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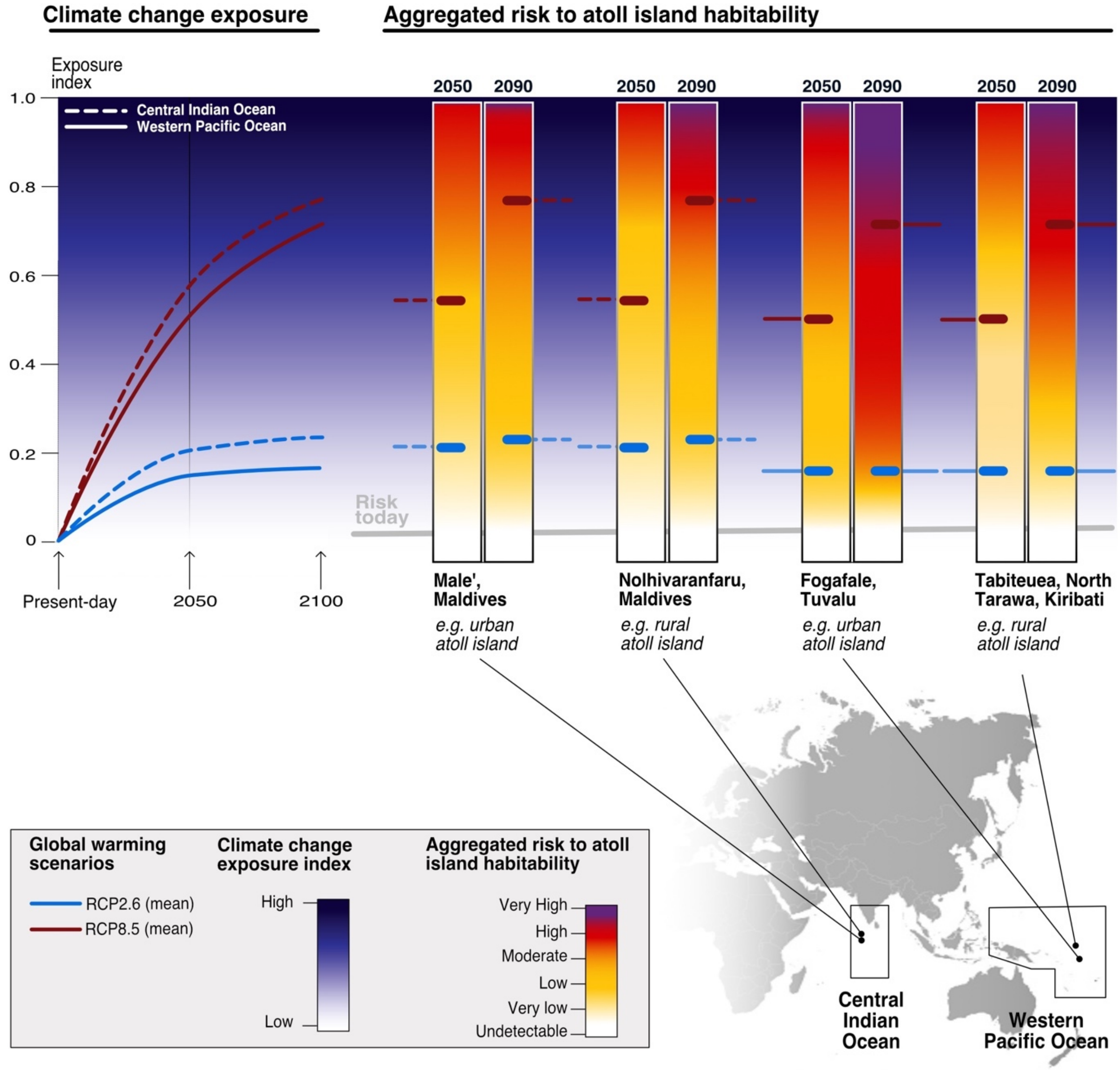
Abstract

Recent assessments of future risk to atoll habitability have focused on island erosion and submergence, and have overlooked the effects of other climate-related drivers, as well as differences between ocean basins and island types. Here we investigate the cumulative risk arising from multiple drivers (sea-level rise; changes in rainfall, ocean-atmosphere oscillations and tropical cyclone intensity; ocean warming and acidification) to five Habitability Pillars: Land, Freshwater supply, Food supply, Settlements and infrastructure, and Economic activities. Risk is assessed for urban and rural islands of the Pacific and Indian Oceans, under RCP2.6 and RCP8.5, in 2050 and 2090, and considering a moderate adaptation scenario. Risks will be highest in the Western Pacific which will experience increased island destabilization together with a high threat to freshwater, and decreased land-based and marine food supply from reef-dependent fish and tuna and tuna-like resources. Risk accumulation will occur at a lower rate in the Central Pacific (lower pressure on land, with more limited cascading effects on other Habitability Pillars; increase in pelagic fish stocks) and the Central Indian Ocean (mostly experiencing increased land destabilization and reef degradation). Risk levels will vary significantly between urban islands, depending on geomorphology and local shoreline disturbances. Rural islands will experience less contrasting risk levels but higher risks than urban islands in the second half of the century.

Graphical/Visual Abstract and Caption



This figure displays the additional risk from climate change to future atoll island habitability. First, islands will experience different futures depending on their type (urban/rural) and region (Pacific/Indian ocean). Second, risk will increase even under a low emission scenario by the mid-century, therefore calling for urgent ambitious adaptation efforts.

Article title (advanced review):
Risks from climate-driven environmental changes to future atoll habitability

1. INTRODUCTION

Climate change impacts will increasingly compromise the essential dimensions of human life in low-lying tropical islands (Magnan et al., 2019). These dimensions include land, freshwater and food availability and the maintenance of settlements and infrastructure, as well as economic activities. The future of populations living on atoll islands in the Indian (Maldives) and Pacific Oceans (especially in the Cook Islands, Tuvalu, Federated States of Micronesia (FSM), Kiribati, Marshall Islands, Tokelau, French Polynesia; Supplementary Material SM1) will in part be determined by how the reef-island systems on which they depend will respond to changes in climate and ocean dynamics. Several recent assessments have focused on the risks of atoll island erosion and their temporary or permanent submergence under increased wave heights and accelerated sea-level rise (SLR; Oppenheimer et al., 2019), and some authors have suggested that these islands may become uninhabitable by 2060-90 under Representative Concentration Pathway (RCP) 8.5 due to annual flooding (e.g. Storlazzi et al., 2018; Giardino et al., 2018). Other studies have proposed that vertical accretion of shoreline systems may limit future flooding and its consequences for settlements (e.g. Beetham and Kench, 2018; Tuck et al., 2019).

These studies generally overlook the effects of drivers other than SLR, especially changes in rainfall and large-scale ocean-atmosphere oscillations, increasing tropical cyclone intensity, and ocean warming and acidification (Gattuso et al., 2015; Mentaschi et al., 2017; Vitousek et al., 2017; Perry et al., 2018; Oppenheimer et al., 2019). However, it is the combined effects of SLR and these drivers which control changes in island-scale reef growth, productivity and structure, terrestrial and marine food resources, and the availability of freshwater on atoll islands. Moreover, contemporary research has neither adequately considered differences in climate and ocean changes between ocean basins or even between islands (Nurse et al., 2014). Although we recognize that human factors, including socio-economic dynamics, human ingenuity, cultural change, population health crises, and geopolitics (e.g. Cinner et al., 2018), are also strong drivers of risks to atoll habitability, here we focus on climate-related environmental drivers and assess the extent to which their changes over the 21st century are likely to compromise atoll habitability.

"Atoll islands" (islands herein) refer to recently-formed (generally < 4,000 yr BP), low-lying (mean elevation generally < 3 m) islands composed mostly of biologically derived carbonate sand, gravel and boulders, resting on reef structures at or near contemporary sea level and often encircling a central lagoon (Woodroffe, 2008; McLean, 2011; Gischler, 2016). Habitability of these islands is understood not only 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" (Weyer et al., 2019, p. 15) but also as the ability of that place to provide economic opportunities, which contribute to health and well-being (Daw et al., 2015; Costanza et al., 2016; Bennett et al., 2019). Accordingly, the atoll island habitability framework (Fig. 1) presented here includes five major interrelated Habitability Pillars (HPs) that will all experience first-order (that is, direct) climate change impacts: i) availability of sufficient and safe land ('*Land*' herein); ii) supply of safe freshwater, especially from local sources ('*Freshwater supply*'); iii) supply of nutritious food from local and/or imported sources ('*Food supply*'); iv) access to safe settlements and infrastructure that sustains freedoms and opportunities, such as for trade, healthcare and education ('*Settlements and infrastructure*'); and v) access to sustainable economic activities ('*Economic activities*'). We evaluate the extent to which each of these HPs will be affected by future climate and ocean changes over the 21st century, thereby increasing risks to life-supporting ecosystems and living conditions. We then assess the implications for future atoll habitability, from a biophysical and environmental perspective, as well as its variability across Indian and Pacific Oceans and across islands representing contrasting socio-economic situations (urban/rural).

Section 2 presents the Materials and Methods used. More particularly, it sheds light on HP significance, regions and islands of interest, climate threats considered, and the expert judgment-based risk assessment protocol. Sections 3 and 4 present the Results, based on CMIP5 climate projections generated for RCPs 2.6 and 8.5 at 2050 and 2090. Section 3 highlights current and future threats to each HP, while Section 4 assesses the risk posed to habitability in four contrasting case study islands. Section 5 discusses the cumulative and cascading risks driven by climate change in atoll settings, as well as the spatial variations of risk to habitability across ocean regions and islands.

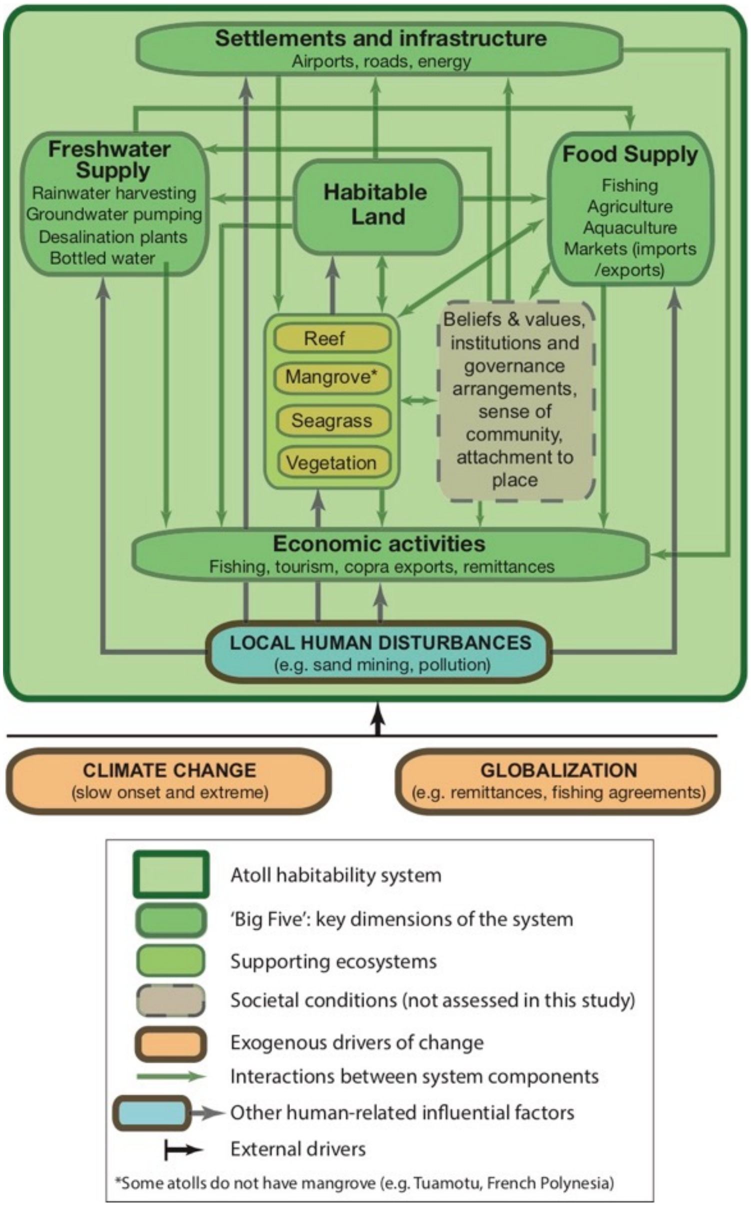


Figure 1. Conceptual model of atoll island habitability.

The atoll island system comprises five pillars supported by ecosystems and societal conditions. Interactions between these pillars are illustrated by green arrows: e.g. habitable land is critical to settlements and infrastructure, freshwater and food supply, economic activities, and natural vegetation development; in turn, the persistence of land is dependent on supporting ecosystems; thus the reef ecosystem provides the island with sediment and reduces wave energy reaching the coastline. Similarly, mangrove, seagrass and the natural strandline vegetation stabilize shoreline systems and can limit erosion and marine flooding.

2. MATERIALS AND METHODS

This assessment relies on three main methods: a comprehensive literature review (especially using the databases Scopus and Web of Science); CMIP5 climate projections for the Indian and Pacific Oceans; and an expert judgment approach to evaluate the risks caused to each HP under the two most documented climate scenarios (RCPs 2.6 and 8.5) at 2050 and 2090. The overall analysis has benefited from the ten-to-thirty-year experience of the authors in atoll environments, in the research fields of geomorphology, ecology, hydrogeology, climate and impact modelling, subsistence and economic activities, development and sustainability. Two three-day workshops in September 2019 and February 2020 allowed for both the framing elements (HPs, geographical scope, case studies, climate scenarios and timescales; sections 2.1 to 2.3) and assessment method (including test phase; section 2.4) to be defined. Due to COVID-19 restrictions, the expert judgement *per se* and results analysis were conducted remotely through video-conferences from February to April 2020.

2.1 Habitability Pillars

The HPs were identified through the literature review, including peer-reviewed scientific papers and recent IPCC reports. This process highlighted that (1) availability of sufficient and safe land (*Land*); (2) supply of safe freshwater, especially from local sources (*Freshwater supply*); (3) supply of nutritious food from local and/or imported sources (*Food supply*); (4) access to safe settlements and infrastructure that sustains freedoms and opportunities such as for trade, healthcare and education (*Settlements and infrastructure*); and (5) access to sustainable economic activities *(Economic activities*) are all key to atoll habitability. These five HPs are under threat from climate change on atolls (Nurse et al., 2014, Table 29-4, p. 1635), with detrimental impacts, especially on well-being and health. These latter two components of habitability were not explicitly included in this study as HPs because they are mainly indirect outcomes of climate-driven changes to HPs. Impacts on well-being essentially arise from impacts on livelihoods, services and landscapes. Although climate change can have a direct impact on health (e.g. loss of lives from extreme events), most consequences for health are expected to be indirect, e.g. through increased water and food insecurity (Lovell, 2011).

2.1.1 Availability of sufficient and safe land

A complex combination of physical and ecological factors determines whether an atoll island is habitable or not. These factors include: island size and the extent of safe and utilizable land area (Spennemann, 1996; Weisler, 1999); island positional stability (Webb and Kench, 2010; Aslam and Kench, 2017); elevation of shoreline and interior, determining susceptibility to wave-driven flooding (Woodroffe, 2008; Owen et al., 2016); island shape and geomorphic components, which influence resistance to storms (Spennemann, 2009; Ford and Kench, 2014; Kumar et al., 2018); sediment composition, which influences groundwater resources and agroforestry potential; and the nature and extent of vegetation cover (Duvat et al., 2017a; Duvat et al., 2020a). Physical processes underpinning these attributes result from the interplay of a number of factors that vary across and within ocean basins (McLean and Kench, 2015). They include seasonal wave regimes (Morgan and Kench, 2014; Kench et al., 2017), exposure to high energy events such as storms and tsunami (Scoffin, 1993; Kench et al., 2006; Hoeke et al., 2013; Ford and Kench, 2014, 2016; Duvat et al., 2017a, 2017b), sea-level change (Perry et al., 2013; Kench et al., 2014), reef growth and related sediment supply and trapping by mangrove, seagrass and island vegetation (Perry et al., 2011; Krauss et al., 2014).

2.1.2 Supply of safe freshwater, especially from local sources

The contemporary resilience of atoll populations partly lies in their ability to exploit diverse water sources: rainwater harvesting, shallow fresh groundwater lenses (FGLs), desalinated water, imported water and, *in extremis,* coconuts (Foale, 2003; Falkland and White, 2020). Access to freshwater remains highly climate-dependent, as shown for example during the severe La Niña drought in 2011 across the southwestern Pacific (Lorrey and Renwick, 2011; Kuleshov et al*.,* 2014) that led to freshwater shortages and national emergencies. Among water sources, FGLs play a major role in habitability, by providing adequate water to local communities and supporting agriculture and economic activities. FGLs result from a delicate balance between rapid rainwater recharge and continuing depletion due to evapotranspiration, discharge of groundwater to the surrounding ocean and lagoons, tidally-driven dispersive mixing with underlying seawater and groundwater pumping. Salinity gradients through FGLs depend on island area; sediment composition; recharge, discharge and pumping rates; tidal mixing; and method(s) of groundwater extraction (White and Falkland, 2010). Islands reliant on rainwater harvesting, either because their geomorphology and size do not support a viable FGL or because pollution or over-extraction has made their FGLs unusable (Falkland and White, 2020), are most at risk of supply failure. For some households on these islands, as little as 10 days without rain can lead to water supply failure (Quigley et al., 2016). At the other extreme, during high rainfalls, rainwater harvesting systems and ponded water increase risks of water-borne diseases (WHO, 2015).

2.1.3 Supply of nutritious food from local and/or imported sources

Achieving autonomous food security has always been a challenge on atolls because of limited land area and soil quality and high dependency on marine resources, both of which are climate-sensitive. *Ad hoc* and unplanned terrestrial food production (typically breadfruit, banana patches, coconut and others) remains common, including on many urban islands (e.g. Funafuti, Tuvalu; Tokelau; South Tarawa, Kiribati), and is key to people's diet. In addition, governments and development agencies support integrated farming practices and invest in soil management. Yet urbanization and human population growth have reduced land availability for locally-produced fruit and vegetables (Thaman, 1995; Connell, 2014; Campbell, 2015; Connell, 2020). Food imports (especially rice, canned meat, sugary drinks and snacks) have therefore become commonplace in both urban and rural islands (Campbell, 2020), inducing a 'nutrition transition' to cheaper, energy-dense, nutrient-poor foods (Hughes and Lawrence, 2005; Thow et al., 2010; Sievert et al., 2019), with a concomitant increase in risk of diet-related noncommunicable diseases. Climate change is poised to adversely affect food systems through disruptions in the ability of countries to import and distribute food, and of households to purchase food, with the potential to magnify food and nutrition insecurity (Savage et al., 2020).

Atoll communities have traditionally exhibited a significant dependence on fish for dietary protein and other essential micronutrients (Charlton et al., 2016). For example, average national fish consumption in Kiribati, Marshall Islands, Tuvalu and Tokelau is five times greater than in the high islands of Melanesia (SM2.1a). Rapid population growth and over-fishing are already reducing levels of *per capita* fish consumption, with consequences for human health (Golden et al., 2016; Hicks et al., 2019). There is an emerging gap in fish supply for urban atoll dwellers (Bell et al., 2011), exacerbated by the damage to proximal coral reef and seagrass habitats (SM2.2) and over-exploitation of coastal fish stocks (McClanahan et al., 2011; Sale et al., 2014; MacNeil et al., 2015). Climate-related declines in fish abundance and associated catches are likely to further amplify existing declines in the nutritional adequacy of diets (Golden et al., 2016). Threats to fish supply are occurring despite availability of more than enough tuna and tuna-like species within the Exclusive Economic Zones (EEZs) of atoll nations to satisfy domestic demand (Bell et al., 2015).

2.1.4 Access to safe settlements and infrastructure that sustains freedoms and opportunities

Owing to the comparatively small size and low elevation of atoll islands, settlements and infrastructure are all coastal in character and therefore more exposed to climate-driven damage than many of their higher island counterparts (Kumar and Taylor, 2015). Risk to settlements is driven by context-specific combinations of climate-related hazards (SLR and waves), the degree of degradation of surrounding ecosystems, and the distance to the shoreline and elevation of buildings and infrastructure. Critical infrastructure for island habitability includes those that are key to the functioning of the island internally (e.g. roads, fishing harbors, power and desalination plants, hydrocarbon reserves, administrative buildings and services) and the ones used for connection with other islands, atolls and countries (e.g. commercial and cruise harbors, regional and international airports, causeways and bridges connecting islands).

2.1.5 Access to sustainable economic activities

Besides declining copra production (Connell, 2014), atolls largely depend on tourism, fisheries, official development assistance (ODA) and remittances for income generation. Most atoll states also have an extraordinary economic dependence on industrial tuna fishing. The Western and Central Pacific Ocean and Indian Ocean are the world's first and second largest tuna production areas, providing 55 and 15% of global tuna catch respectively (Pew, 2016; Lecomte et al., 2017). The economies of atoll nations such as Kiribati, Tuvalu, Marshall Islands and Tokelau therefore have a high dependence on fishing license fees, deriving the majority of their government revenue in this way (SPC, 2019; Lam et al., 2020). Tourism represents a unique opportunity because small and dispersed land areas and remoteness from markets can be attractive in a niche tourism context (Cagua et al., 2014; Jiang and DeLacy, 2014; Zimmerhackel et al., 2019). Many atoll nations also rely on ODA to bolster economic development (representing ca. 15% of Gross National Income in Kiribati; Dornan and Pryke, 2017), and remittances from migrants working overseas largely contribute to national incomes (14, 11 and 10% of GDP respectively in the Marshall Islands, Tuvalu and Kiribati). Other activities include aquarium fisheries (e.g. Marshall Islands, French Polynesia and Kiribati), pearl farming (e.g. French Polynesia and Cook Islands), and subsidized copra production (e.g. Kiribati and French Polynesia). These economic activities are highly sensitive to both climate shocks (e.g. changes in temperatures, flooding) and ecosystem health, making the economy of atolls disproportionally vulnerable to climate change impacts.

2.2 Regions and islands of interest

This study focuses on the two regions in which 96% of the world's atolls and the most populated atolls are located, namely the Indian (56 atolls, according to Goldberg, 2016) and Pacific Oceans (367 atolls; Goldberg, 2016). Specifically, we assess the exposure of atolls to climate stressors in three distinct sub-regions, the Central Indian Ocean, Central Pacific and Western Pacific (section 2.3). We also assess climate risk to habitability for four contrasting islands in the Central Indian Ocean and Western Pacific (listed below; see SM5 for detailed description). These islands are representative of the diversity of atoll contexts and, with the exception of Nolhivaranfaru, Maldives, are documented and well-known by the authors. We considered urban and rural islands to highlight variable exposure and vulnerability conditions to climate stressors (Duvat et al., 2017). Urban case studies are illustrated by Male', North Kaafu Atoll, Maldives, which is a 'fortified' island, and Fogafale, Funafuti Atoll, Tuvalu, which is flood-prone and has limited coastal protection. Rural case studies include Tabiteuea, North Tarawa, Kiribati, bordering the South Tarawa Urban District, and the remote island of Nolhivaranfaru, Haa Alifu-Noonu Atoll, Maldives.

2.3 Climate stressors

The scientific literature, including recently released IPCC reports (IPCC 2018, 2019) and peer-reviewed papers, allowed identification of the major climate stressors affecting HPs considered in this study. These include slow onset climate changes (in atmospheric temperatures and rainfall patterns), slow onset ocean changes (in sea level, sea surface temperatures (SST) and ocean acidification), and changes in extreme events, especially tropical cyclones, El Niño/La Niña events, marine heat waves and distance-source waves. Using these stressors, we generated CMIP5 projections to estimate the exposure of each abovementioned sub-region to climate change-related risk (section 3.1, SM3). These projections also served as starting points to assess climate risk to island habitability (section 4).

CMIP5 data (Taylor et al., 2012) show how the magnitudes of SLR, SST, rainfall, ocean pH and aragonite saturation, ENSO and tropical cyclones will influence the five HPs. All vary (1) under two contrasting greenhouse gas (GHG) emission scenarios, i.e. RCP2.6 representing a drastic mitigation scenario and RCP8.5 assuming continued acceleration of GHGs emissions; and (2) at two time horizons, 2050 and 2090. The abovementioned stressors were aggregated into a cumulative exposure index for each RCP scenario, timespan and sub-region, following a 3-step approach: selection of the mean, minimum and maximum value for each parameter (SM3.1) from future projections, and regional baseline values; development of a scoring system by sub-region (SM_File 2_SM3); and establishment of index scores (SM3.2).

2.4 Risk assessment protocol

2.4.1 Expert judgment and scoring system

The expert judgment-based assessment of the climate risk posed to habitability relied on an extensive literature review (including especially case study papers), available datasets, and the authors' own expertise. It followed a 6-step approach (Fig. 2; SM4). Briefly, the protocol consisted of defining a set of prominent criteria contributing to risk for each HP and in each of the four case studies considered (step 1); as well as a scoring system to assess the additional climate risks to each criterion under RCP2.6 and RCP8.5, and for 2050 and 2090 (step 2, SM7). Six risk levels were considered: undetectable, very low, low, moderate, high, very high, (Table SM4b). For each HP, between two and four of the authors conducted a separate assessment for the criteria and then convened (virtually) to discuss their respective scores and agree on a final score and articulate underlying rationales. Confidence levels were attributed to each score (step 3). The aggregation of scores for each HP (step 4) allowed identification of climate risk to island habitability as a whole (step 5). The results were then translated into a color scale to develop synthesis figures of climate risk to habitability across HPs and case studies (step 6; Figs. 5 and 6).

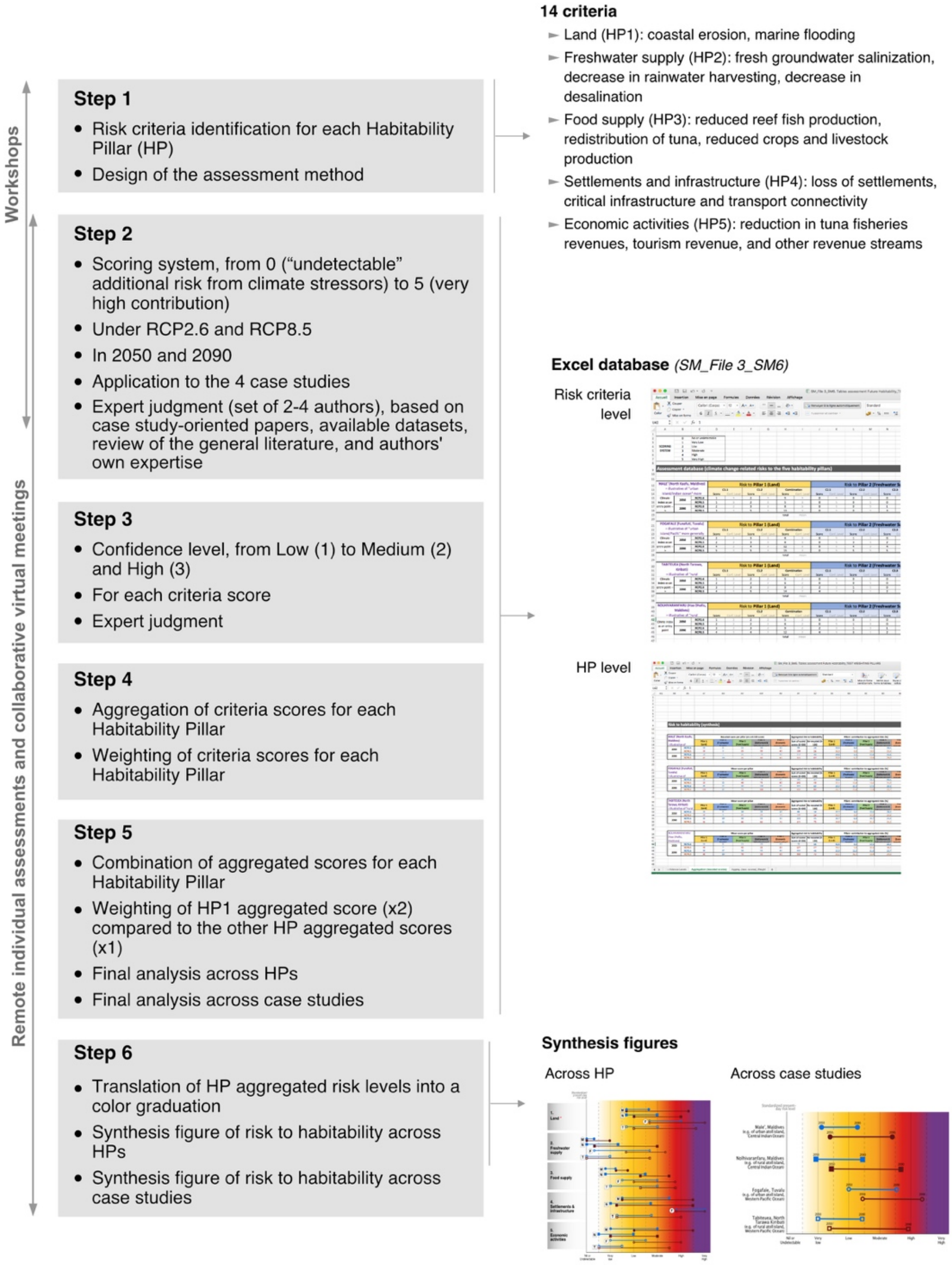


Figure 2. Assessment protocol used in this study.
See SM4 for further details.

2.4.2 Adaptation assumptions

We assume that, over the timeframe of analysis, future adaptation responses in urban and rural islands will remain similar in nature and magnitude to currently observed responses. Two main reasons support this argument. First, because atoll communities have adapted to climate stress for centuries to millennia (Nunn, 2007), and still implement climate risk reduction actions, we excluded the "no adaptation" scenario (section 3.2). Second, due to a lack of precise and empirically-based information on the extent and nature of adaptation limits in atolls (Roy et al., 2018; Mechler et al., 2020), especially across the diversity of case study settings chosen, we did not consider a "high adaptation" scenario involving more transformational changes. We therefore assume the continuation of the current level of adaptation measures, i.e. moderate adaptation, which is considered feasible and helps the understanding of risk under a non-transformational adaptation pathway. This adaptation scenario considers mechanisms already implemented on the ground, including water desalination (to counter water stress), remittances from islanders working abroad, food imports (which help compensate for locally-produced food decline), hard protection to contain coastal erosion and flooding, and, in the Pacific Ocean, emerging tuna fishing governance arrangements between countries. In the absence of local-scale modelling studies, our adaptation assumptions do not consider exogenous parameters such as, in the tourism sector for example, the effect of climate policy on international transportation or the ability for local operators to adapt to changing circumstances, including COVID-19 impacts.

3. CURRENT AND FUTURE CLIMATE THREATS TO HABITABILITY PILLARS

3.1 Climate projections

The mean rate of global SLR for 2006–2015 was 3.6 mm yr^{-1} (IPCC, 2019). Under RCP2.6, mean rates of 4.5 and 4.8 mm yr^{-1} are projected for 2050 for the Central Indian and Western Pacific Oceans respectively, and 4.6 and 5.1 mm yr^{-1} for 2090 (Fig. 3, SM3). Under RCP 8.5, mean rates are 7.6 and 8.2 mm yr^{-1} for 2050, and 15.0 and 15.4 mm yr^{-1} for 2090. SLR is projected to increase water depths above reefs surrounding many islands (Perry et al., 2018), meaning that higher waves will reach shorelines, amplifying flooding frequency and rates of shoreline erosion.

For SST, there is little projected change between 2050 and 2090 under RCP2.6 (Fig. 3). Under RCP8.5, projected SST increases from 2050 to 2090 by around 1.5°C, likely increasing the frequency and magnitude of marine heat waves (Frölicher et al., 2018; Dalton et al., 2020) and pushing mean SST levels above local coral bleaching thresholds more frequently in all regions, except the Central Pacific (Fig. 3). This is consistent with projections of the onset of annual bleaching by ca. 2040 in Kiribati, Marshall Islands, Tokelau and Tuvalu in the Pacific Ocean, and in the Maldives (van Hooidonk et al., 2016).

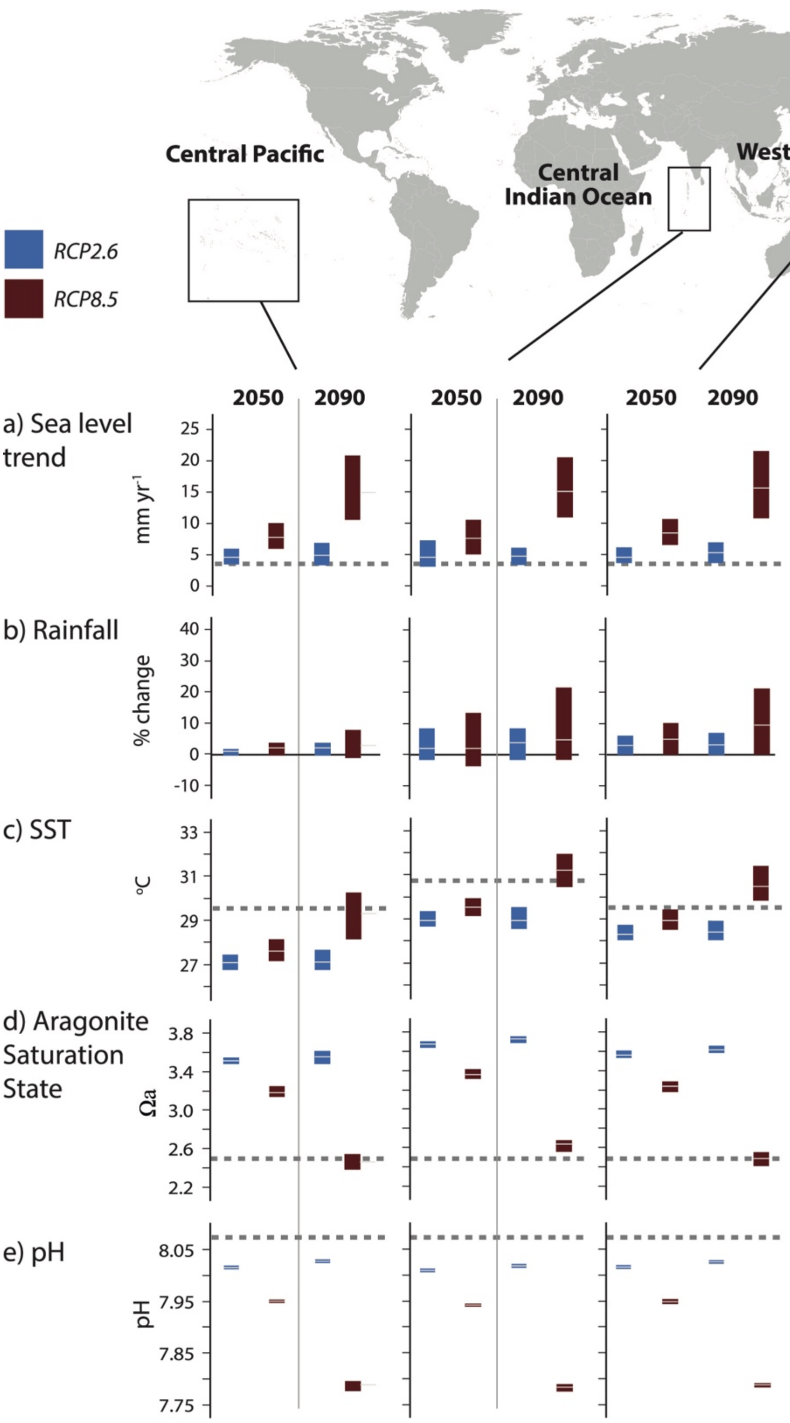
Rainfall projections indicate overall positive changes within ± 10° of the equatorial Pacific and northern Indian Oceans (Fig. 3). While under RCP2.6 small increases are projected for 2050 and 2090, larger (6% or more) positive increases are projected under RCP8.5, especially for the Western Pacific. No decrease in annual rainfall is projected for any of the emission scenarios considered. Mean rainfall change is therefore regarded as a minor driver in this assessment. In contrast, projections suggest that the frequency of intense droughts may double over the course of the 21st century (IPCC, 2019).

IPCC (2019) also finds that the frequency of extreme ENSO events will double under both RCP2.6 and RCP8.5 in the 21st century, with the average frequency increasing from once every two decades to once per decade (Cai et al., 2014a; Cai et al., 2015; Cai et al., 2018). Extreme Indian Ocean Dipole (IOD) events are also projected to increase in frequency (Cai et al., 2014b).

In non-equatorial atoll regions, the proportion of high-intensity tropical cyclones is projected to increase whereas the total number of cyclones is expected to remain the same or decrease slightly (Knutson et al., 2019; Murakami et al., 2020). Analysis of cyclones globally over the past 39 years has shown a significant increase in intensity globally but in the northern Indian Ocean, equatorial and southern Pacific Ocean changes in intensity have not been significant ($p > 0.1$).

Increased wind speeds in the Southern Ocean and tropical Eastern Pacific are projected to increase wave heights (Morim et al., 2018; 2019) and thus raise the potential for long period swell waves to impact distant atoll islands.

Regarding ocean acidification, under RCP2.6 pH and aragonite saturation rate are projected to continue to fall until 2050 in the three sub-regions and revert to slightly higher values between 2050 and 2090 (Fig. 3). Under RCP8.5, both pH and the aragonite saturation rate (Ω_a) continue to fall between 2050 and 2090, reaching by 2090 Ω_a values of <2.5, below the typical values found in coral reef waters (Kleypas et al., 1999).



Tropical cyclones: projections for the late 21st century are summarized as follows: 1) there is medium confidence that the proportion of TCs that reach Category 4–5 levels will increase, that the average intensity of TCs will increase (by roughly 1–10%, assuming a 2 degree global temperature rise), and that average tropical cyclone precipitation rates (for a given storm) will increase by at least 7% per degree Celsius sea surface temperature (SST) warming, owing to higher atmospheric water vapour content, 2) there is low confidence (low agreement, medium evidence) in how global TC frequency will change, although most modelling studies project some decrease in global TC frequency and 3) sea level rise will lead to higher storm surge levels for the TCs that do occur, assuming all other factors are unchanged (very high confidence). Source: IPCC SROCC

ENSO: Extreme El Niño and La Niña events are likely to occur more frequently with global warming and are likely to intensify existing impacts, with drier or wetter responses in several regions across the globe, even at relatively low levels of future global warming (medium confidence). Source: IPCC SROCC

Wave exposure: Data on projected changes in wave energy exposure are limited to RCP4.5 and 8.5 scenarios at 2090. Projected % mean changes in extreme significant wave heights, relative to the historical (1979-2004) period, are generally low, but there is very high variability (5th and 95th percentiles); RCP4.5: Central Pacific (mean: -1.9%, range: -16.1 to +21.6%); Indian Ocean (mean: -2.27%, range: -15.8 to +21.6%); Western Pacific (mean: -3.5%, range -19.7 to +26.4%); RCP8.5: Central Pacific (mean: +0.3%, range: -16.3 to +19.2%); Indian Ocean (mean: +0.9%, range: -16.8 to +20.8%); Western Pacific (mean: -0.73%, range -20.5 to +24.5%). Source: Morim et al. 2019).

Figure 3. Projected changes in relevant climate change-driven ocean and atmospheric parameters within different atoll regions for each emissions scenario in 2050 and 2090.

Plots a-e show upper, mean and lower limit projected changes in each parameter under RCP2.6 and RCP8.5 in 2050 and 2090 for each atoll sub-region (see also SM3.1). The threshold levels (grey bars) denote the following: for sea level trend, the mean rate of global sea-level rise (3.6 mm yr^{-1}) between 2006-2015 (IPCC, 2019); for SST trends, regional bleaching thresholds (from NOAA Coral Reef Watch, 2001-2020 time series data); for Aragonite Saturation State trends, the threshold below which conditions for tropical reef-building corals are deemed to be "extremely marginal" (Guinotte et al., 2003); for surface pH, the mean surface pH in tropical regions during the period 1980-2000 (IPCC, 2014, Fig. 30.7).

These projections provide a basis for assessing the cumulative exposure of each sub-region (Fig. 4; SM3.2). Our assessment suggests low overall levels of increased exposure under RCP2.6 but increased SST stress in the Central Indian Ocean, with a significantly increased cumulative exposure to climate stressors to at least 2090 under RCP8.5. Under RCP8.5, changing ocean chemistry conditions will be the most sustained drivers of this increased exposure. The combination of risks generated by SLR and changes in SST will become significant between 2050 and 2090 and will almost certainly be further exacerbated in most regions by increased cyclone intensity, and in all regions by increased frequency of intense ENSO and IOD events (Figs. 3 and 4 and SM3).

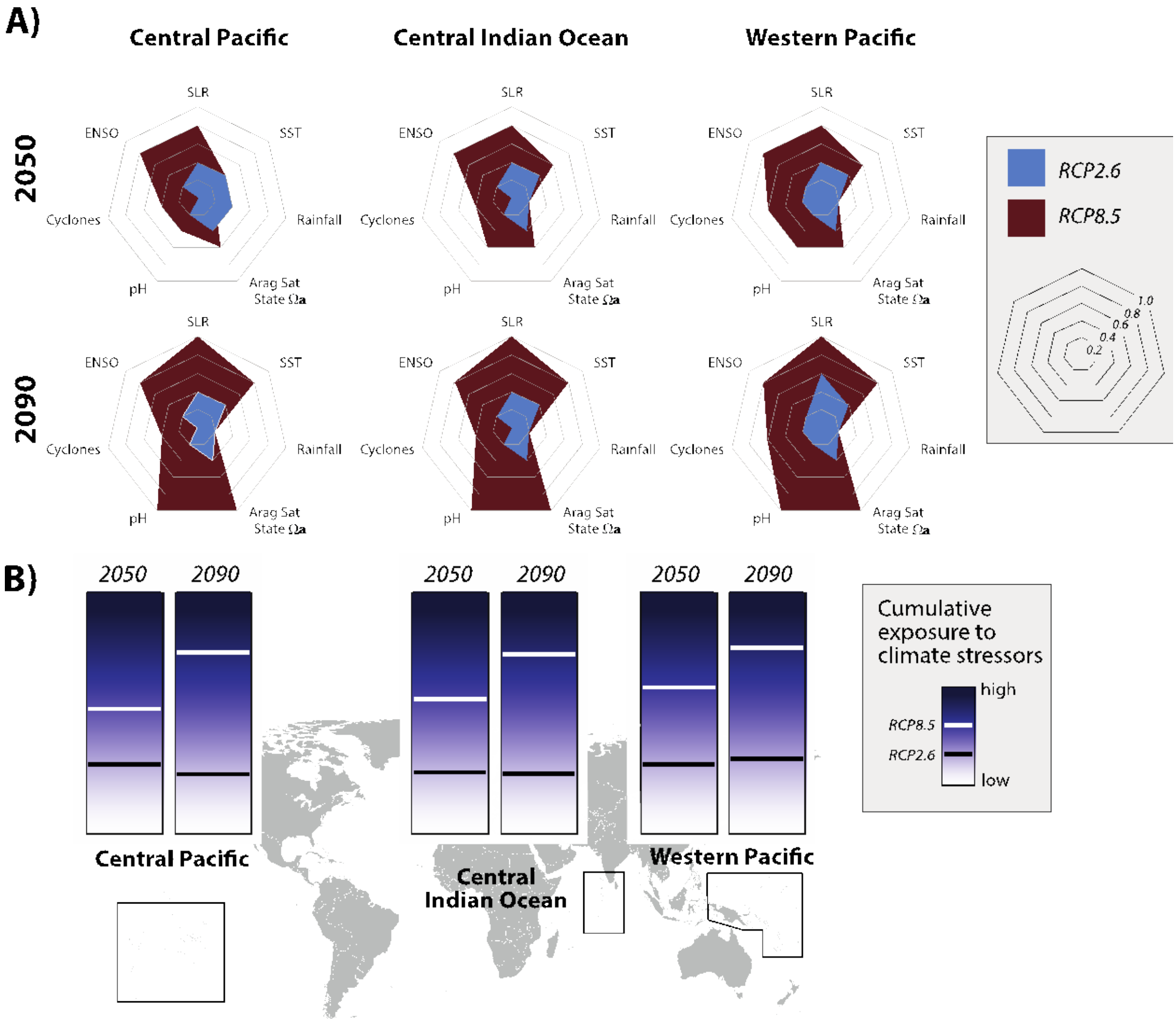


Figure 4. Cumulative climate change threats and related exposure of atoll regions, for two emission scenarios in 2050 and 2090, based on mean projected rates of change.
SM3.1 provides the full details. Panel A illustrates the cumulative climate and climate-related ocean threats (high = 1.0, low = 0.0) to atoll habitability for each of the three delineated atoll regions. Panel B shows resultant cumulative exposure index for each RCP scenario and atoll region. The index is described in SM3.2. The color graduation represents increasing exposure levels from low (white to light blue) to high (deep blue).

3.2 Literature-based perspective on threats to Habitability Pillars

3.2.1 Land (HP1)

A review of shoreline change of 709 Indo-Pacific atoll islands over the past 3-5 decades found no widespread trend in land area change for larger (>10 ha) habitable islands (Duvat, 2019), indicating shoreline resilience in the face of recent climate-driven changes. Nevertheless, the low elevation and permeable structure of all islands expose them to overtopping-induced flooding, marginal breaching and/or saltwater intrusion (Hoeke et al., 2013; Canavesio, 2019; Wadey et al., 2017). The likelihood of island flooding associated with extreme sea levels arises from a combination of factors (regional sea-level, storm frequency variations, wave climate changes) and operates over multiple spatial-temporal scales (Walsh et al., 2012; Chand et al., 2013). Major contributors are distant ocean waves that reach the shorelines of atolls, resulting in enhanced wave setup and runup, overtopping of berms and protection structures, and inundation of island interiors.

Direct impacts of climate-ocean changes will result from extreme wave energy (from tropical cyclones and distant storms) altering shorelines, whilst indirect effects will come from changes in the ecological make-up and structural complexity of reefs (Perry et al., 2011; Quataert et al., 2015; Harris et al., 2018), and in the extent and health of mangroves (Schuerch et al., 2018) and seagrasses, as well as terrestrial vegetation (Hernandez-Delgado, 2015). Changes affecting reefs will limit their capacity to keep pace with SLR (Perry et al., 2018), attenuate wave energy, and contribute to sediment supply to islands. Increased frequency and intensity of coral bleaching events and increased ocean acidification will be the most immediate drivers of such changes (Frölicher et al., 2018; Perry et al., 2018). Precisely how the former will impact reef sediment generation is unclear, although short-term pulses of enhanced sediment generation have been observed after bleaching events (Kayanne et al., 2016; Perry et al., 2020). Likewise, the implications of pH and aragonite declines on sediment generation rates are poorly known. Despite these uncertainties, under RCP8.5 from 2050, the accumulation of threats to reefs will severely exacerbate island flooding, as a result of SLR and reef erosion, leading to island destabilization through increased wave impact on shorelines and a net reduction in sediment supply to islands (Beetham et al., 2017; Shope et al., 2017; Storlazzi et al., 2018; Shope and Storlazzi, 2019; East et al., 2020). Decreased sediment supply, from both external minerogenic and *in situ* organic sources, will compromise the ability of mangrove substrates to keep pace with SLR (Lovelock et al., 2015).

In densely settled areas, human constructions will increasingly compromise the natural ability of island shorelines to vertically adjust to SLR by altering reef productivity, obstructing alongshore and cross-shore sediment transport pathways, and reducing the coastal accommodation space available for landform adjustment, including opportunities for the landward migration of coastal habitats (McLean and Kench, 2015; Schuerch et al., 2018; Duvat and Magnan, 2019). If pathways of *in situ* adaptation continue to be followed, this will make atolls increasingly dependent on protection structures, aimed at limiting shoreline erosion and flooding (Naylor, 2015; Wadey et al., 2017; Hinkel et al., 2018), and possibly island raising (e.g. Hulhumale', Maldives; Brown et al., 2020).

3.2.2 Freshwater supply (HP2)

Mean annual and wet-season rainfall are projected to increase across the equatorial Eastern and Central Pacific in the 20-year periods centered on 2050 and 2090 (relative to 1986-2005) but there is little change expected further from the equator (ABoM and CSIRO, 2014) (Figs. 3 and 4). The frequency and intensity of extreme rainfall events are projected to increase across the Western and Central Pacific, but their magnitude is uncertain (ABoM and CSIRO, 2014). Projected increases in frequency of the 1-in-20 year daily rainfall (baseline 1985-2005) for RCP2.6 and RCP8.5 are locationspecific, with doubling frequency for RCP2.6 (ABoM and CSIRO, 2014). The low confidence in the magnitudes of these projected changes hinders the quantification of their impacts on freshwater supply, particularly as there are no comparable projections for evapotranspiration (Falkland and White, 2020). Qualitatively, these intensifications suggest increased local flooding as groundwater rises to the surface, increased pollution of FGLs (Falkland and White, 2020) and polluted discharge onto surrounding reefs (Graham et al., 2018), with cascading negative impacts on shoreline protection, sediment supply, food production and health (White et al., 2007; WHO, 2015; UNICEF and WHO, 2019).

Increased frequency (and intensity under RCP8.5) of major ENSO and IOD events may challenge water security, especially for rainwater harvesting on urban atolls. Modelling shows that, when there is no land area loss, the store of freshwater increases slightly with SLR up to 0.4 m, as groundwater moves up from karst limestone basements into overlying unconsolidated Holocene sediments (Alam and Falkland, 1997; Galvis-Rodriguez et al., 2017). This magnitude of SLR is comparable to sea-level differences experienced during major ENSO events (Widlansky et al., 2017) and to SLR projected under RCP2.6 to 2090 (ABoM and CSIRO, 2014). With SLR rates of ~15 mm yr^{-1} projected for RCP8.5 at 2090 (ABoM and CSIRO, 2014), land area loss could reduce groundwater availability by over 70% by 2090 (e.g. South Tarawa; Alam and Falkland, 1997). Likewise, in the Maldives, islands narrower than 200 m are expected to experience drastic reductions of their FGLs from the combined effects of variable rainfall patterns and SLR (Deng and Bailey, 2017). More frequent island overtopping will cause salinization of FGLs (Burns, 2002; Storlazzi et al., 2018; Hughes et al., 2020). Experiences in the Pacific and Indian Oceans and overwash modelling suggest that FGL recovery takes between one to five years (Chui and Terry, 2015; Bailey and Jensen, 2014; Bailey, 2015). The implication is that alternative sources of water will be needed during periods of FGL recovery.

Since projected increases in annual rainfall are relatively small, future freshwater security in atolls will depend significantly on changes in the frequency and intensity of ENSO and IOD events, the intensity of cyclones and accompanying storm surges (Chui and Terry, 2013), as well as the ability of islands to build vertically to adjust to SLR (Tuck et al., 2019). However, at least until 2030, non-climate-change factors, including increasing freshwater demand, urbanization, water pollution, governance and management failures, are expected to pose greater threats to freshwater security than climate change (Falkland, 2011).

3.2.3 Food supply (HP3)

Rapid population growth (3.2.4), urbanization and over-fishing of coastal stocks will continue compounding food security challenges by reducing land availability for agriculture and levels of *per capita* fish consumption (SM2.3). These challenges will be exacerbated by projected declines in fish abundance and catches in relevant sub-regions (Asch et al., 2018, Bell et al., 2018a). For reef fisheries, recent coral bleaching and mortality (e.g. Hughes et al., 2018), and resultant reef structural collapse, have led to declines in fish commonly targeted by these fisheries (Robinson et al., 2019a).

Minimizing the gap in fish supply is achievable through adequate protection of coral reef and seagrass habitats (Brodie et al., 2020), improved management of coastal fish stocks (Bell et al., 2018a), increases in the catch of tuna and tuna-like species from nearshore waters (e.g. Maldives; Yadav et al., 2019), as well as greater access afforded to offshore tuna and tuna-like species for domestic consumption (Bell et al., 2015; FFA & SPC, 2015). For Pacific atolls, expanding the use of nearshore fish aggregating devices (FADs) would increase supplies of tuna for local food security (Bell et al., 2018a) (SM2.4). Filling the gap in fish supply is all the more crucial that climate-driven changes to soil moisture and salinization levels, rainfall and land area will increasingly constrain food production on atolls (Taylor et al., 2016; Barkey and Bailey, 2017).

Ocean warming and acidification are expected to significantly reduce live coral cover (Hoegh-Guldberg et al., 2011). Although increased CO_2 concentrations should promote growth of seagrasses, on balance, climate change is likely to continue to reduce this important fish habitat within atoll lagoons (Waycott et al., 2011) (SM2.5). Together, these effects and the direct impact of ocean warming on coastal fish species are projected to reduce coastal fish stocks by 20–50% by 2050 (Pratchett et al., 2011, 2014; Asch et al., 2018). Degraded coral reefs may, however, support higher catches of fast-growing herbivorous fish species (Pratchett et al., 2011), helping offset predicted declines in productivity of other coastal fish species (Robinson et al., 2019b) (SM2.6). Climate change risks to coastal fish productivity, exacerbated by inadequate management, are of particular concern for rural communities (Thow and Snowdon, 2010) (SM2.1.b, SM2.3).

Climate change will also alter the distribution of tuna in both the Pacific and Indian Oceans (Bell et al., 2016; 2018b). This is unlikely to affect plans to assist communities to catch more tuna around FADs because, even under RCP8.5 in 2050, a large biomass of tuna is still expected to exist within atoll nations' EEZs (Bell et al., 2018a). Projected decreases in tuna biomass in the Marshall Islands, Tokelau and Tuvalu (SPC, 2019) will necessitate allocation of a higher proportion of their (reduced) tuna resources to domestic consumption.

3.2.4 Settlements and infrastructure (HP4)

In 2017, 676,000 people were living in the Maldives, Kiribati, Marshall Islands, Tuamotu-Gambier, Tuvalu, FSM and Tokelau (SM1). Together, these archipelagoes have experienced a 68% population increase since the mid-1980s, with the main growth observed in the Maldives and Kiribati (SM1a). Urban/capital islands are home to most people, as a consequence of better services and infrastructure, higher life expectancy and rural exodus (Yamano et al., 2007; Duvat et al., 2013; Speelman et al., 2017). For example, in 2017, 49% of the 114,160 I-Kiribati were living in South Tarawa (<2% of the country's land area), and in 2016, 32% of the 402,000 Maldivians were concentrated on Male' (<1% of the country's land area). This resulted in high population densities ranging from 1,354 persons km^{-2} on Rangiroa (Tuamotu) to 65,697 persons km^{-2} on Male'.

On these islands, limited available land area forces the settlement of risk-prone areas, further increasing population exposure to environmental hazards (Duvat et al., 2017c). For atoll nations as a whole, Kumar and Taylor (2015) estimated that 90% of built assets are located <100 m from the shoreline. On the capital islands of Rangiroa and Funafuti, land constraints have led to swamp reclamation for construction purposes, amplifying population exposure to flooding (Yamano et al., 2007; Magnan et al., 2019; Duvat et al., 2020b). The expansion of Male' through land reclamation (+67% since the 1970s, mostly <1m above Mean Sea Level) has also increased the exposure of people and urban assets to sea-level extremes (Naylor, 2015).

About 59% and 61% of the populations of Tuvalu and the Marshall Islands respectively currently live on land below annual flood levels. These proportions will increase by about 10 and 27% respectively in the case of a 1 m SLR by 2100 (Kulp and Strauss, 2019). On Ebeye, Kwajalein Atoll, Marshall Islands, the population annually affected by flooding and erosion will increase from 5,000 persons (>50% of its population) to 8,800 (10,800) under RCP2.6 (RCP8.5) by 2100; and Expected Annual Damages (EAD) to buildings and infrastructure are projected to increase 2.4 to 3.8 times by 2100 (Giardino et al., 2018).

Estimating future threats to settlements and infrastructure on atolls for the 21st century is challenging because of a lack of knowledge of the influence of human drivers of exposure and vulnerability. In Tuvalu, migration flows have the potential to slow population growth by the mid-century, from 3700 additional inhabitants if no out-migration occurs against 320 inhabitants with substantial emigration (Milan et al., 2016). Future risk to settlements and infrastructure will also depend on the effectiveness and sustainability of responses (Nunn and Kumar, 2018). On Ebeye, hard defenses have the potential to reduce end-century flooding/erosion-induced EAD by 30%, and the annually affected population by 40% (Giardino et al., 2018). Likewise, building seawalls 0.5, 1.0 and 1.5 m high could delay flooding for 0.2, 0.4 and 0.6 m of SLR respectively on the raised island of Hulhumale', Maldives, (Brown et al., 2020). Future threats to settlements and infrastructure will also depend on accommodation efforts, especially floor raising (e.g. Tuamotu; Magnan et al., 2019).

3.2.5 Economic activities (HP5)

In 2016, fisheries revenues related to license fees contributed 60-98% of all (non-aid) government revenue of Kiribati, Tuvalu, Marshall Islands and Tokelau (FFA, 2017). Overall, climate-driven redistribution of tuna is expected to have greater effects on the economies of Pacific Ocean than Indian Ocean atolls (Bell et al., 2016, 2018a). Under RCP8.5 by 2050, tuna biomass in national waters is projected to decrease by 15% in the Marshall Islands and 9% in Tuvalu and Tokelau, and to increase by 18% in Kiribati (SPC, 2019). Proportional decreases and increases in tuna license revenue are expected to occur.

Together with other Pacific Island countries that are Parties to the Nauru Agreement (PNA), Kiribati, the Marshall Islands, Tokelau and Tuvalu have responded to climate variability and change through the 'vessel day scheme' (VDS), which enables the benefits of purse-seine fishing within their combined EEZs to be distributed equitably among them, regardless of where the fish are caught (Aqorau et al., 2018; Johnson et al., 2020). Nevertheless, under RCP8.5 by 2050, tuna biomass within the combined EEZs of PNA members is likely to decrease because conditions for tuna will become more favorable further east in high-seas areas (SPC, 2019). This will necessitate new management arrangements and could potentially set the stage for conflict between tuna-fishing nations (Pinsky et al., 2018).

Tourism grew in the Maldives between 1995 and 2017 from 315,000 international arrivals and US$211 million in tourism receipts to 1.4 million and US$2,742 million respectively. In 2017, tourism accounted for 23% of GDP and 32% of government revenue (Ministry of Tourism, 2018). While Pacific atoll nations are less likely to benefit from positive visitor projections (World Bank, 2017) due to less developed tourism assets, FSM, Marshall Islands, Kiribati and Tuvalu are well placed to capitalize on nature-based experiences (e.g. diving, sport-fishing). Atoll tourism is assumed to be as much at risk as in coastal areas elsewhere, where it relies on beach and marine activities (Klint et al., 2015; van der Veeken et al., 2015; Bindoff et al., 2019; Fauzel, 2019; Seetanah and Fauzel, 2019). SLR, warmer SSTs and extreme events are likely to affect tourism through damage to essential infrastructure (UNFCCC, 2005), loss of beaches and coral bleaching (Wielgus et al., 2002; Koike et al., 2014; Weatherdon et al., 2016).

ODA allocations to atoll nations have declined over the past decade (OECD, 2015). While commitments in climate finance to Small Island Developing States have been made, current climate finance models may not be appropriate or large enough to meet needs, and lack the required governance to effectively support resilience and promote sustainable development (Williams and McDuie-Ra, 2018). The role of remittances for increased household resilience, and to finance adaptation, could increase in importance if other income sources decline and externally-provided climate finance is insufficient (Bendandi and Pauw, 2016; Musa-Surugu et al., 2018; Nunn and

Kumar, 2019). Remittances may also help limit rural exodus and international migration attributable to climate change (Damette and Gittard, 2017). However, falling remittances as a result of crises such as the current COVID-19 pandemic (IMF, 2020) may have profound and unforeseen economic impacts.

4. ASSESSMENT OF CLIMATE RISK TO FUTURE HABITABILITY IN FOUR ATOLL ISLANDS

4.1 Risk by Habitability Pillar

Risk to Land (HP1, SM7.1) includes permanent coastal erosion, and permanent and temporary marine flooding. This risk is estimated very low-to-low for all four islands in 2050 under RCP2.6, except for Fogafale which shows a low-to-moderate risk due to its high susceptibility to flooding (Fig. 5). By 2090 under RCP2.6, this risk increases to low-to-moderate for Male', moderate for Nolhivaranfaru and Tabiteuea, and high for Fogafale. While there is a relatively small difference in risk level between RCP2.6 and RCP8.5 in 2050, the risk to land increases substantially under RCP8.5 in 2090 compared to RCP2.6, and is high for Nolhivaranfaru, high-to-very high for Male' and Tabiteuea, and very high for Fogafale. This is due to sea-level projections diverging between low and high emission scenarios after 2050 only. Differences in risk level are generally small between rural islands, but high between urban islands. Male' exhibits lower risk than Fogafale, owing to its higher elevation and complete protection by engineered structures, while Fogafale is both extremely low-lying and mostly unprotected.

Risk to Freshwater supply (HP2, SM7.2) includes groundwater salinization/loss and decrease in rainwater harvesting and desalination. This risk is estimated as undetectable in 2050 under RCP2.6 for all islands, except for Fogafale where the predominant source of freshwater, rainwater harvesting, will likely be disrupted by increased cyclone-driven damage and drought frequency (Fig. 5). While risk remains undetectable-to-very low in Male' under all RCPs even in 2090 – because it mainly relies on desalination – it slightly increases under RCP2.6 in 2090 in Nolhivaranfaru and Tabiteauea (to very low-to-low and very low, respectively) and, more in Fogafale (to low-to-moderate). This increase is even more important under RCP8.5 in 2090 (moderate for Nolhivaranfaru; low-to-moderate for Tabiteuea; moderate-to-high for Fogafale). Fogafale exhibits the highest risk level because of its main reliance on rainwater harvesting which will be increasingly affected by droughts, cyclones, and flooding-induced damage over time. On rural islands, risk thus becomes significant under RCP8.5 in 2090.

Risk to Food supply (HP3, SM7.3) includes reduced reef fish production, redistribution of oceanic tuna and reduced production of crops and livestock. This risk is assessed as very low for all islands under RCP2.6 in 2050 (Fig. 5). Differences between islands are pronounced in 2090 under both RCP2.6 (slightly above very low-to-low for Male', low-to-moderate for Nolhivaranfaru, moderate for Fogafale and Tabiteuea) and RCP8.5 (from moderate to high, except for Male' where it remains very low-to-low). The lower risk level for Male' is due to the relatively low dependence of households on local food compared to imports; these are assumed to increase over time to compensate for decreasing tuna catches. The comparatively higher risk level for Fogafale results from the cumulative effects of decreased reef fish (60% of total catches in Tuvalu) and tuna catches, and a reduction in agricultural productivity and livestock due to marine flooding. In all cases, food imports are likely to increase to compensate for decreased local-to-national food production, especially in the second half of this century.

Risk to Settlements and infrastructure (HP4, SM7.4) includes loss of settlements, critical infrastructure and transport connectivity. Since this risk is strongly influenced by risk to Land, risk levels partly reflect those of Land, being very low to low under RCP2.6 in 2050, except for Fogafale (close to high); and low-to-moderate for Nolhivaranfaru and Tabiteuea, moderate-to-high for Male' and very for Fogafale under RCP2.6 in 2090 (Fig. 5). Mid- and end-century risk levels are thus higher in Fogafale compared to other settings, as a result of both the higher exposure of settlements and critical infrastructure to coastal risks (especially flooding) and the reduced extent and effectiveness of protection structures. In contrast, because it is protected by its encircling engineered structures, Male' exhibits very low-to-low risk under RCPs 2.6 and 8.5 respectively in 2050. Since the effectiveness of coastal protection decreases over time under SLR and increased wave height (e.g. Giardino et al., 2018; Brown et al., 2020), risk to settlements and infrastructure increases to moderate-to-high and high-to-very high respectively under both RCP2.6 and RCP8.5 in 2090. Under RCP2.6 in 2090, risk levels are lower in rural islands compared to Male' because they exhibit lower exposure of settlements and infrastructure compared to urban settings.

Risk to Economic activities (HP5, SM7.5) includes declines in tuna fisheries revenues, tourism revenues (especially in the Maldives), and other revenue generating activities (e.g. aquaculture). This risk, which is highly influenced by risks to Land and Food supply, is at most very low and at most low under RCP2.6 and RCP8.5 in 2050 respectively, with higher levels on urban islands where these activities are more common (Fig. 5). Consequently, end-of-century risk to economic activities under RCP8.5 reaches much higher levels for urban islands (high for Fogafale and high-to-very high for Male') compared to rural islands (moderate for Nolhivaranfaru and moderate-to-high for Tabiteauea).

These findings firstly highlight that Freshwater supply (HP2), where use of desalination is always an option, is less threatened by climate change than the other HPs. Conversely, Land (HP1) is at high risk from climate change impacts. This risk cascades down to land-based Food supply (HP3), Settlements and infrastructure (HP4), and land-based Economic activities (HP5). Second, risks are commonly very-low-to-low (in 2050) to moderate (in 2090) under RCP2.6 for most HPs. Risks increase significantly between 2050 and 2090 under RCP8.5, from around low classifications to moderate or very high risk for most HPs and islands. Third, even the best protected urban island (Male'), with estimates of undetectable to at most moderate risk under RCP 2.6 both in 2050 and 2090, faces high-to-very high risk under RCP8.5 in 2090 for Land (HP1), Settlements and infrastructure (HP4), as well as Economic activities (HP5).

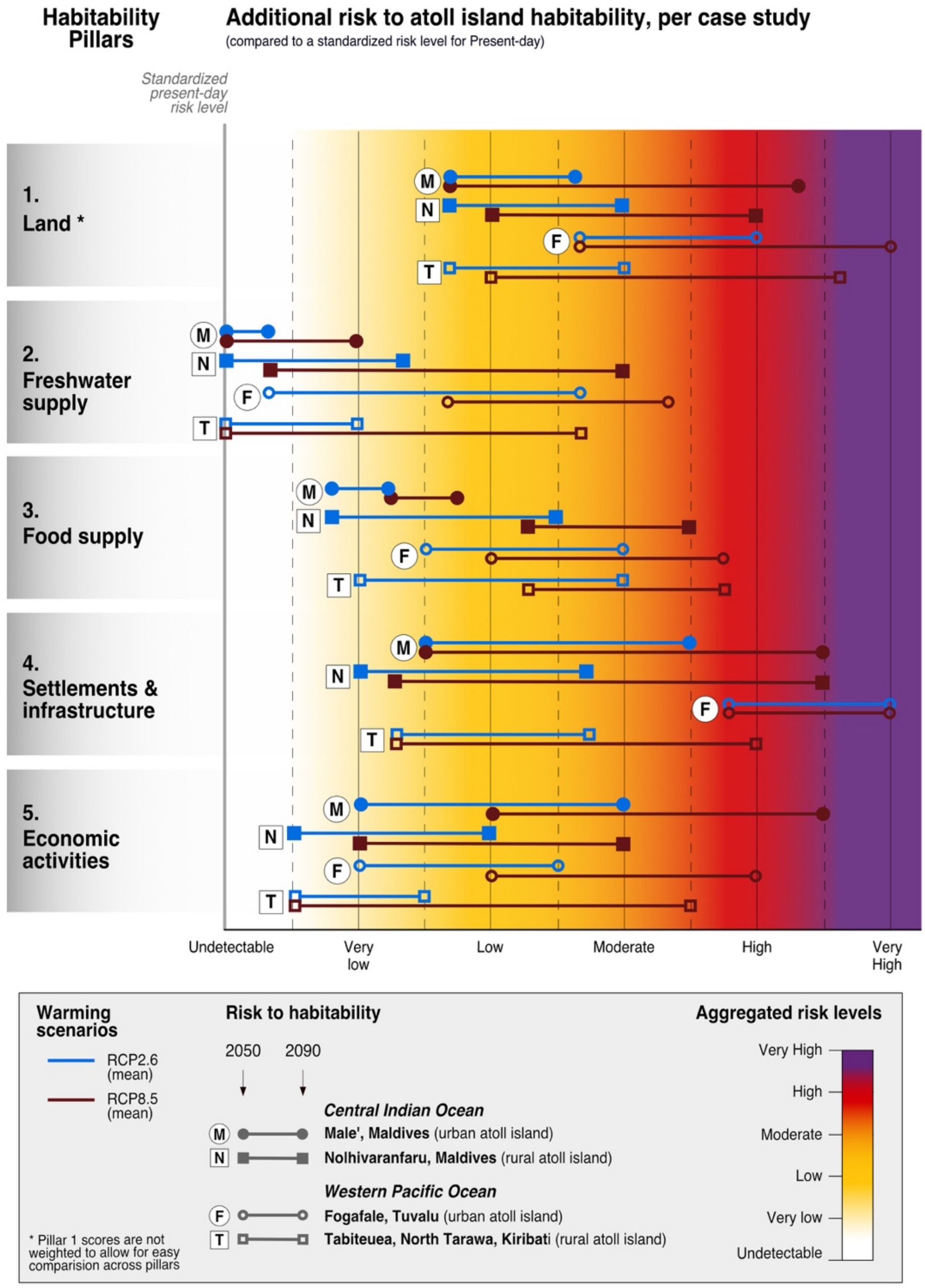


Figure 5. Additional climate risks to the five habitability pillars for four atoll islands in the Central Indian and Western Pacific Oceans.
"Additional" means additional risk to habitability compared to a present-day baseline. See Part II of the Supplementary material for details on the assessment method and results.

4.2 Cumulative risk

Aggregated risk levels (i.e. cross-HP; Fig. 6) are relatively comparable for Male' and the two rural islands under both RCP2.6 and RCP8.5 for both time horizons, with a slightly higher risk level for rural islands under RCP8.5 in 2090. In comparison, Fogafale exhibits much higher risk levels under both RCPs and at both time markers, due to its exceptionally flood-prone nature and exposure to other risks, especially related to Food supply (tuna fishing) and Land, with cascading impacts to the three other HPs. Generally, the aggregated risk remains close to low-to-moderate under RCP2.6 in 2090 for rural islands having no or limited coastal protection structures, increasing to relatively high risk under RCP8.5 in 2090. This is mainly because rural areas are more dependent on local resources and may be less able to offset impacts through imports (for Food supply) or technology (for Freshwater supply) compared to urban islands. Finally, this assessment shows that even a well-protected urban island like Male' will experience moderate-to-high additional risk under RCP8.5 in 2090, suggesting limits to future reliance on the current heavily engineered adaptation strategy.

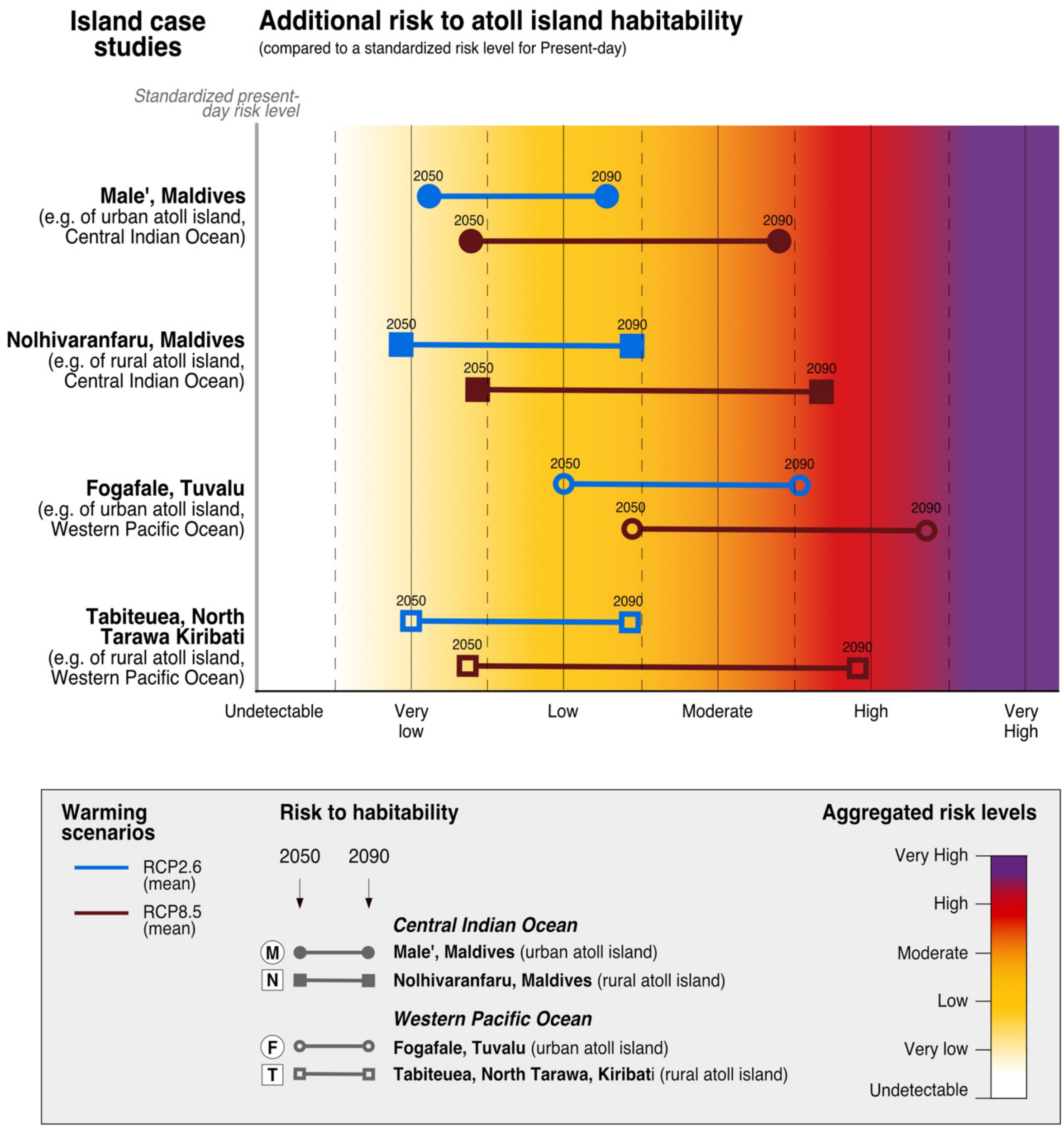


Figure 6. Aggregated additional climate risk to habitability for four atoll islands in the Central Indian and Western Pacific Oceans.
See especially SM8 for details on the method.

5. DISCUSSION

Our findings first highlight that climate change-related risk in atoll settings is driven by the cumulative and cascading effects of a large set of climate stressors on HPs. Taken together, SLR, extreme ENSO events, storm wave height, and coral reef degradation will cause major environmental changes on atolls from 2050 onwards under both RCP2.6 and RCP 8.5. Expected changes include shoreline erosion and increased flooding of island interiors (threats to Land) potentially leading to island physical destabilization, with multiple direct (e.g. through the deterioration of soil and FGL quality, disruption of economic activities) and indirect (e.g. through the effects of decreased FGL quality on land-based food production) cascading impacts on other HPs. Also, the declines in coastal fish stocks (and tuna and tuna-like species' biomass within the EEZs of Western Pacific nations from 2050 onwards) will significantly reduce locally-sourced fish supply. Therefore, climate risk to habitability is driven by multiple, interrelated climate stressors, where their additive effect will challenge the adaptation capacity of atolls.

Second, this study shows that climate risk to habitability will vary significantly between and within ocean basins, irrespective of the climate scenario and timescale considered. Risk will be highest in the Western Pacific. For example, Tuvalu is projected to experience (i) a high threat to Land, resulting from the cumulative effects of the highest SLR rates in atoll regions (5.1 and 15.4 mm yr^{-1} in 2090 under RCP2.6 and RCP8.5 respectively), and increased tropical cyclone and distant-source wave height; (ii) a high threat to both Freshwater supply and land-based Food supply, as a result of increased flooding and frequency of intense droughts; (iii) the negative impacts of increased SST and ocean acidification on nearshore habitats which will reduce reef-dependent fish stocks and contribute to Land destabilization, through reef degradation and ensuing erosion; and (iv) a decrease in tuna and tuna-like resources, which will further impact Food supply from local sources. The Central Pacific (e.g. French Polynesia) is expected to be less subject to climate risk, as a result of (i) a lower increase in SST and extreme tropical cyclones having more limited impacts on the reef ecosystem and therefore on Land and land-dependent HPs, as well as on reef-based Food supply, at least until 2050; and (ii) an increase in tuna and tuna-like species in EEZs, which may offset the expected decrease in reef fish. Risk accumulation will also occur, but at a lower rate, in the Central Indian Ocean compared to the Western Pacific. However, the Maldives are projected to experience (i) increased Land destabilization (exacerbated by the small size of most islands), as a result of the combination of relatively high rates of SLR (4.6 and 15.0 mm yr^{-1} in 2090 under RCP2.6 and RCP8.5, respectively) and increased distant-source wave height (which will increase erosion and flooding) with the highest SST values (under both RCP2.6 and RCP8.5 in 2050 and 2090) and increased frequency of extreme El Niño events (which will destabilize islands through reef degradation); (ii) the negative impacts of marine ecosystems' decline and Land destabilization on all HPs.

Third, this study highlights marked variations in climate risk to habitability across islands, depending on both their geomorphology (especially size, elevation and exposure to storms) and the effects of human activities on shoreline and island stability. This is illustrated by the comparative analysis of future risk in Fogafale (emblematic of the cumulative and destabilizing effects of climate change and human activities) and Male' (where encircling engineered structures are expected to reduce climate risk at least until 2050). Contrasts between rural islands are much lower due to limited human intervention in shoreline and island dynamics. Furthermore, our assessment shows that aggregated risk levels for rural islands are (i) lower in 2050 under both RCP2.6 and RCP8.5 compared to urban islands, especially Fogafale (Fig. 6); and (ii) higher than in Male' in 2090 under both RCP2.6 and RCP8.5. This is due to the increased degradation of ecosystems and natural resources over time, which will challenge the capacities of rural islands to offset losses through imports (for food supply) and technology (for freshwater supply and shoreline stabilization), under the moderate adaptation scenario considered.

Conclusion

This study introduces a new perspective on climate risk to future atoll island habitability. Based on an interdisciplinary assessment investigating the cumulative risk arising from multiple climate-ocean stressors –SLR; changes in rainfall, ocean-atmosphere oscillations and tropical cyclone intensity; ocean warming and acidification–, it assesses the risk caused to five major and interconnected Habitability Pillars (HPs; Land, Freshwater supply, Food supply, Settlements and Infrastructure, and Economic Activities). It does so at two spatial (ocean sub-regions and island) and temporal (2050 and 2090) scales, under the greenhouse gas concentration pathways RCP2.6 and RCP8.5 and a moderate adaptation scenario. The findings reveal that climate risk to atoll habitability is not only driven by the impacts of SLR and increased wave height on Land but rather, and importantly, by the cumulative and cascading effects of the abovementioned multiple climate stressors on these five HPs. The risk to Land, considered as the major HP (because it is the support to human life) and expected to be severe from 2050 onwards under both RCP2.6 and RCP8.5, will impact Freshwater supply from local sources, land-based Food supply, Settlements and Infrastructure, and Economic Activities. At the same time, ocean warming and acidification will increasingly contribute to Land destabilization, and decrease Food supply from local sources (including EEZs). Unless technology, human and finance capacity are significantly increased in a timely manner to effectively offset climate change impacts, the cumulative effects of climate stressors under a moderate adaptation scenario will generate impacts in the second half of the 21st century that will likely exceed the adaptive capacity of atoll islands in the Western and Central Pacific and Indian Ocean.

Our findings indicate there will be significant spatial variations in risk across both ocean basins and islands. We project that islands in the Western Pacific will experience disproportionate high risk from SLR, increased tropical cyclone and distant-source wave height, increased frequency of intense droughts, ocean warming and acidification, and a marked decrease in fish, including tuna and tuna-like species. In this sub-region, the five HPs will all be significantly and simultaneously challenged, with limited compensation opportunities (e.g. through the replacement of nearshore fish catches by pelagic catches) at the nation scale. In such locations, risk accumulation is thus expected to seriously challenge atoll habitability from 2050 onwards under RCP8.5. Conversely, in the Central Pacific and Indian Ocean, risk accumulation is projected to increase at a lower rate. This is due, in the Central Pacific, to lower rates of SLR, lower exposure to tropical cyclones, lower SST and increasing pelagic fish stocks and, in the Central Indian Ocean, to lower exposure to tropical cyclones and droughts.

This study not only highlights an urgent need for future assessments of risk to atoll habitability not only to consider a wide range of climate-driven factors and island cases but also to highlight how these may differentially impact islands across ocean basins. There is also a pressing need in future work to consider how these climate drivers of risk will impact upon different adaptation scenarios and changes in non-climatic drivers of risk, so as to include other resultant habitability dimensions, especially societal health.

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