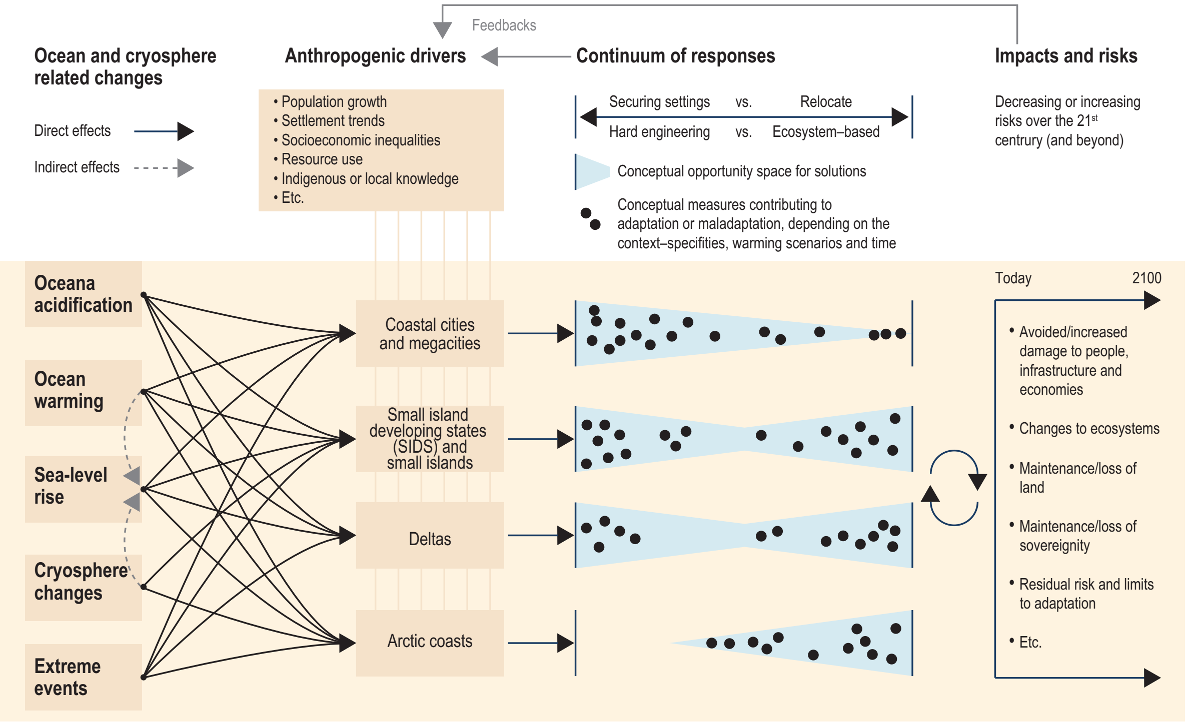

Figure CB9.2 | The storyline of risk for Low-Lying Islands and Coasts (LLIC). From left to right, this figure shows that ocean- and cryosphere-related changes (ocean acidification, ocean warming, sea level rise, etc.) will combine with anthropogenic drivers (population growth, settlement trends, socioeconomic inequalities, etc.) to explain impacts on various LLIC geographies (cities, islands, deltas, Arctic coasts). Depending on the combinations of responses (black dots; stylised representation of potential responses) along a continuum going from hard engineering to ecosystem-based approaches, and from securing current settings to relocation (light blue triangles), risks will increase or decrease in the coming decades. Some responses (black dots) will enhance either adaptation or maladaptation. SIDS is Small Island Developing States.

protection and ecosystem-based adaptation will reach significant limits by 2100 in the case of a 1 m rise in sea level, suggesting the need for research into the crossing of environmental and/or anthropogenic tipping points (Sections 6.2). The SROCC report confirms that high risk to various geographies (Arctic communities remote from regions of rapid positive glacial-isostatic adjustment, megacities, urban atoll islands and large tropical agricultural deltas) are to be expected before a 1 m rise in global mean sea level (Section 4.3.4.2.1). More broadly, this report suggests, first, that the drivers and timing of the future habitability of LLIC will vary from one case to another (Manley et al., 2016; Hay et al., 2018). Second, future storylines of risks will also critically depend on the multi-decadal effectiveness of coastal nations' and communities' responses (*medium evidence*, *high agreement*). This will, in turn, partly depend on transformation of risk management regimes in order to harness these potentials and shift course towards climate-resilient development pathways (*low evidence, high agreement*) (Solecki et al., 2017).

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