Cross-Chapter Box 7: Low-lying Islands and Coasts

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Executive Summary

The changing ocean and cryosphere already impact Low-Lying Islands and Coasts (LLIC), including Small Island Developing States, with cascading and compounding risks, and may push beyond current adaptation limits (*high confidence*[1]). With a significant contribution to the global population (>10%), Gross Domestic Product (~14%), livelihoods and cultural heritage, LLIC of all latitudes are hotspots, sharing commonalities as well as showing context-specificities in their exposure and vulnerability to climate change (*high confidence*). The continuum of coastal adaptation options ranges from hard engineering to ecosystem-based measures, and from 'holding-the-line' to relocation of people, assets and activities. The combinations of measures will vary across geographies, depending on the scale of observed and projected impacts, societies' adaptive capacity and the establishment of new, transformational governance structures (*high confidence*) (Sections 4.4.3, 4.4.4, 5.5.2, 6.8, 6.9, Cross-Chapter Box 2 in Chapter 1).

Introduction

Low-Lying Islands and Coasts (LLIC) include a wide diversity of systems, from continental coasts (including deltas and marine habitats such as coral reefs and wetlands) to small islands (including Small Island Developing States, SIDS); from the tropics to polar regions; and with various demographic, political and socio-economic characteristics (e.g., urban or rural, developing and developed) (Figure CCB7.1). LLIC below 10 m of elevation are estimated to host >10% of the global population (Neumann et al., 2015) and generate about 14% of the global Gross Domestic Product (GDP) (Kummu et al., 2016). LLIC are at the frontline of the impacts of climate-related changes to the ocean and cryosphere, for both extreme events and slow onset changes, due to their low elevations, sensitive ecosystems and natural resources (Section 1.4.2), as well as increasing anthropogenic pressures at the coastline (Sections 1.4.3, 4.3.2.2). Impacts on coastal morphology, ecosystems and dependent human communities are already detectable, with high risks expected to increase in the course of the 21st century (Gattuso et al., 2015; Nagelkerken and Connell, 2015) (*medium evidence, high agreement*), even under a +1.5°C warming scenario (Hoegh-Guldberg et al., in press). The magnitude of risks (Cross-Chapter Box 1 in Chapter 1) will depend on future greenhouse gas emissions and the associated climate change, other drivers such as population movement into risk-prone areas, and societies' additional efforts to adapt. This integrative Cross-Chapter Box focuses on societal impacts of, and adaptation to climate-related ocean and cryosphere changes, including discussing the future habitability of LLIC.

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[1] FOOTNOTE: 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 1.9.3 and Figure 1.4 for more details).

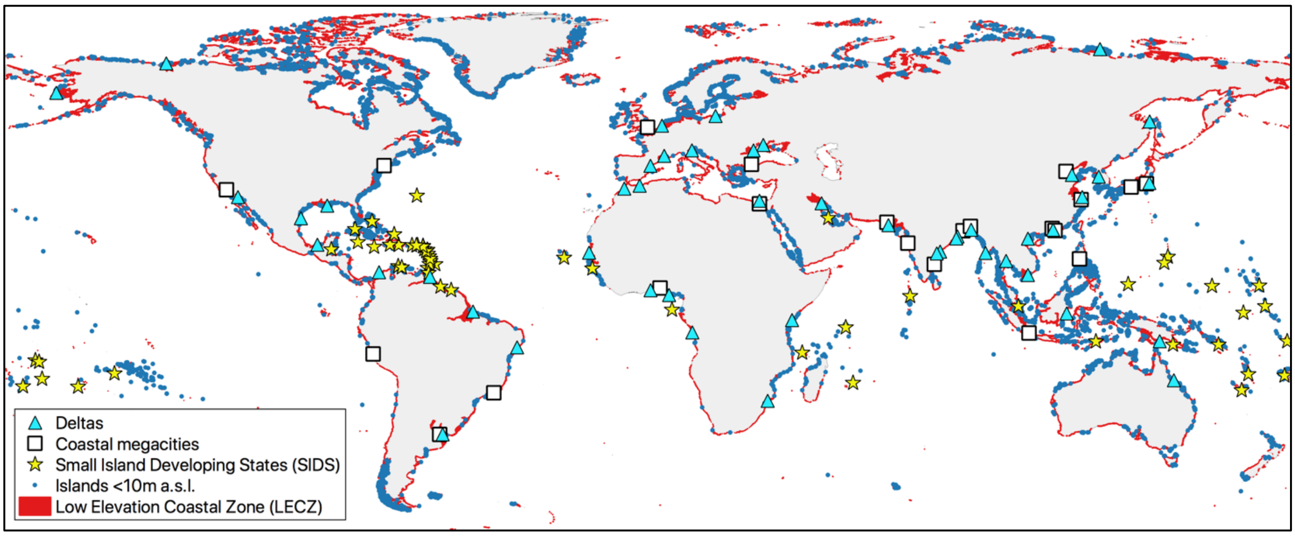

Figure CCB7.1: The global distribution of low-lying islands and coasts (LLIC), illustrated by the Low Elevation Coastal Zone (elevation data from National Geophysical Data Center, 1999; LECZ, as defined by McGranahan et al., 2007) and islands with highest elevation up to 10 m above sea level (Weigelt et al., 2013). In addition, the map shows geographies that the scientific literature identifies as being particularly at risk: 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).

Drivers of Impacts and Risks

LLIC are subject to the same ***climate-related drivers*** of impacts and risks as for other islands and coasts (overview in IPCC Working Group II AR5 Chapter 5: Wong et al., 2014), for both extreme events, e.g., marine heat waves, tropical/extra-tropical storms and associated storm surges; and slow onset changes, e.g., retreat of ice sheets, sea ice and permafrost thaw (and hence exposure to waves and erosion), sea level rise, hypoxia, and ocean warming and acidification (processes detailed in Sections 1.3.2, 2.3, 3.3, 3.4, 4.2, 5.2, 6.2-6.6).

Despite regional to local variability in magnitude (Carson et al., 2016; Cazenave et al., 2018), accelerating sea level rise will combine with storm surges and waves to increase flooding, shoreline changes (including erosion) and salinization of soils, groundwater and surface waters (Section 4.3.3). Arctic sea level rise also has the potential to accelerate permafrost thawing (Sections 4.3.4.1, 6.8, Box 6.1). Moreover, projections of extreme sea levels show that, for many coastal areas, events which are presently occurring once every hundred years will occur once every year by the end of the century (Section 4.2.3.4.1, Figure 4.10).

In addition, changes in the ocean and cryosphere physics and chemistry will have major impacts on marine and coastal organisms and ecosystems, including transitional zones such as seagrass and mangroves (*very high confidence*) (Sections 1.3.1, 1.3.2, 4.3.3, 5.2, 5.3). Ocean acidification will combine with ocean warming and deoxygenation to cause major impacts on benthic and pelagic organisms, associated ecosystems (e.g., coral reefs, oyster beds) and top predators. Species' abundance and distribution will therefore change, with consequences on ecosystem services to human societies (e.g., coastal protection, food security). Such impacts are extensively discussed in Sections 4.3.3.2, 5.2.2.4, 5.2.3-5.2.5, 5.3.3, 5.4.1, 6.4.2, 6.5.2, 6.6.2, 6.7.2 and 6.8.2.

Anthropogenic drivers already play a major role in shaping exposure and vulnerability to climate-related hazards, e.g., in the Arctic (e.g., Ford et al., 2012; Ford et al., 2014; Marino, 2015), in temperate (e.g., Muir et al., 2014; Petzold, 2017) and tropical (e.g., Ratter et al., 2016; Duvat et al., 2017; Weir and Pittock, 2017) small islands, and in coastal cities (e.g., Kates et al., 2006; Rosenzweig and Solecki, 2014; Paterson et al., 2017; Texier-Teixeira and Edelblutte, 2017). Such a contribution is expected to increase in the absence of adequate adaptation measures (*high confidence*). At the local scale, the drivers of exposure and vulnerability include, for example, coastal constructions, pollution, sand mining and unsustainable resource extraction (e.g., in the Comoros; Betzold and Mohamed, 2016; Ratter et al., 2016). Another example is the loss of

Indigenous Knowledge and Local Knowledge (IK & LK; see Cross-Chapter Box 3 in Chapter 1 and Section 4.3.2.6) due to modern, externally-driven socioeconomic dynamics that diminish the cultural importance of IK- & LK-based practices, in combination with dependency on monetization and external markets (Hay, 2013; Campbell, 2015), unsustainable livelihood practices and poor consideration of natural hazards (Ignatowski and Rosales, 2013; Miller Hesed and Paolisso, 2015; Ford et al., 2016; Janif et al., 2016). The loss of IK & LK and associated cultural heritage limits both the ability to recognise and respond to environmental risk (Hiwasaki et al., 2014; McMillen et al., 2014; Campbell, 2015; Lazrus, 2015; Morrison, 2017; Nunn et al., 2017) and the empowerment of local communities (*high confidence*) (Walshe and Nunn, 2012; Hilhorst et al., 2015; Tharakan, 2015; Iloka, 2016; Nunn et al., 2016).

Population growth is another major driver of exposure and vulnerability (Kummu et al., 2016; Bongaarts and O'Neill, 2018), especially in medium-to-mega coastal cities (e.g., Garschagen and Romero-Lankao, 2015; McCubbin et al., 2015; Yan et al., 2015; Yin et al., 2015; Kummu et al., 2016; Liu et al., 2016; Fawcett et al., 2017; Hay, 2017). For the year 2000, the Low Elevation Coastal Zones (LECZ) 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). At the local scale, intertwined drivers including population growth, rural exodus and marginalisation, coastal tourism development, changes in construction modes, human-induced sediment starvation, and degradation of vegetated coastal ecosystems (e.g., mangroves and salt-marshes) drive—as well as are driven by—more overarching processes such coastal urbanisation, inadequate land use planning, coastal squeeze, conflicting resource use and socioeconomic inequalities (Section 4.3.2). Such a complexity in territorial dynamics have resulted in major changes in coastal settlement patterns in recent decades (Section 4.3.2.2), especially a growing concentration of people and assets in risk-prone coastal areas (*very high confidence*). This is also the case in rural LLIC, e.g., remote atolls in the Pacific (Storey and Hunter, 2010; Kumar and Taylor, 2015; Lazrus, 2015; Duvat et al., 2017), that are now increasingly exposed to brackish and polluted groundwater, with implications for water security, wealth and health.

Overview of the Observed and Projected Impacts on Geographies and Major Sectors

Coastal cities and megacities—Cities, especially megacities with over 10 million inhabitants, are at serious risk from climate-related ocean and cryosphere changes (Pelling and Blackburn, 2013; Hinkel et al., 2014; Abadie, 2018). Over half of today's global population lives in cities and megacities, many of which are located in the LECZ, including New York City, Tokyo, Jakarta, Mumbai, Shanghai, Lagos and Cairo (see Figure CB5.1; UN-DESA, 2015). In some of the world's largest coastal cities, present flood losses reach up to 1% of city GDP (Hallegatte et al., 2013). The direct economic impacts of Hurricane Sandy in 2012 in New York, New Jersey and Connecticut, USA, were ~62.5 billion USD, >11% of which has been attributed to anthropogenic sea level rise (Strauss et al., submitted). Future flood losses in the 136 largest coastal cities are projected to rise from 6 billion to USD/year at present to 1 trillion USD/year in 2050, based on the compounding effects of future growth in population and assets, sea level rise and continued subsidence, along with the assumption of no significant adaptation measures (Hallegatte et al., 2013). In addition to important impacts on coastal megacities and large port cities (Box 4.3), small and mid-sized cities are also considered highly vulnerable because of fast growth rates and lack of political, human and financial capacities for risk reduction compared to larger cities (Birkmann et al., 2016).

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

Coastal megacities, especially, are critical nodes for transboundary risks (Atteridge and Remling, 2018; Miller et al., 2018) as they substantially contribute 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 massive flow-on effects on supply chains across the globe (Abe and Ye, 2013). Urbanisation could, however, also provide opportunities for risk reduction, given cities are engines of economic growth and centres of innovation, political attention and private sector investments (Garschagen and Romero-Lankao, 2015).

Small islands**—**In the context of accelerating sea level rise, the extreme events occurring today, such as storms, tropical cyclones, droughts and increasing marine heat waves (Herring et al., 2017), provide striking illustrations of the high vulnerability of small island systems (*high confidence*). With respect to category five tropical storms, for example, cyclone 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). Tropical cyclone Winston in 2017 caused 43 deaths in Fiji and losses of more than 1.4 billion USD for an economy with a GDP of 3.4 billion USD (Government of Fiji, 2016). In 2017, hurricanes Maria and Irma swept through 15 Caribbean countries and islands, such as Saint-Martin/Sint-Maarten (Duvat et al., 2019). 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 of 930.9 million USD and losses of 380.2 million USD, which amounts to 226% of 2016 GDP (The Government of the Commonwealth of Dominica, 2017; Section 6.8.5 and Box 6.1). In 2018, category four tropical cyclone Gita struck the islands of ‘Eua and Tongatapu, impacting 80% of the population of Tonga and resulting in 165 million USD of losses (Government of Tonga, 2018).

A growing concern is the risk that some island nations may become uninhabitable due to climate change (Gerrard and Wannier, 2013; Yamamoto and Esteban, 2014; Donner, 2015), with implications for sovereignty and statehood. Recent studies suggest some atolls may become uninhabitable by the middle of the 21st century because sea level rise exacerbates wave-driven flooding that, in turn, compromises the integrity of freshwater lenses (Cheriton et al., 2016), as observed on Roi-Namur Island, Marshall Islands (Storlazzi et al., 2018). On the other hand, and consistent with greater sediment delivery from increased wave height and energy associated with rising sea level and extreme events, other studies document positive shoreline and surface area changes over the recent decades to century for atoll reef islands in the Pacific and Indian oceans (Mann and Westphal, 2014; McLean and Kench, 2015; Albert et al., 2016; Kench et al., 2018; Duvat, accepted). Out of ~700 studied islands to date, ~73% were stable in surface area over the last forty to seventy years, and ~15% and ~11% increased and decreased in size, respectively (Duvat, accepted). In Tuvalu, for example, total land area of eight out of nine atolls occurred despite relatively rapid sea level rise of ~15 cm between 1971 and 2014 (Kench et al., 2018). In the Solomon Islands with rates of sea level rise of 7–10 mm per year exceeding the global average (Becker et al., 2012), a study of 33 reef islands showed five vegetated islands had disappeared and six islands showed 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). There is thus *high confidence* that atoll reef islands are not ‘static landforms’ and that, for a modest rate of sea level rise, they can accommodate rising sea levels over time. Such a capacity will, however, probably be limited in the case of higher sea level rise rates (Section 4.2) as well as by the impacts of ocean warming and acidification on the reef system (Gattuso et al., 2015; Hoegh-Guldberg et al., in press; Sections 4.3.3, 5.3.3).

Deltas and estuaries—In a context of both sea level rise and high human disturbances to sediment supply, e.g., due to 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). It is estimated that ~260,000 km^2 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). Another major issue in deltas is the intrusion of saline and/or brackish water due to sea level rise and storm surges (Section 4.3.3.1.3, Box 4.3). A positive correlation between rising sea level and increasing residual salinity has been 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). In Bangladesh, freshwater fish species are expected to lose habitat as a result of increasing salinity, with important consequences for fish-dependent communities (Dasgupta et al., 2017). Other concerns include limitations in drinking water supply (Wilbers et al., 2014), the induced effects of salinity on the abundance and toxicity of cholera vibrio (*vibrio cholerae*), for example in the Ganges Delta (Batabyal et al., 2014), and consequences on future local agriculture. With respect to rice cultivation, recent studies emphasise the prevailing role of combined surface elevation and soil salinity, e.g., in the Ebro delta, Spain, where Genua-Olmedo et al. (2016) estimate the rice production index will decrease from 61.2% in 2010 to 33.8% by 2100, for a 1.8 m sea level rise scenario—which is considerably above the likely range of Representative Concentration Pathway 8.5 (RCP8.5; Section 4.2). In coastal Bangladesh, oilseed, sugarcane and jute cultivation have ceased due to already high salinity levels (Khanom, 2016). Negative effects are expected on all dry-season crops over the next 15 to 45 years, especially in the southwestern coastal Bangladesh (Kabir et al., 2018).

Polar regions—In Arctic LLIC especially, climate-related ocean and cryosphere changes combine to negatively impact not only the economy and life-styles of the communities, but also the local cultural identity, self-sufficiency, IK & LK and related skills (Lacher, 2015; Sections 3.4.3, 3.5, 4.3.2.2). Changes in fish and seabird populations amplified by climate change have an impact on ecosystems and livelihoods in Arctic island communities dependent on their local natural capital, such as the Lofoten, Norway (Dannevig and Hovelsrud, 2016; Kaltenborn et al., 2017), or West Greenland (Hamilton et al., 2003). There are currently 178 Alaskan communities facing coastal erosion issues, with 26 in a very critical situation, such as Newtok, Shishmaref, Kivilina, and north-western coastal communities on the Chukchi Sea (Bronen and Chapin III, 2013). An additional factor unique to the polar regions compared to other LLIC is the decrease in seasonal sea ice extent in the Arctic (Section 3.1.1), which reduces the physical protection of the land (Overeem et al., 2011; Fang et al., 2018). Autumn storms also have greater open water fetch due to lower sea ice extent and can produce strong wind-generated waves in the open water (Lantuit et al., 2011). At the same time, the increase in ground temperatures weakens the mechanical stability of frozen ground (Romanovsky et al., 2010). Together these mechanisms of increased wave energy, decreased stability of permafrost and sea level rise, are increasing erosion of locations where coastal settlements are situated on permafrost and discontinuous permafrost (Section 3.4.3). In Alaska, for example, coastal communities such as Selawik are facing both permafrost thawing, subsidence and river bank erosion (AMAP, 2017).

As in other LLIC, impacts in polar regions will be reinforced by anthropogenic drivers enrooted in the recent decades of history (e.g., socio-economic adjustments after government policies requiring children to attend school) and that resulted in the construction of infrastructure in near-shore areas, with the assumption of stable coastlines. While risk levels vary by village, in several cases, infrastructure has been lost and subsistence use areas modified (Bronen, 2011; Marino, 2012; Gorokhovich et al., 2013; Marino, 2015). More broadly, in the Arctic, 'indigenous peoples (…) have been pushed into marginalized 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—Climate change economic impacts for LLIC are expected to be particularly significant in the coming decades to 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 remaining 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). The degree of economic impacts will, however, vary across geographies due to context-specific physical settings and exposure and vulnerability levels (Birkmann and Welle, 2015). For example, the average annual losses due to climate change as a percentage of the GDP are expected to be much higher in SIDS compared with the global average (UN-OHRLLS, 2015; Section 5.5.3.1).

Ocean and cryosphere changes threaten critical LLIC sectors, both economy-related and non-economic, such as employment, livelihood, poverty, health (Kim et al., 2014; Weatherdon et al., 2016; Sections 1.4.3., 5.4.2), well-being and food security (Sections 4.4.4, 5.4.2), as well as public budgets and investments. For example, considering 21st century sea level rise scenarios of 25–123 cm (all RCPs considered), Hinkel et al. (2014) estimate that annual losses from future marine flooding to amount to 0.3–9.3% of global GDP in 2100. Coastal protection will inevitably have economic costs (DiSegni and Shechter, 2013), whether it involves hard coastal protection (Muis et al., 2017) or ecosystem-based approaches (Narayan et al., 2016; Pontee et al., 2016). Coastal agriculture (e.g., rice crops; Smajgl et al., 2015; Genua-Olmedo et al., 2016), and fisheries and aquaculture provide another example (Sections 4.3.3.3.2, 4.3.3.3.5, 5.4.1). Marine fisheries revenues are projected to be negatively impacted in 89% of the world's fishing countries under RCP8.5 in the 2050s relative to the present day (Hilmi et al., 2015). The fact that >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 (Blanchard et al., 2012), raises a serious concern about future food security (FAO et al., 2017). But not all regions are equally threatened, 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 5.4.1, 5.4.2).

Coastal tourism contributes to LLIC economies through direct and indirect employment and income. It could be affected in various ways by ocean- and cryosphere-related changes (Sections 4.3.3.3.4, 5.4.2.2.3). Coastal infrastructure and facilities, such as harbours and resorts (e.g., in Ghana; Sagoe-Addy and Appeaning Addo, 2013), as well as ecosystems that are of value for tourism—e.g., coral reefs supporting diving and snorkelling (Spalding et al., 2017)—are prone to storm waves. For coral reefs for recreational activities and tourism only, 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/year. Saline intrusion due to sea level rise challenges island resorts relying to a substantial degree on groundwater and (sub-)surface water reservoirs for their freshwater supply (Emmanuel et al., 2009). The future appeal of tourism destinations will also 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), as well as 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., in press) 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).

From a broader perspective, human migration, relocation and displacement will be a growing challenge for LLIC (*medium evidence*, *high agreement*) (Adger et al., 2014; Birk and Rasmussen, 2014; Milan and Ruano, 2014; Thomas, 2015; Hajra et al., 2017; Stojanov et al., 2017; Sections 3.3.5, 3.5.5, 4.4.3, 6.3.5). Changes in the basic conditions of LLIC habitability—e.g., shoreline retreat, soil and groundwater salinization, depletion in fish resources, increase in health diseases—will impact people's mobility and may result in displacement to safer locations (Connell, 2016; Janif et al., 2016). It is estimated that sea level rise associated with a 2°C warmer world could submerge the homeland of 280 million people globally by the end of this century (Strauss et al., 2015). 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. People displaced by hurricanes in the Gulf Coast, USA, are already creating an economic impact on both permanent and temporary hosting areas, e.g., in tourism-dependent coastal cities and harbours (Logan et al., 2016). However, based on empirical evidence that people are rarely moving exclusively due to changes in ocean- and cryosphere-based conditions, recent studies conclude that migration pressures as a result of habitual disasters and increasing hazards strongly interact with other migration pressures on the ground, including other environmental stresses and/or economic and political motivations (*high confidence*) (Hartmann, 2010; Kelman, 2015; Marino and Lazrus, 2015; Hamilton et al., 2016; Bettini, 2017; Stojanov et al., 2017; Perumal, 2018).

Responses: Adaptation Strategies in Practice

A wide range of adaptation measures are currently implemented worldwide (Sections 1.5.2. 2.4.3.3., 3.5.5, 4.4.2, 4.4.3, 5.5.2, 6.9, Figure 1.3), including the installation of major infrastructures to address sea level rise, such as armouring of coasts (e.g., seawalls, groynes, revetments, rip-raps), soft engineering (e.g., beach nourishment, dune restoration), reclamation works to build new lands seaward and upwards, ecosystem-based measures (e.g., vegetation planting, coral farming), community-based approaches (e.g., social networks, education campaigns, economic diversification) and institutional innovations (e.g., marine protected areas, evacuation plans). The effectiveness of the measures to reduce vulnerability highly depends on local context-specificities (Gattuso et al., 2018), in addition to the magnitude and timing of local climate impacts (Hoegh-Guldberg et al., in press).

Protection with hard coastal defences is commonly used to prevent inundation from peak tides and storm surges (Section 4.4.2). In already severely damaged environments, such as megacities, hard coastal defences are considered to be successful options (Hallegatte et al., 2013; Hinkel et al., 2018). In less disrupted environments, however, they can lead to detrimental effects, such as seawalls exacerbating processes of coastal erosion, e.g., by reflecting wave energy (Donner and Webber, 2014; Albert et al., 2016; Betzold and Mohamed, 2016), and hamper the ability of beach-dune systems to buffer waves (Pilkey and Cooper, 2014; David et al., 2016). These effects are resulting from to the typical design and placement of such coastal structures. For example, during the tropical cyclone Oli in 2010 on Tubuai Island, French Polynesia, the waves extracted many blocks from the non-consolidated coastal structures, which then acted like cannonballs and increased the damages (Etienne, 2012). 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 (Schlurmann et al., 2014), plantations of seagrass (Paul et al., 2012; Paul and Gillis, 2015), artificial reefs made from bio-rock materials (Beetham et al., 2017; Goreau and Prong, 2017) and bamboo breakwater (Schmitt et al., 2013; David et al., 2016). Soft protection systems used in 69 studies were found to be 70% effective for coral reefs, 62–79% for salt marshes, 36% for seagrass meadows and 31% for mangroves (Narayan et al., 2016). Ecosystem-based measures are usually considered low-regret in that they 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*) (Sections 2.4, 3.5, 5.5.2, 6.9). Other options being considered include the construction of new, artificial islands or floating islands anchored to the seabed (Yamamoto and Esteban, 2014).

Relocation of communities and economic activities is increasingly being considered as an adaptation option to climate-related changes in the ocean and cryosphere (*medium confidence*) (IPCC, 2014; Shayegh et al., 2016; Allgood and McNamara, 2017; Hauer, 2017; Morrison, 2017; Perumal, 2018; Section 4.4.3.5). It is, however, accompanied 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, e.g., in Alaska and the US (Bronen and Chapin III, 2013; 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). Environmentally-induced relocation is not necessarily new, e.g., 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 periods of droughts and subsequent environmental degradation (Birk and Rasmussen, 2014; Tabe, 2016; Weber, 2016). In Papua New Guinea, several (unsuccessful) attempts to relocate the Carteret Islanders have been made since the 1960s as a result of land shortages, salt-water inundation, food insecurity, sea level rise and coastal erosion (Edwards, 2013; Burkett, 2015; Pascoe, 2015; UNDP, 2016). According to a new relocation programme established in 2006, half of the population is expected to be relocated to Bougainville mainland by 2020 (Ferris, 2011; UNDP, 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), while the inhabitants of Ontong Java and Sikaina atolls have requested the government to assist with the relocation to the mainland of Malaita, or elsewhere, due to recent prolonged droughts and salt-water intrusion (Monson and Foukona, 2014). In Alaska, some communities (e.g., Newtok) responded to changing environmental conditions with self-initiated relocation efforts, and Alaska state funding has been allocated to assist them (Bronen, 2015; Hamilton et al., 2016). Relocation also covers 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). It is important to note that 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).

Regardless the option, 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 socio-political and economic framings, coping capacities and cross-scale social and economic impacts. As a result, community-based decision-making, sustainable spatial planning and new institutional arrangements gain increasing attention (Sections 4.4.5, 4.4.6, Box 5.4, Cross-Chapter Box 2 in Chapter 1). 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 & LK (see McMillen et al., 2014; Cross-Chapter Box 3 in Chapter 1). Small island communities, in particular, can strengthen their adaptive capacities by building on relatively high degrees of social capital, i.e., dense social networks, collective action, reciprocity, and relations of trust (Petzold and Ratter, 2015; Barnett and Waters, 2016; Petzold, 2016; Kelman, 2017). 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 also already applied and 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 the Pacific region (Burnside-Lawry et al., 2017). This observation suggests that 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). It is illustrated by the development of 'adaptation pathways'—i.e., long-term adaptation strategies based upon decision cycles that, over time, explore and sequence a set of possible actions (including cost-benefits) 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 4.4.5.3.4). 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 and Duvat, 2018). Practical applications of adaptation pathways in LLIC are occurring, e.g., 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). As adaptation pathways usually bring together multiple sectors, institutions and stakeholders, they lay the foundations for the elaboration of LLIC-specific Climate Resilient Development Pathways (CRDP), broadly defined as sustainable development pathways simultaneously promoting climate resilience (Olsson et al., 2014; Roy et al., in press).

Conclusions

LLIC are hot spots of climate-related changes to the ocean and the cryosphere, whether they are urban or rural, continental or island, at any latitude and regardless their 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 adaptation (Figure CCB7.2; Section 4.3.4.2), which has the potential to significantly increase the level of loss and damage experienced by local to global coastal livelihoods (e.g., fishing, logistics or tourism) (Djalante et al., in press). 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*) (Box 6.1). This is the case when coastal flooding and riverine inundation occur together (Section 4.3.4.1), e.g., 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); or 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). There is *medium confidence* that these findings may well be indicative of the situation for other LLIC (Hay et al., accepted).

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 (McCarthy et al., 2001; IPCC, 2014). 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 that the potential for coastal protection and ecosystem-based adaptation will reach significant limits by 2100 in the case of a 1-m rise in sea level (see also Section 4.2.2.5), suggesting the need for research into the crossing of environmental and/or anthropogenic tipping points (Sections 6.2, 4.2.3). The evidence presented above 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, that 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 CRDPs (*low evidence, high agreement*) (Solecki et al., 2017).

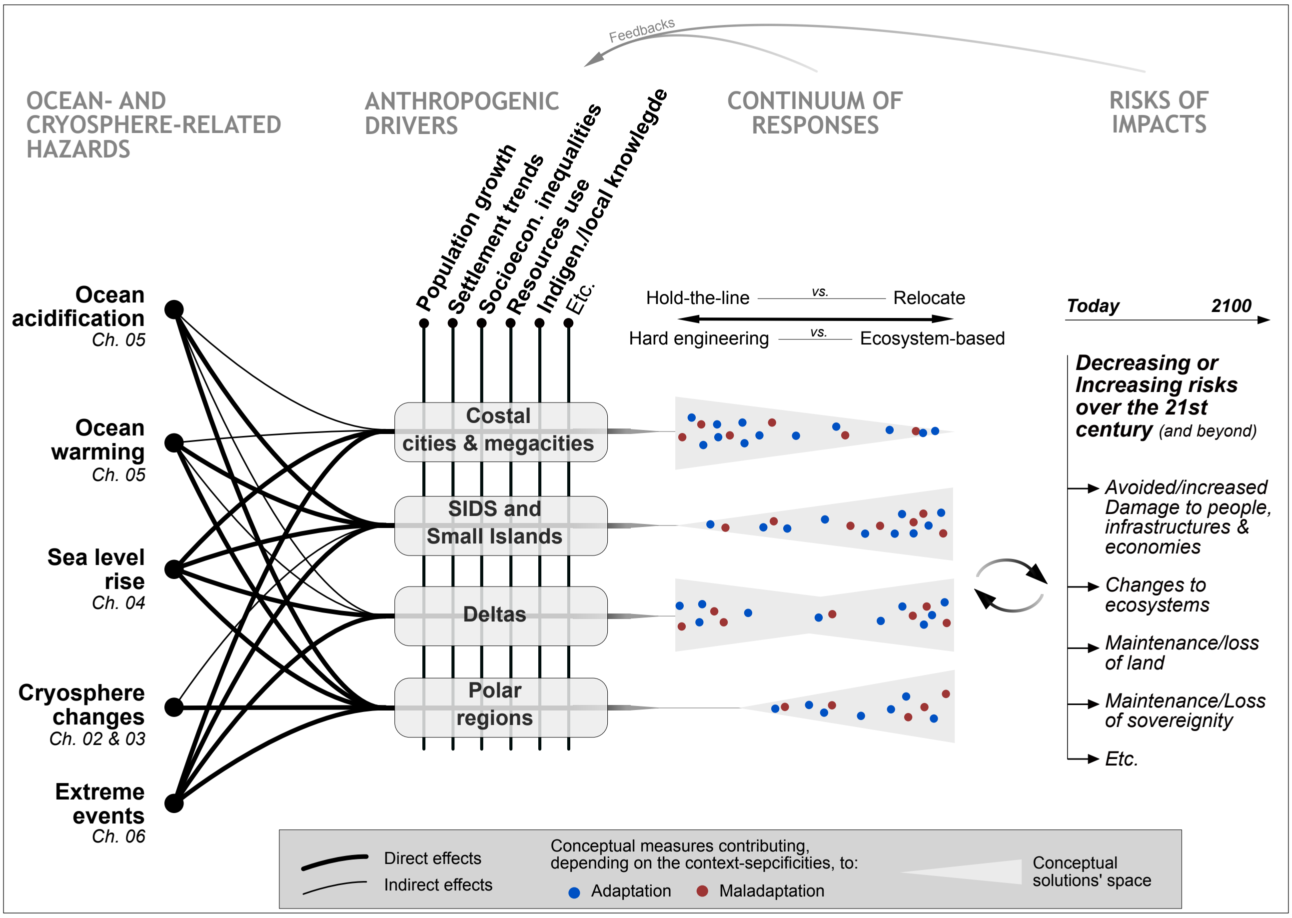

Figure CCB7.2: The storyline of risk for LLIC. From left to right, this figure shows that ocean- and cryosphere-related hazards (e.g., ocean acidification, sea level rise) will combine with anthropogenic drivers (e.g., settlement trends, socioeconomic inequalities) to explain impacts on various LLIC geographies (cities, islands, deltas, polar regions). Depending on the combinations of responses (dots) along a continuum going from hard engineering to ecosystem-based approaches, and from 'holding-the-line' to relocation, risks will increase or decrease in the coming decades. Some responses will enhance adaptation (blue dots), when others will rather contribute to maladaptation (brown dots).

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