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Habitability of low-lying socio-ecological systems under a changing climate

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Abstract

Climate change will push the planet worryingly close to its boundaries, across all latitudes and levels of development. One question therefore is the extent to which climate change does (and will) severely affect societies' livelihoods, health, well-being, and cultures. This paper discusses the "severe climate risks" concept developed under Working Group II's contribution to the Fifth and Sixth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC, AR5, and AR6). Focusing on low-lying coastal socio-ecological systems (LCS) and acknowledging that attempts to define "severe" climate risk have been problematic at the level of global syntheses, we argue for a more place- and people-based framing relating to "habitability under a changing climate." We summarize habitability in terms of five habitability pillars: land, freshwater, food, settlement and infrastructure, and economic and subsistence activities; we acknowledge social and cultural factors (including perceptions, values, governance arrangements, human agency, power structures) as critical underlying factors rather than as separate pillars. We further develop the habitability framing and examine climate risk to future human health and habitability for three climate "hotspot" archetypes (arctic coasts, atoll islands, densely populated urban areas). Building on the IPCC AR6 framing of severe climate risks, we discuss three key parameters describing severe climate risks in LCS: the point of *irreversibility* of changes, physical and socio-ecological *thresholds*, and *cascading effects* across various habitability dimensions. We also highlight the variability of severe risk conditions both between coastal archetypes and within each of them. Further work should consist of refining the case study framing to find the right balance between capturing context-specificities through real-world local case studies and commonalities derived from more generic archetypes. In addition, there is a need to identify appropriate methods to assess *irreversibility*, *thresholds*, and *cascading effects*, and thus severe climate risks to habitability.

Keywords Severe climate risks · Coastal adaptation · Social-ecological systems · Settlement archetypes (arctic, atoll, cities)

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1 Introduction

Low-lying coastal socio-ecological systems (LCS), also known as Low Elevation Coastal Zones (McGranahan et al. 2007), are systems contiguous and hydrologically connected to the sea at mean elevations below 10 m above mean sea level. LCS include a wide diversity of system types, from small rural islands to megacities, distributed around the world, at all latitudes, and in both developing and developed countries. They therefore offer a wide panorama of climate-related and socio-ecological risks, and hence adaptation challenges. LCS host ~ 11% of the global population (~ 680 million people), at densities and growth rates greater than the global average (Neumann et al. 2015), generate ~ 14% of the global gross domestic product (Kummu et al. 2016) and are key systems for food security worldwide (Loring et al. 2019). LCS are threatened by shoreline erosion, groundwater and soil salinization, river flooding, and marine incursions associated with both sea-level rise (global mean of + 0.84 m by 2100 and 10–20 mm/year under a high emission scenario known as RCP8.5; Oppenheimer et al. 2019; Fox-Kemper et al. 2021), and extreme sea level events (Kirezci et al. 2020), including the significant shortening of the recurrence interval of the 100-year flood (Seneviratne et al. 2021). LCS link these significant hazards to high levels of exposure and vulnerability which are likely to increase over time if no ambitious adaptation is implemented. For example, global economic damages to coastal assets from tropical cyclones are projected to increase by > 300% by 2100, due solely to coastal development, a much larger effect than that projected for the climate change hazard alone, even under RCP8.5 (Gettelman et al. 2018). Furthermore, human actions that removed, altered, and fragmented coastal ecosystems have lessened the ability of these ecosystems not only to adapt to climate change but also to act as natural protective barriers at the coast (van Zelst et al. 2021; Wedding et al. 2022). Finally, while modelling studies have shown that adaptation measures can substantially reduce future coastal flood impacts to people and infrastructure (e.g., Kirezci et al. 2023), most LCS exhibit (as yet at least) relatively low levels of adaptation (Berrang-Ford et al. 2021; Petzold et al. 2023).

A key objective of the IPCC's Working Group II is to identify "key" risks which may result from increases in the hazards due to continued climate change and/or changes in exposure and vulnerability, resulting from socio-economic development trends such as coastal urbanization as well as from the effects—both positive and negative—of adaptation. The initial motivation was to identify large-scale risks that could qualify as "dangerous anthropogenic interference" with the climate system, hence being relevant to the interpretation of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) (Oppenheimer et al. 2014). Defining the key risk in this manner hinges on what elevates risk to a "severe" or "dangerous" level. This is inherently challenging as it may require normative judgments while at the same time being intrinsically dependent on context-specific social and cultural values. These contextual influences are likely to be particularly strong at regional to local spatial scales. This debate about what constitutes a severe risk under the IPCC terminology resonates with that of discussing "(in)tolerable" or "(un)acceptable" risks from climate change (Handmer and Nalau 2019; Farbotko and Campbell 2022).

Following the introduction of limits (both "hard" and "soft") to adaptation in IPCC AR5 (Klein et al. 2014) and the gathering of evidence for such limits for systems, sectors, and regions in the IPCC Special Report on 1.5 °C (Mechler et al. 2020), IPCC AR6 (O'Neill et al. 2022) developed a systematic process of defining severe risk from climate change at the crossroads of four overarching criteria: *magnitude* of adverse consequences (high level of pervasiveness and high degree of change), *likelihood* of adverse consequences (high probability), *temporal characteristics* of the risk (occurring sooner or increasing more rapidly than expected over time), and *ability to respond* to the risk (more severe if the affected ecosystems or societies have compromised the ability to cope with hazards). This framing has been applied to various geographical systems and sectors in O'Neill et al. (2022) but does not fully resolve the underlying challenge of identifying the level at which "severity" is reached on the ground, that is, the risk thresholds that irreversibly push a given socio-ecological system to, and beyond, its adaptation limits. O'Neill et al. (2022) therefore identified a further three qualifiers, though still conceptual: *irreversibility* of consequences, potential for *thresholds* beyond which the magnitude or rate of an impact substantially increases, and potential for *cascading effects* within and beyond system boundaries. *Irreversibility* was particularly identified in AR6 as a key descriptor of severe risk to LCS, following the IPCC's "very high" qualitative risk level characterized by significant irreversibility or persistence of impacts (Oppenheimer et al. 2019).

While these definitions help inform the boundary for "severe risk," they are usually coarse in scale and generally physically determined. Here, we argue that normative approaches can help create a foundation for more grounded assessments of climate risk that engage with the societal (e.g., risk awareness levels, socioeconomic patterns, governance arrangements) and environmental context (types of soils, vegetation species, topography, and bathymetry). Used as such, normative approaches can lead to an understanding of risk levels across contexts and populations and, in this way, identify hotspots of risk and priority areas for action.

In this paper, we show, first, that the three qualifiers—*irreversibility* of consequences, potential for *threshold*s, and likelihood of *cascading effects*—can be applied to human dimensions to understand severe climate risk to LCS in a more comprehensive way; and second, that their precise characterization requires a place-based analysis. We focus on the future habitability (for definition see Sect. 2.2 below) of some key LCS archetypes (Arctic regions, atoll islands, and densely populated urban areas) to illustrate such a more place- and people-based definition of severe climate risk, based on an exploration into how *irreversibility*, *thresholds*, and *cascading effects* could materialize and how the question of un-habitability sits within the wider context of adaptation visions, options, and limits on the ground (Farbotko et al. 2023).

2 Coastal settings and habitability

2.1 Towards a bottom-up approach to severe climate risk

While global scale concepts and generalized metrics of risk are useful to provide consistency in the way climate change effects are analyzed across contexts and results fed into international policy discussions on climate action (Magnan et al. 2021), they are limited when it comes to addressing more regional to local-scale challenges. As a result, the "top-down" approach needs to be complemented by "bottom-up" thinking that stresses local situations, i.e., place-and people-based climate risk drivers and local adaptation visions, as well as adaptive responses (Conway et al. 2019; Ford et al. 2019; Horton et al. 2021). A grounded approach has several benefits:

- First, risks need to be viewed in their entirety, including their physical (e.g., in LCS, beach-dune systems, and intertidal wetlands), ecological (terrestrial, tidal, and ocean ecosystems), and human (people, buildings, critical infrastructure, subsistence, economic activities, and cultural values and assets) components, as well as the interactions among these components, including ecosystem services and human-induced environmental degradations (Tokunaga et al. 2021). Considering the overall integrity of any impacted system becomes critical to the subsequent understanding of the *cascading effects* of climate risks.
- Second, risk appraisals require a consideration of the multiple types of climate hazards and their interactions, which is critical to understanding risk *thresholds*. In LCS, climate impact drivers include chronic, progressive changes (sea-level rise, ocean warming and acidification, permafrost thaw and sea-ice loss) alongside acute, event-driven extremes (shocks from storms, marine heatwaves, fires, river floods, droughts), all in combination with local non-climatic anthropogenic risk drivers, including (but not limited to) land use changes, disruptions of coastal sediment supply, the degradation of ecosystems, and the shrinkage of environmentally rooted cultural values.
- Third, past and present disasters often illustrate the dramatic and complex, context-dependent consequences of compound extreme events (e.g., in LCS: storm surge high water levels accompanied by freshwater runoff from heavy rains, or a sequence of tropical hurricanes making landfall; Zscheischler et al. 2018) and *cascading effects* (from ecosystems to settlements and infrastructure, economic activities, social equity, and policy challenges) that lead to related risk accumulation (Rusca et al. 2021; Smiley et al. 2022).
- Fourth, LCS illustrate the profound and intergenerational challenges posed by climate change through the long-term commitment to several climate impact drivers, including global mean sea-level rise that is expected to range in 2300 from 0.3–3.1 to 1.7–6.8 m under RCP2.6 and RCP8.5, respectively (Fox-Kemper et al. 2021). In this way, LCS also underscore the long-term risks (beyond 2100) and the potential role of the intergenerational dimension to describing risk *irreversibility* and *cascading effects*, and thus severity.

2.2 The habitability framing

All the dynamics above (system integrity, multi-driver influences, compounding, and cascading effects, long timescales) can be captured for human lives and livelihoods through the concept of "habitability." In the context of climate change, habitability can be defined as "the ability of a place to support human life by providing protection from hazards which challenge human survival, and by assuring adequate space, food and freshwater" (IPCC 2019a, 688). The concept also defines how a specific location can engender economic opportunities, contributing to productive livelihoods, and support human health and well-being (Bennett et al. 2019), now and across generations (Horton et al. 2021). Last, Farbotko and Campbell (2002, 182) emphasize the importance of cultural aspects when writing that "the qualities that make a particular place acceptable to live in are culturally and historically specific, involving local [and Indigenous] knowledges, cosmologies and place attachments." Next to geo-bio-physical settings, habitability therefore strongly depends on the inhabitants' tangible (e.g., technological, financial, and institutional) and intangible (e.g., cultural identity and place attachments) resources to adapt, as well as on the impact tolerance of inhabitants and the acceptability of response strategies (Whitney et al. 2017; Handmer and Nalau 2019; Tschakert et al. 2019; Farbotko et al. 2023).

Few frameworks exist to assess climate risks to habitability in a pragmatic way and across various warming scenarios and timeframes. One such framework has been developed by Duvat et al. (2021), in the context of atoll islands, that identifies five “habitability pillars” or safe spaces from climate threats: available land, freshwater supply, food supply, safe settlements and infrastructure, and sustainable access to economic and subsistence activities. This framework does not consider some important human dimensions, such as cultural identity, risk perceptions and values, governance arrangements, human agency, power structures, and human health for example, as habitability pillars per se, but rather as both underlying drivers of vulnerability and outcomes of response to climate risk, including, in the case of the latter, the shaping of adaptation choices.

Figure 1 is modified from Duvat et al. (2021) to illustrate the LCS habitability system considered in this paper. It shows the central role of the abovementioned five habitability pillars, as well as the influence of other factors, be they either endogenous (supporting natural and societal conditions, local human disturbances) or exogenous (effects of globalization and climate change). Importantly, the figure shows the degree to which all these components are interconnected, and therefore the importance of accounting for *cascading effects* when assessing climate risk. This degree of interaction makes it hard to distinguish how each habitability pillar influences climate risk trends and levels. Nevertheless, one can imagine situations, varying by site contexts, where a particular pillar is most strongly affected by climate change and, being located “upstream” in a chain of impacts, being triggers of *cascading effects* on other pillars. It should also be recognized that Fig. 1 should not be taken as a “closed system.” There are important tele-connections to influential processes outside of any LCS, including flows of resources, people, information, and, in some cases, policy—and that these processes can bring with them structural power imbalances.

For example, Duvat et al. (2021) show that in atoll islands, the pillar of land that is safe from sea-level extremes sets critical foundations to settlements and infrastructure (allowing for safe space for settlements), freshwater availability (e.g., influences the size of the groundwater lens), food supply (e.g., arable land quality and extent), and economic and subsistence activities (e.g., for building fishing facilities). So *irreversible* changes to land and/or the overshoot of land-related *thresholds* is critical to determine climate risk severity throughout the entire atoll island habitability system. The next section further develops these ideas.

3 Assessing risk to habitability through the use of coastal archetypes

The habitability approach can lead to a more grounded and comprehensive appraisal of severe climate risk. One consequence is that severe risk may be predicted to occur sooner, or later, and/or with greater impact magnitude than with global scale temperature-based assessments. For example, it is predicted that 90 (by 2050) to 380 (by 2100) million more people will be exposed to annual flood levels under a high-end warming scenario compared to 250 million people today (Kulp and Strauss 2019). But in reality, it is probable that the consequences of compounding physical changes on living conditions—such as the greatly increased incidence of “nuisance” flooding events (Moftakhari et al. 2018), combinations of episodic coastal flooding from spring tide storm surges and storm waves on top of a rising sea level baseline (Wolf and Flather 2005), and melting permafrost—will make some

Fig. 1 Conceptual model of low-lying coastal socio-ecological system habitability. The five habitability pillars (dark blue cells) are supported by natural and societal conditions (grey cells) and interact with each other (blue arrows). Source: modified from Duvat et al. (2021) ▶

LCS uninhabitable, by the local definition, long before global sea-level rise causes permanent inundation (Duvat et al. 2022; Magnan et al. 2022). The critical remaining question therefore is how, and at what point do these threats to habitability translate into habitability loss and thus severe risk to LCS?

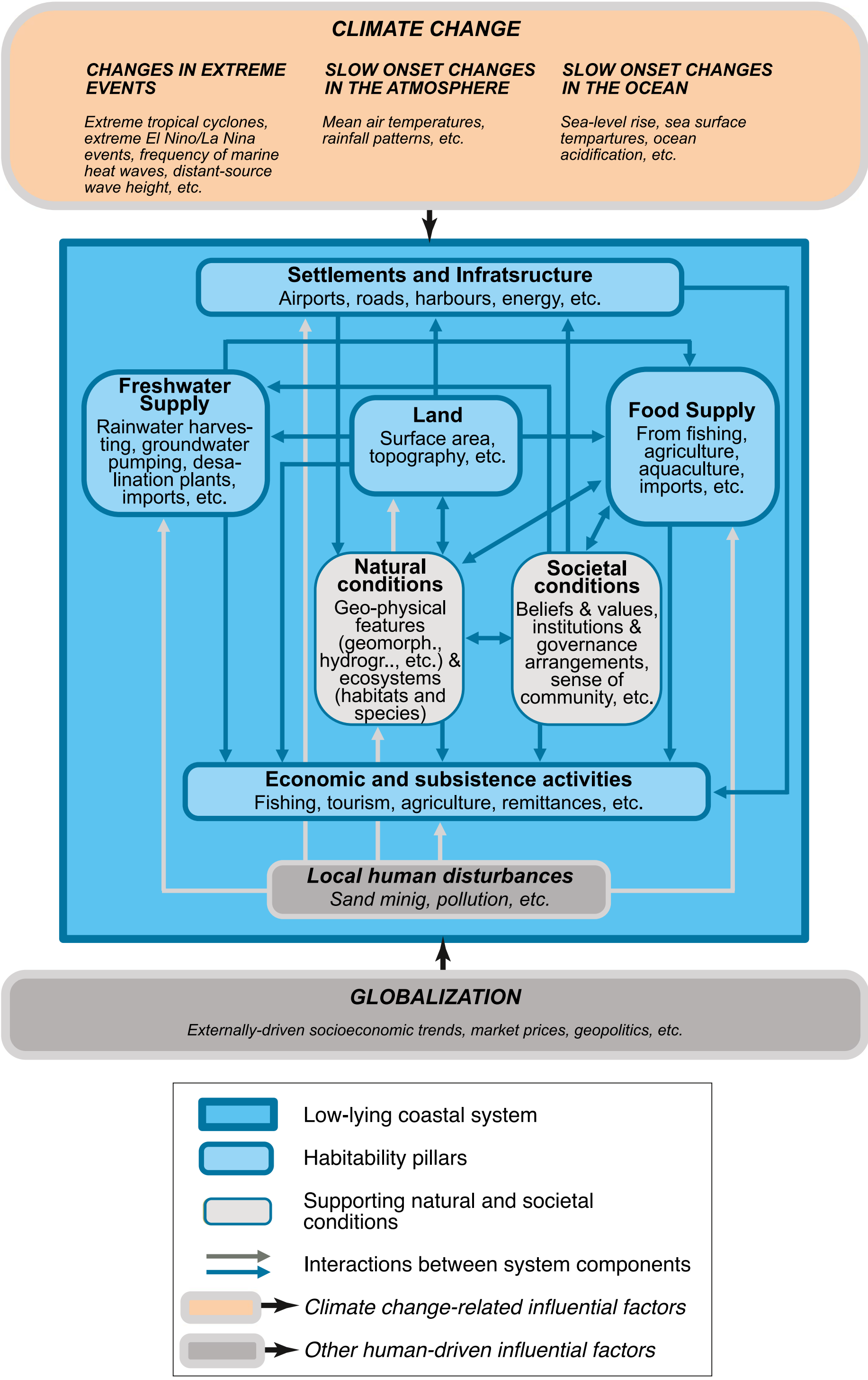
Using the qualifiers of *irreversibility*, *thresholds*, and *cascading effects* drawn from O'Neill et al. (2022), we explore these questions for three low-lying coastal archetypes: Arctic regions, atoll islands, and densely populated urbanized coasts. These archetypes were chosen to illustrate a range of coastal settlements, from polar to tropical environments and from high to low population and infrastructure density. The objective is to give a preliminary illustration of using the habitability approach in LCSs to identifying risk severity rather than to deliver a comprehensive assessment of case-specific severe risk conditions at the intersection of warming scenario, exposure and vulnerability trajectories, and climate adaptation efforts.

3.1 Arctic coasts

Of the five habitability pillars identified in Fig. 1, the availability of land that is safe from climate- and sea-related hazards is clearly one of the most influential for Arctic environments. This induces *cascading effects* on two other pillars: settlements and infrastructure and economic and subsistence activities (see black arrows in Fig. 2). There are two central climate drivers that influence the future availability of land, and in turn other habitability pillars, along Arctic coasts: permafrost thawing and sea ice loss.

First, permafrost thawing threatens coastal settlements and infrastructure, through shoreline retreat and inland collapse. In the circumpolar Arctic, 15% of critical infrastructure assets would be affected by climate change under RCP8.5 by 2050, with lifecycle replacement costs projected to increase by 28% if the infrastructure is to be preserved at current adaptation levels (Suter et al. 2019). Regional-focused studies suggest costs could significantly exceed this figure (Debortoli et al. 2023). More broadly, the IPCC concludes with *high confidence* that "Arctic permafrost thaw is projected to impact most infrastructure (almost 70% under RCP4.5, according to the report citing Hjort et al. 2018) by the middle of this century, impacting millions of people and their economies, and costing billions in damages" (Constable et al. 2022, 2321). The loss of permafrost clearly represents an *irreversible* trend. However, the point at which the level of land surface affected by permafrost thaw becomes a critical *threshold* for the declaration of severe risk remains underexplored in the literature. Such a *threshold* would vary from one local case to another, for example depending on both the density of assets in at-risk-of-thawing areas, the setback potential in areas less threatened by permafrost thaw, and the cultural value of land at risk. In addition, there will be *cascading effects* on human assets, including buildings, infrastructure, transportation routes, and sites of significant cultural and historical value.

Second, changes in sea ice associated with rapid warming induce higher risks of temporary and permanent flooding due to more ice-free open water and thus diminished coastal protection, exacerbated by sea level rise and permafrost thaw which makes coasts more susceptible to erosion (Schweiger et al. 2019; Irrgang et al. 2022; Constable et al. 2022). Sea-ice loss is measured on a seasonal basis, but there is growing concern that trends in


CLIMATE CHANGE
CHANGES IN EXTREME EVENTS
Extreme tropical cyclones, extreme El Nino/La Nina events, frequency of marine heat waves, distant-source wave height, etc.
SLOW ONSET CHANGES IN THE ATMOSPHERE
Mean air temperatures, rainfall patterns, etc.
SLOW ONSET CHANGES IN THE OCEAN
Sea-level rise, sea surface tempartures, ocean acidification, etc.
Settlements and Infratsructure
Airports, roads, harbours, energy, etc.
Freshwater Supply
Rainwater harves-ting, groundwater pumping, desa-lination plants, imports, etc.
Land
Surface area, topography, etc.
Food Supply
From fishing, agriculture, aquaculture, imports, etc.
Natural conditions
Geo-physical features (geomorph., hydrogr.., etc.) & ecosystems (habitats and species)
Societal conditions
Beliefs & values, institutions & governance arrangements, sense of community, etc.
Economic and subsistence activities
Fishing, tourism, agriculture, remittances, etc.
Local human disturbances
Sand minig, pollution, etc.
GLOBALIZATION
Externally-driven socioeconomic trends, market prices, geopolitics, etc.
Low-lying coastal system
Habitability pillars
Supporting natural and societal conditions
Interactions between system components
Climate change-related influential factors
Other human-driven influential factors

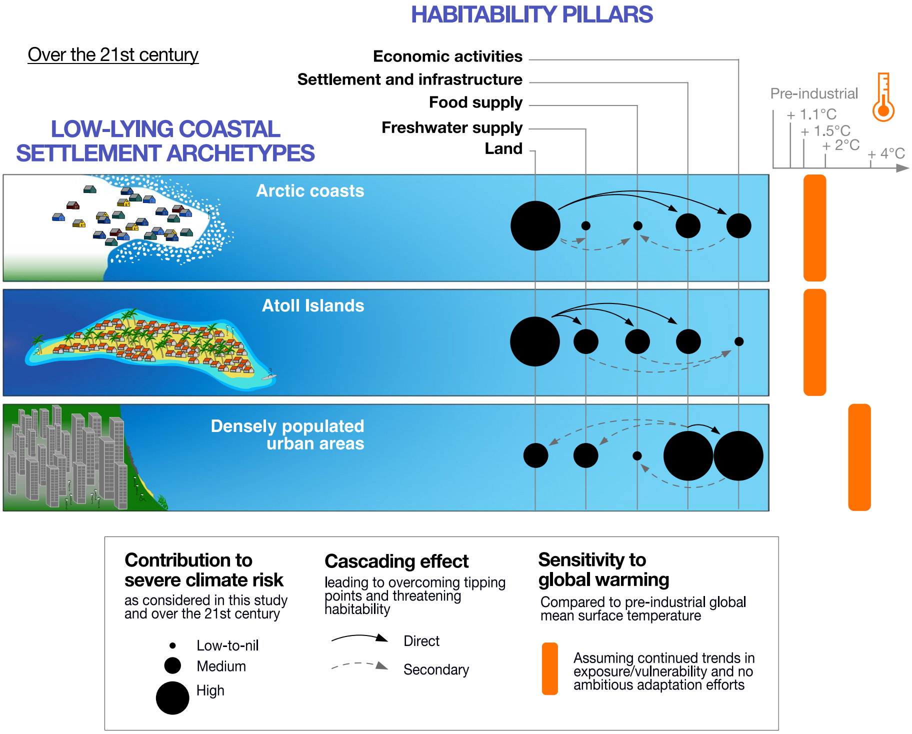


Fig. 2 Conceptual diagram of the contribution of five habitability pillars to severe climate risk over the twenty-first century for three illustrative coastal archetypes. The size of each bubble represents the sensitivity of the habitability pillar to severe climate risk, from low (small bubble) to high (large bubble), respectively. The arrows show the possible direct (solid) and indirect (dotted) cascading effects between pillars. The vertical bars on the right-hand side summarize the main conclusions of the IPCC AR6 report (O'Neill et al. 2022) on the warming conditions under which risk could become severe in low-lying coastal areas, at the coastal archetype level (so indicative mean situations rather than for specific locations). For example, Arctic coasts and atoll islands show greater sensitivity to twenty-first-century warming, implying an earlier onset of severe climate risk in these archetypes than on developed coasts. The atoll island panel rather reflects the situation of urban and rural islands with moderate to low population and asset densities; densely populated capital islands are not fully considered as their configurations could rather look to the bottom panel on densely populated coasts

sea-ice loss are *irreversible* (Ford et al. 2021; Mudryk et al. 2021; Nielsen et al. 2022). Regarding *thresholds*, abrupt shifts in several Arctic parameters including sea ice are expected between 1.5 and 2.0 °C of global warming, with a 10–35% chance under + 2.0 °C for the region to become largely ice-free in summer (IPCC 2019b; Lenton et al. 2019). This may create new opportunities for shipping if carefully managed, with potential community benefits, although benefits may be offset by the declining usability of winter roads and impacts of permafrost thaw on infrastructure (Dawson et al. 2020; van Luijk et al. 2022).

Identifying *thresholds* for habitability depends on the potential for adaptation through planned relocation or investment in coastal protection, both of which are challenged by limited suitable land base and high costs (Ford et al. 2015; Melvin et al. 2017; Devine et al. 2021; Debortoli et al. 2023). The concept of "land" for Indigenous and local communities in the Arctic brings additional dimensions linked to traditional resource use practices that underpin identity, culture, food systems, and worldviews (Cunsolo and Ellis 2018).

Climate-driven changes to ice and weather regimes have substantially affected traditional coastal-based hunting and fishing activities, with *cascading effects* on the economic and subsistence activities habitability pillar, and then on food systems, culture, and health (Devine et al. 2021; Ford et al. 2021, Huntington et al. 2022; see arrows in Fig. 2). Defining climate risk severity, therefore, has to be context-specific, whereas climate change will continue to threaten archeological sites in many places in Greenland and Canada (Yukon's Beaufort coast, Auyuittuq), for example (Desjardins et al. 2020; Constable et al. 2022; Nicu and Fatoric 2023), the "acceptable" level of cultural heritage loss will strongly depend on local values and cannot be decided externally. At the same time, risk severity cannot be defined only through the cultural lens as it should also integrate tangible, quantifiable parameters, e.g., the effects on food security. So despite the complexity to reflect local and multi-dimensional context specificities, some general land-based elements (e.g., sea-ice loss and permafrost thaw levels threatening a substantial proportion of settlements and infrastructure) can help identify habitability *thresholds*.

Constable et al. (2022, see online Supplementary Material) estimate that due to the combination of sea-ice loss, higher waves, and permafrost thaw, coastal erosion risk in the Arctic will move from *moderate* to *high*[1] within a 1.8–2.0 °C range of warming. They also estimate that risks to infrastructure and risk of local mobility will move from *moderate* to *high* within a 2.0–3.0 °C range of warming. This suggests key temperature-driven *thresholds* start to determine severe risk to habitability in Arctic regions, albeit with variability by region. In the Canadian Arctic, for example, recent modelling suggests that limits to adapting community trail networks to changing sea-ice conditions will become evident in more southerly communities by as early as 2060, but access to such trials will be maintained in more northern communities even under SSP585 by the end of the century (Ford et al. 2023).

3.2 Atoll islands

Safe land availability is also of primary concern for atoll islands (Duvat et al. 2021), which in turn calls for paying attention to life-supporting natural conditions, especially geophysical features (ground elevation, sand resource, etc.) and marine and terrestrial ecosystems (see Fig. 1). Warm-water coral reefs, in particular, are critical ecosystems for atoll island protection against waves (e.g., Duvat and Magnan 2019), sediment supply for island building (Perry et al. 2011), and fisheries and food security (Hughes et al. 2012). Yet, they are already experiencing widespread degradation due to coral bleaching and are at risk of net erosion this century even under 1.5 °C of global warming (Cooley et al. 2022). The switch to such a negative balance (erosion > accretion) would define an *irreversible* change under projected climate trends, as well as highlighting a clear risk *threshold* around 1.0 °C of warming in sea surface temperature[2]. Together, increasing climate pressures and the loss of marine and coastal biodiversity will have *cascading effects* on the other dimensions of human life, and hence habitability (Mycoo et al. 2022).

It is important to consider net shoreline erosion (i.e., not only seasonal change) and permanent and temporary marine flooding together (Pollard et al. 2018). For a set of urban

[1] Risk levels in italics refer to the IPCC framing: *undetectable* means "risks that are undetected;" *moderate* means "detected and attributed to climate change with at least medium confidence;" *high* means "severe and widespread;" *very high* means "very high probability of severe risks and significant irreversibility or persistence of impacts".

and rural atoll islands in the Western Pacific and Central Indian oceans, Duvat et al. (2021) estimate risk to land to be relatively *low*[2] by the mid-century even under RCP8.5. However, by the end of this century, risk to land will substantially increase to *moderate* in rural islands and *high* in urban islands under RCP2.6, and to *high* in rural islands and up to *very high* in urban islands under RCP8.5. In Fogafale, Tuvalu, for example, the end-century *very high* level of risk to Land results from the synergies between high rates of sea-level rise (+5.1 and+15.4 mm/year under RCP2.6 and RCP8.5, respectively), a progressive impact, and increases in tropical cyclone and distant-source wave height events.

In the Western Pacific and Central Indian oceans, these land impacts will *cascade* through into *moderate* (RCP2.6) to *moderate-to-high* (RCP8.5) risk levels to both freshwater supply and land-based food supply (Duvat et al. 2021; and see also Tigchelaar et al. 2021), and up to *very high* risk to settlement and infrastructure, whatever the warming scenario (Wadey et al. 2017). Another *cascading effect* (solid arrows in Fig. 2) comes from freshwater insecurity through groundwater degradation (Storlazzi et al. 2018). All these effects have the potential to feed into economic decline (dotted arrows in Fig. 2). Moving downstream of the chain of impacts, the undermining of the five habitability pillars will cause the degradation of human health and well-being (Jenkins et al. 2018; Zheng et al. 2020), and the loss of cultural heritage, indigenous and traditional knowledge, and associated identities (Hofmann 2017; McNamara et al. 2021). By insidiously reducing the adaptive capacity of islanders, these *cascading effects* will likely limit habitability and lead to population movement to other islands (Oakes et al. 2016) or even abroad (Shen and Gemenne 2011) in extreme cases.

Bearing in mind the small size of many atoll islands, a habitability-based *threshold* for severe climate risk could be considered to occur when a substantial fraction of the island surface (e.g., >20%, in Duvat et al. 2021) or a culturally or economically vital part of the island is affected by frequent, hazardous flooding. Following this method, Duvat et al. (2021) identified that 0.20 to 0.60 m water depth flooding with a 1–5 year return period, or a monthly return period, would classify as generic thresholds for *moderate* risk and *high* risk, respectively. Such risk may be offset if there is "space for nature" which can be defined as setback potential. Some locations have no such potential. It is, for example, nonexistent in Male, Maldives, due to an already high density of hard assets over the whole surface of the island; there, even 10% land loss could represent a severe risk. The setback potential is possibly higher in other contexts such as in Rangiroa Atoll, French Polynesia. There, a loss of 20% of the surface area of the most populated islands might be compensated through community relocation to other locations on the atoll rim (Duvat et al. 2022),

[2] In Duvat et al. (2021; Supplementary Material p. 12): "low" risk level means that "climate change-related risk will affect a low proportion of the island land area/built area/agricultural area/freshwater or food supply and/or have a low frequency and/or remain at a low level;" e.g., a "low frequency (approx. every 5–10 years) nuisance flooding (<20 cm water depth) over 20 to 50% of the island surface". "Moderate" level means that "climate change-related risk will affect a significant part of the island land area/built area/agricultural area/freshwater or food supply, and/or have a medium frequency and/or reach a moderate level;" e.g., a "moderate frequency (approx. every 1 to 5 years) hazardous flooding (water depth comprised between 0.20 and 0.60 m) over 20 to 50% the island surface." "High" means that "climate change-related risk will affect a significant part of the island land area/built area/agricultural area/freshwater or food supply and/or have a high frequency and/or reach a high level;" e.g., a "monthly hazardous flooding (water depth comprised between 0.20 and 0.60 cm) over most of the island surface." "Very high" means "climate change-related risk will affect most of the island land area/built area/agricultural area/freshwater or food supply and/or have a very high frequency and/or reach a very high level," e.g., a "permanent threatening flooding (water depth>0.60 m) over most of the island surface.".

thereby in effect raising the *threshold* for “severe” climate risk above the 20% land loss figure. This discussion points to the fundamental role of local settings—and local values in terms of what is acceptable/unacceptable to given communities—in determining *thresholds* to severe climate risk.

3.3 Densely populated urban areas

The majority (63%) of the global urban population is coastal (Barrangan and De Andres 2015), and these urban areas are critical nodes for transboundary risks, contributing substantially to national economies and often serving as hubs for global trade and transportation networks (Glavovic et al. 2022; Verschuur et al. 2023). By 2050, 800 million people are projected to live in more than 570 coastal cities exposed to a 0.5 m rise in sea level (WEF 2019). Many coastal cities will experience enhanced sea-level rise from the contribution of human-induced land subsidence: a net subsidence of > 4 m has occurred during the twentieth century in areas of Tokyo, and 2 to 3 m in Shanghai, Bangkok, Jakarta, and New Orleans (Nicholls et al. 2021). Along with sea-level rise and greater storm potential, near-future urban coastal flood risk is also expected to increase as a result of changes in exposure due to continued coastal urbanization (Mahtta et al. 2022) and a related increase in economic activities (Neumann et al. 2015; Pycroft et al. 2016). Finally, increased coastal flooding has the potential to drive large-scale out-migration (Hauer et al. 2020) of 17 to 72 million people over the twenty-first century according to a recent estimate (Lincke and Hinkel 2021).

Clearly, coastal urban flooding impacts the habitability pillar of settlements and infrastructure directly, with strong *cascading effects* to economic activities with the potential loss of key transportation infrastructure due to more frequent and higher sea-level extremes and, more broadly, the loss of the powerful local agglomerative economies that come with high-density settlement (Desmet et al. 2021). Macroeconomic losses are potentially very high, due to sea floods destroying large amounts of the essential means of production, such as buildings and machinery, and reducing labor supply. More secondary, but possibly important, *cascading effects* will affect both land availability (in cases where whole districts are frequently flooded and damaged) and freshwater supply where saltwater intrusion impacts urban groundwater supply and/or where desalination plants operate sub-optimally. In contrast, links to the habitability pillar of food supply are likely to be weaker than in other archetypes due to the heavy dependence of urban populations on externally sourced foodstuffs.

The centuries-long human response to flood risk exposure in heavily urbanized settings has typically taken the form of the progressive upgrading of coastal protection in response to local extreme water levels. Here, the notion of *irreversibility* therefore applies to the long-term commitment to sea defense increasing as extreme water levels increase. The motivation for this action is strong. At the present day (2015), the mean Expected Annual Population Affected (EAPA) by flooding from the 1 in a 100-year event in the LCS is 34 M (range: 30–61 M). Accounting for future changes in population, GDP and extreme sea levels, future projections of EAPA rise to 63–88 M by 2050 and 57–212 M by 2100. Mean Expected Annual Damage (EAD) reaches 1.37–1.51% of GDP by 2050 and 1.78–2.76% by 2100 (Kirezci et al. 2023). However, where modelling allows for coastal defense heights to be adjusted in response to changing extreme water levels (alongside concomitant changes in population and GDP), then risks to lives and GDP are reduced dramatically: EAPA projections fall to 15–30 M by 2050 and 11–85 M by 2100. Mean EAD falls to 0.54–0.56% of GDP by 2050 and 0.79–1.02% by 2100 (Kirezci et al. 2023).

Such global-scale estimate is informative for identifying thresholds for severe climate risk, as in the recent IPCC assessments which inform this work (Oppenheimer et al. 2019; O'Neill et al. 2022), yet require top-down assumptions which may not reflect the variability in real-world experiences. For example, the perceived safety of living behind such coastal defense can greatly increase vulnerability should such structures fail, such that severe risk suddenly becomes a reality. The human (over 1800 lives lost) and economic cost (damages of US$ 125B) from defense failures associated with Hurricane Katrina (2005) serves as a reminder that developed coasts can lack the ability to properly prepare for, and respond to, extreme events (ASCE 2007). Furthermore, there is evidence from the US East and Gulf coasts that in spite of decades of regulatory efforts to decrease vulnerability in developed coastal zones, exposure of residential assets to hurricane damage is increasing, even in hurricane corridors, with "building back bigger" (Lazarus et al. 2018). And megacity coastal wetlands, important for flood storage and storm wave energy dissipation, have often been degraded or lost by urban development (Hartig et al. 2002), and extant wetlands on the margins of megacities are threatened by urban expansion (Simkin et al. 2022).

In our habitability pillar framing, out-migration results from *cascading* climate risks to economic activities and land. As with GDP, high figures for migration are dramatically reduced with evolving coastal protection. In the absence of further investments in coastal adaptation, and according to models, the total number of people flooded in Europe is projected to rise, across all RCP and SSP combinations, to 0.5–6.9 M by 2100. With additional protection, this range falls to 0.7–1.3 M (Vousdoukas et al. 2020). But even these estimates may be too pessimistic as there is little evidence for relocation actually taking place under flooding impacts. Using examples from areas subject to land subsidence in the twentieth and early twenty-first twenty-first centuries as proxies for future accelerated sea-level rise, Esteban et al. (2020) have shown that inhabitants of densely populated coastal areas in Tokyo, Jakarta/Kepulauan Seribu, and some urban islands in the Philippines have not out-migrated, despite higher water levels. Adaptation has been achieved through a five-phase process: construction of basic seawalls, followed by the use of pumps to drain water, then improved seawalls, reclamation of land, and finally land-building or even more robust sea defenses ("super levees"). Thus, Bachner et al. (2022) suggest that the *threshold* to actually drive migration is inordinately high, perhaps best described by the 1 in 1-year coastal flood.

4 Conclusions

The exemplar of low-lying coastal socio-ecological systems (LCS) provides an opportunity to raise a critical point when discussing severe climate risk: what does "severity" refer to on the ground? In this paper, we highlight the role of "habitability" and a 5-pillar framework as a complementary vehicle to both understand and assess key qualifiers (*irreversibility* of changes, physical and socio-ecological *thresholds*, and *cascading effects* across various habitability dimensions) to describe severe climate risk, including at local scales. Further work is needed to clarify how to concretely account for the underlying, cross-cutting cultural drivers in the five initial pillars. While this requires further thought, the central point that we wish to make in this paper, at this stage, is that the habitability framing proposes a place- and people-based approach that expands the IPCC discussion of risk severity from a more theoretical exercise conducted to define dangerous levels of warming (often at a global level) to one that can speak directly to local and regional environmental policy formulation. A provisional exploration of three key coastal archetypes (Arctic regions, atoll islands, densely populated urban areas) shows that identifying *irreversible* changes, precise *thresholds* at the habitability pillar level, as well as *cascading effects* across the entire habitability system is practicable. Here also, the next steps would benefit from further disaggregating these archetypes, for example by distinguishing between rural and urban atoll islands, or middle-size and larger cities. We also recognize that expanding this embryonic analysis into further archetypes would be beneficial. One critical methodological issue, however, is how to find the balance point between studying local case studies as such and drawing lessons across case studies through using an archetype approach. Recent experiences (e.g., Duvat et al. 2021; Magnan et al. 2022, 2023) suggest that informing archetypes based on a series of real-world case studies is a promising avenue of research, providing some generic understanding based around context-specificities.

Still on methods, frameworks need to be explored to assess the role, interactions, and possible future trends in the habitability pillars, despite knowledge gaps. Structured expert judgments offer a way forward, as shown in Duvat et al. (2021) on estimating risk levels, or in Magnan et al. (2023) on assessing levels of adaptation efforts, because they bring multiple types of information together, from quantitative to qualitative and from published to oral (e.g., traditional knowledge) sources. Such judgments can, therefore, help overcome the classic data gap bottleneck, and thus support analyses at the crossroads of tangible and intangible information. Overall, scientific insights need to be carefully confronted with local values and aspirations to define risk severity conditions. In this way, scientific insights need to be seen as triggers for more grounded discussion about risk severity conditions. Such an approach would therefore give high added value because the risk severity topic raises difficult questions (including distributional impacts and equity/solidarity issues, relocation of people and assets).

If employed in this way, the risk severity concept could become highly valuable in helping decision-makers, practitioners, and communities, in particular to (i) concretely discuss risk acceptability (*thresholds* under which risk remains manageable) and *cascading* risks, and therefore worst case scenarios of coastal futures; (ii) confront the major question of the shrinking solution space as sea-level rises and climate changes intensify (i.e., obsolescence of adaptation options once severity *thresholds* are reached; Haasnoot et al. 2021); (iii) decide about priority areas and actions; and (iv) move towards more pragmatic and just responses to high-end as well as long-term sea-level rise and climate scenarios. We appreciate that discussing habitability in LCS over the twenty-first century will rightly continue to be a very sensitive issue, with considerable finance barriers and potential for social conflict (Hinkel et al. 2018). We also appreciate the call for locally driven alternative narratives of adaptation futures to take a central role in the wider adaptation discourse (Farbotko et al. 2023). But questions of (un-)habitability are nevertheless becoming unavoidable. They require critical investigation as well as social and political debates, ideally pursued in a proactive manner.

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Declarations

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