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ADVANCED REVIEW

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Risks to future atoll habitability from climate-driven environmental changes

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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-

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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.

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KEYWORDS

atolls, climate change impacts, habitability, Indian Ocean, Pacific Ocean, reef island

1 | INTRODUCTION

Climate change impacts will increasingly compromise the essential dimensions of human life on low-lying tropical islands (Magnan, Garschagen, 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 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). 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., Giardino et al., 2018; Storlazzi 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 & Kench, 2018; Tuck et al., 2019).

These studies, however, 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; Oppenheimer et al., 2019; Perry et al., 2018; Vitousek et al., 2017). It is the combined effects of SLR and these drivers that 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 also 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 socioeconomic 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 hereafter) refer to recently-formed (generally <4000 years 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 (Gischler, 2016; McLean, 2011; Woodroffe, 2008). 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 (Bennett et al., 2019; Costanza et al., 2016; Daw et al., 2015). Accordingly, the atoll island habitability framework (Figure 1) presented here includes five major interrelated Habitability Pillars (HPs) that will all experience first-order (that is, direct) climate change impacts: (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

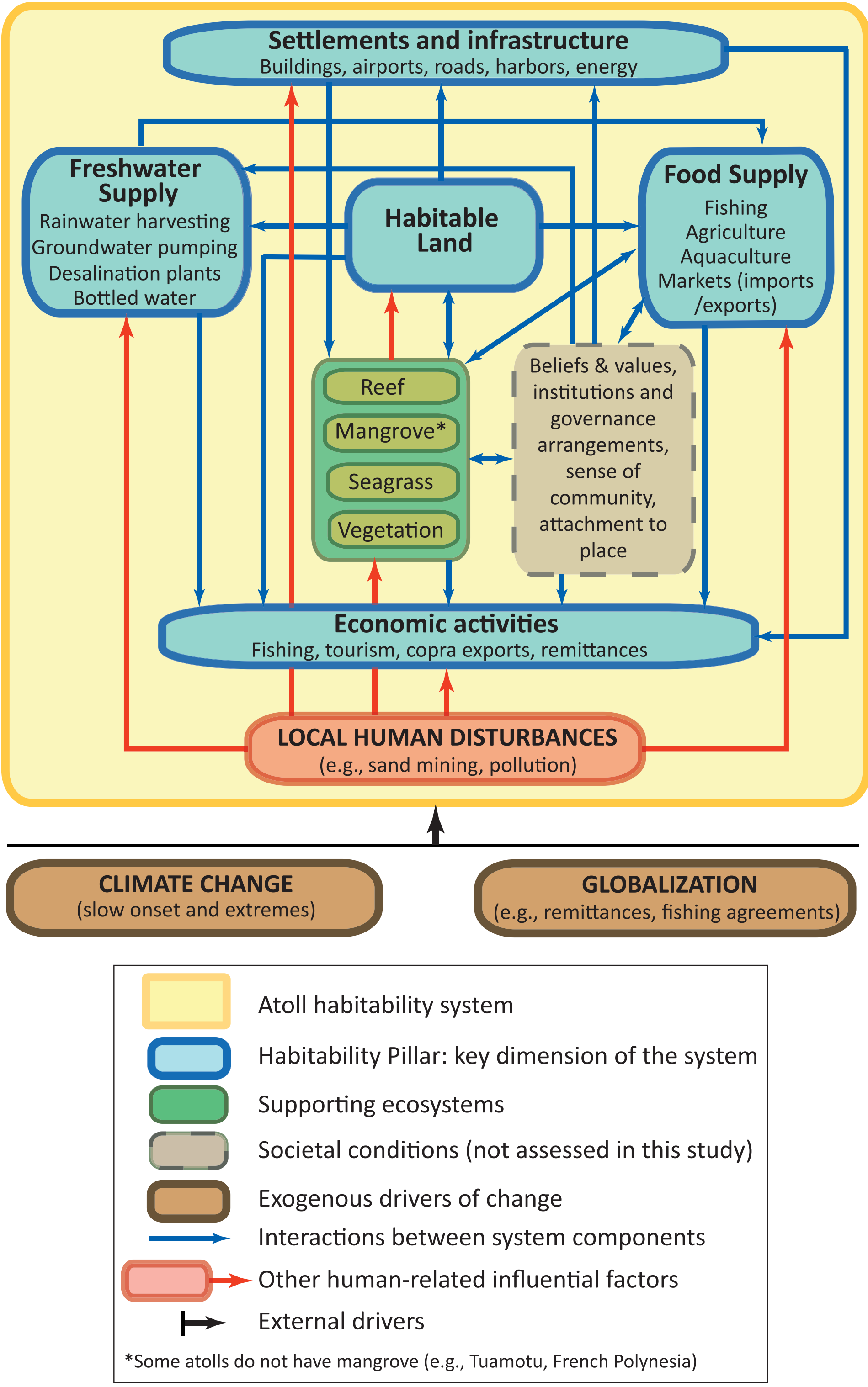


FIGURE 1 Conceptual model of atoll island habitability. The atoll island system comprises five pillars supported by ecosystems and societal conditions. Interactions between these pillars are illustrated by blue arrows: For example, habitable land is critical to settlements and infrastructure, freshwater 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

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*"). In accordance with the definition of the Intergovernmental Panel on Climate Change (IPCC, 2019), risk is referred to as the potential for adverse consequences to atoll social–ecological systems from climate change, recognizing the diversity of values and objectives associated with such systems. Risk can arise from potential impacts of climate change as well as human responses to climate change.

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 socioeconomic 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 Coupled Model Intercomparison Project (CMIP) 5 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.

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 10-to-30-year experience of the authors in atoll environments, in the research fields of geomorphology, ecology, hydrogeology, climate and impact modeling, subsistence and economic activities, development and sustainability. Two 3-day workshops in September 2019 and February 2020 allowed for both the framing elements (HPs, geographical scope, case studies, climate scenarios and timescales; Sections 2.1–2.3) and assessment method (including test phase; Section 2.4) to be defined. Due to COVID-19 restrictions, the expert judgment 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 to 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, for example, 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 (Aslam & Kench, 2017; Webb & Kench, 2010); elevation of shoreline and interior, determining susceptibility to wave-driven flooding (Owen et al., 2016; Woodroffe, 2008); island shape and geomorphic components, which influence resistance to storms (Ford & Kench, 2014; Kumar et al., 2018; Spennemann, 2009); sediment composition, which influences groundwater resources and agroforestry potential; and the nature and extent of vegetation cover (Duvat, Pillet, et al., 2020; Duvat, Volto, & Salmon, 2017). Physical processes underpinning these attributes result from the interplay of a number of factors that vary across and within ocean basins (McLean & Kench, 2015). They include seasonal wave regimes (Kench et al., 2017; Morgan & Kench, 2014), exposure to high energy events such as storms and tsunami (Duvat, Salvat, & Salmon, 2017; Duvat, Volto, & Salmon, 2017; Ford & Kench, 2014, 2016; Hoeke et al., 2013; Kench et al., 2006; Scoffin, 1993), sea-level change (Kench et al., 2014; Perry et al., 2013), reef growth and related sediment supply and trapping by mangrove, seagrass and island vegetation (Krauss et al., 2014; Perry et al., 2011).

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 (Falkland & White, 2020; Foale, 2003). Access to freshwater remains highly climate-dependent, as shown for example during the severe La Niña drought in 2011 across the southwestern Pacific (Kuleshov et al., 2014; Lorrey & Renwick, 2011) 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 & Falkland, 2010). Islands reliant on rainwater harvesting, either because their geomorphology and size do not support a viable FGL or because pollution or overextraction has made their FGLs unusable (Falkland & 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; Nukunonu, 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 (Campbell, 2015; Connell, 2014; Connell, 2020; Thaman, 1995). 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 & Lawrence, 2005; Sievert et al., 2019; Thow et al., 2010), 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 overfishing 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 overexploitation of coastal fish stocks (MacNeil et al., 2015; McClanahan et al., 2011; Sale et al., 2014). 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 & 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 ship harbors, regional and international airports, causeways and bridges connecting islands).

2.1.5 | Access to sustainable economic activities

Besides copra production (which is declining; Connell, 2014), atolls largely depend on fisheries, tourism, 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 (Lecomte et al., 2017; Pew, 2016). Consequently, the economies of atoll nations such as Kiribati, Tuvalu, Marshall Islands and Tokelau have capitalized on their tuna resources and now have a particularly high dependence on tuna-fishing license fees, deriving the majority of their government revenue in this way (Lam et al., 2020; SPC, 2019). In some atoll countries such as the Maldives, 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 & 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 & Pryke, 2017), and remittances from migrants working overseas largely contribute to national incomes (14%, 11%, and 10% of GDP, respectively, in 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 subregions, the Central Indian Ocean, Western Pacific and Central 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. In addition, we considered urban and rural islands to highlight variable exposure and vulnerability to climate stressors (Duvat, Magnan, et al., 2017). Urban case studies are illustrated by Male', North Kaafu Atoll, Maldives, which is a "fortified" island, and Fogafale (pronounced "Fongafale"), Funafuti Atoll, Tuvalu, which is flood-prone and has limited coastal protection. These two urban islands are extreme situations that are not representative of atoll urban islands worldwide. They allow us however to capture the wide spectrum of urban island situations. 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 the 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 subregion 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, that is, RCP2.6 representing a strong 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 subregion, following a three-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 subregion (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 risk posed to habitability by climate change relied on an extensive literature review (including especially case study papers), available datasets, and the authors' own expertise. It followed a six-step approach (Figure 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 (first round of scoring), shared their respective scores, and then convened (virtually) to discuss differences in assigned scores. Differences in scoring were discussed with special attention paid to the rationale supporting scoring. Discussions allowed the collective refining of scores and arrival at a final score (second round of scoring) and its consistency with the underlying rationale. Most first round scores were convergent. Where differences in initial scores arose, these mainly resulted from differences in case study-oriented knowledge and/or from differences in understanding of the underlying rationale. Discussing scores, and the related rationale, therefore led to the strengthening of the description of case studies (SM5, SM7). Knowledge gaps are reflected in the confidence levels which 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; Figures 5 and 6).

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 (Mechler et al., 2020; Roy et al., 2018), 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, that is, moderate adaptation, which is considered feasible and helps the understanding of risk under a nontransformational 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 the decline in locally-

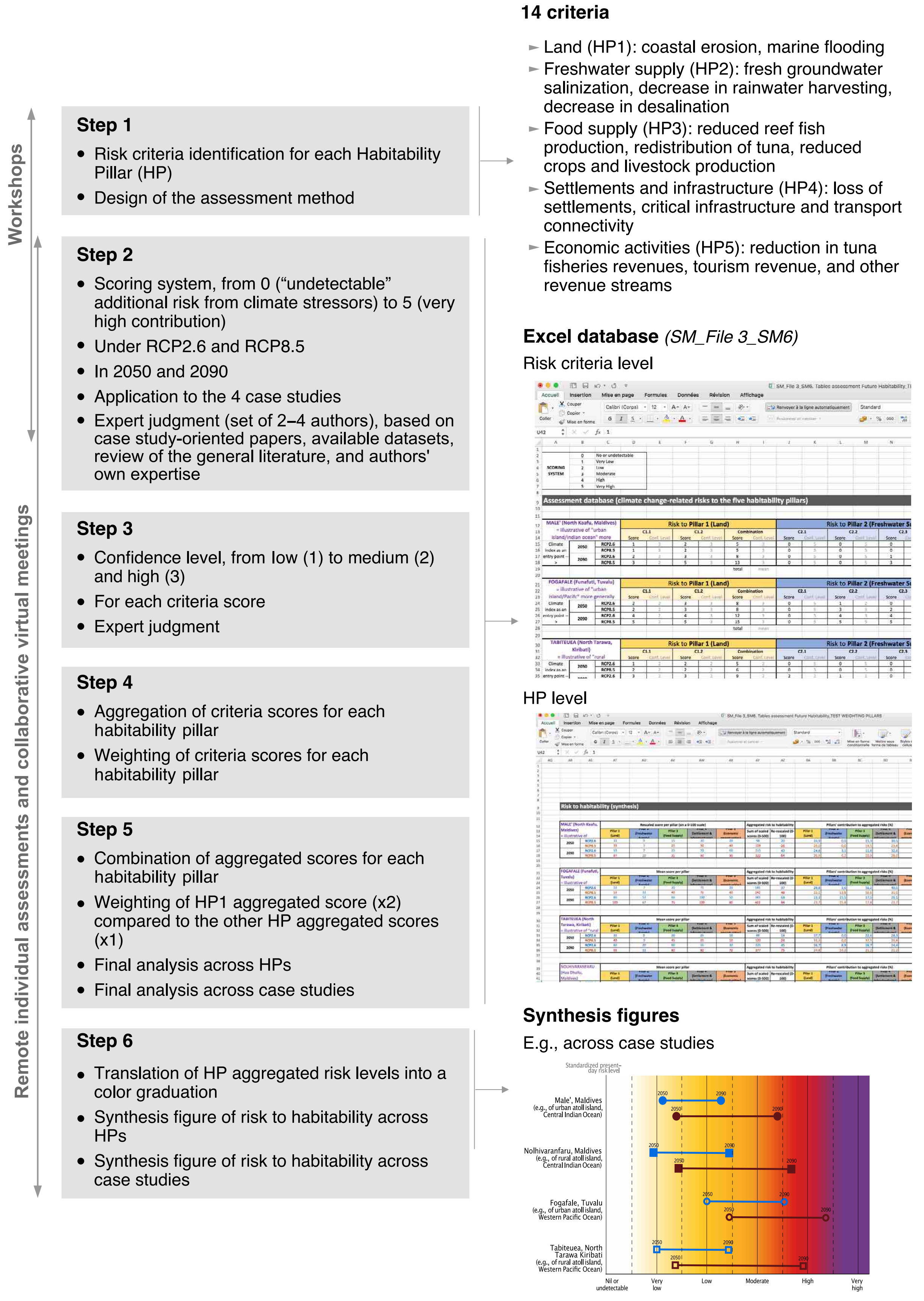


FIGURE 2 Assessment protocol used in this study. See SM4 for further details

produced food), 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 modeling 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 year^{-1} (IPCC, 2019). Under RCP2.6, mean rates of 4.5 and 4.8 mm year^{-1} are projected for 2050 for the Central Indian and Western Pacific Oceans respectively, and 4.6 and 5.1 mm year^{-1} for 2090 (Figure 3, SM3). Under RCP 8.5, mean rates by region are 7.6 and 8.2 mm year^{-1} for 2050, and 15.0 and 15.4 mm year^{-1} for 2090, respectively. 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.

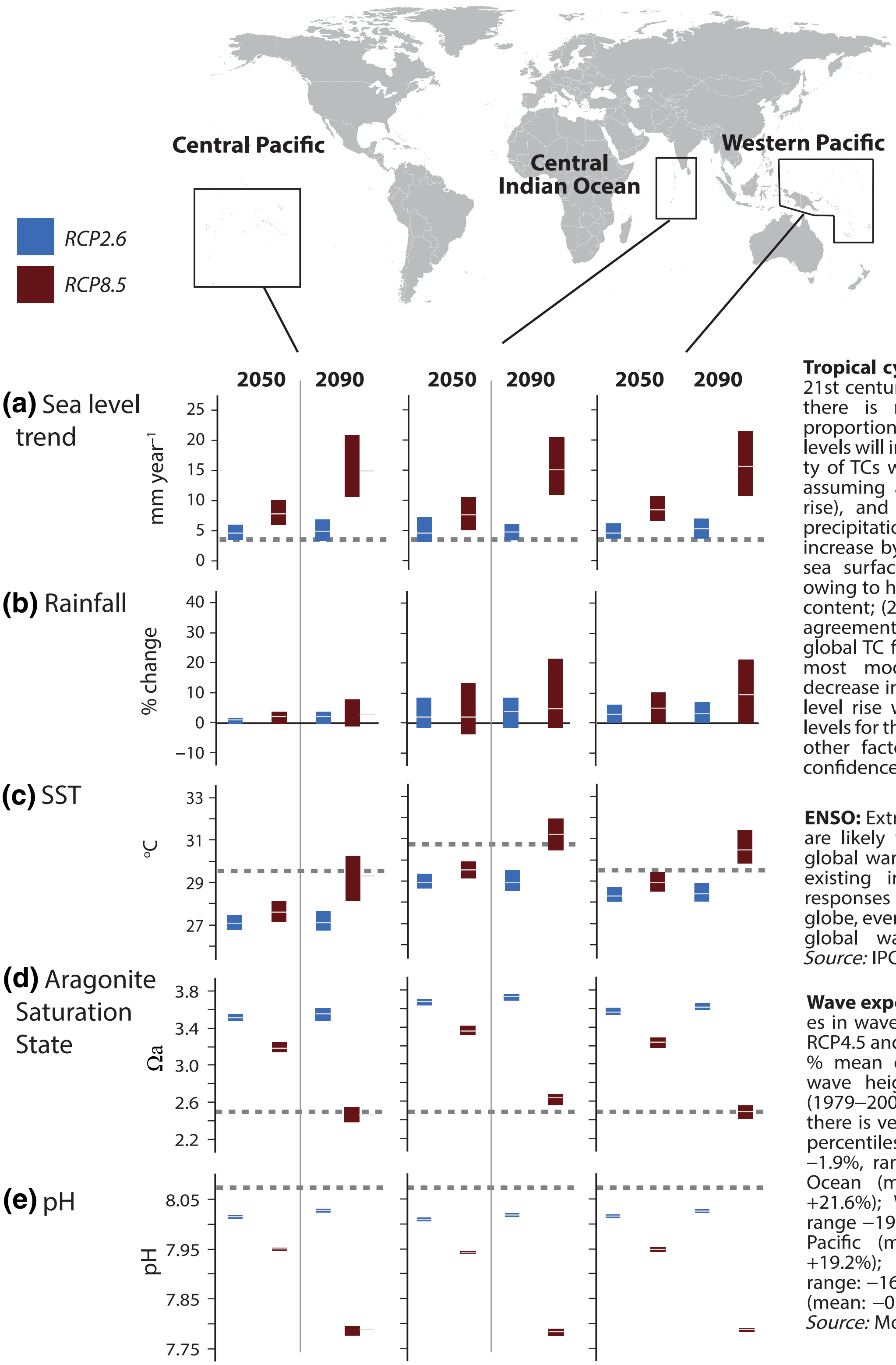
For SST, there is little projected change between 2050 and 2090 under RCP2.6 (Figure 3). Under RCP8.5, projected SST increases from 2050 to 2090 by around 1.5°C, likely increasing the frequency and magnitude of marine heat waves (Dalton et al., 2020; Frölicher et al., 2018) and pushing mean SST levels above local coral bleaching thresholds more frequently in all regions, except the Central Pacific (Figure 3). This is consistent with projections for 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 $\pm 10^{\circ}$ of the equatorial Pacific and northern Indian Oceans (Figure 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., 2015; Cai et al., 2018; Cai, Borlace, et al., 2014). Extreme Indian Ocean Dipole (IOD) events are also projected to increase in frequency (Cai, Santoso, et al., 2014). In nonequatorial 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 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 subregions and revert to slightly higher values between 2050 and 2090 (Figure 3). Under RCP8.5, both pH and the aragonite saturation rate (Ω_a) continue to fall between 2050 and 2090, reaching Ω_a values of <2.5 by 2090, that is, below the typical values found in coral reef waters (Kleypas et al., 1999).

These projections provide a basis for assessing the cumulative exposure of each subregion (Figure 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 (Figures 3 and 4 and SM3).



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 subregion (see also SM3.1). The threshold levels (gray bars) denote the following: for sea level trend, the mean rate of global sea-level rise (3.6 mm year^{-1}) between 2006 and 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)

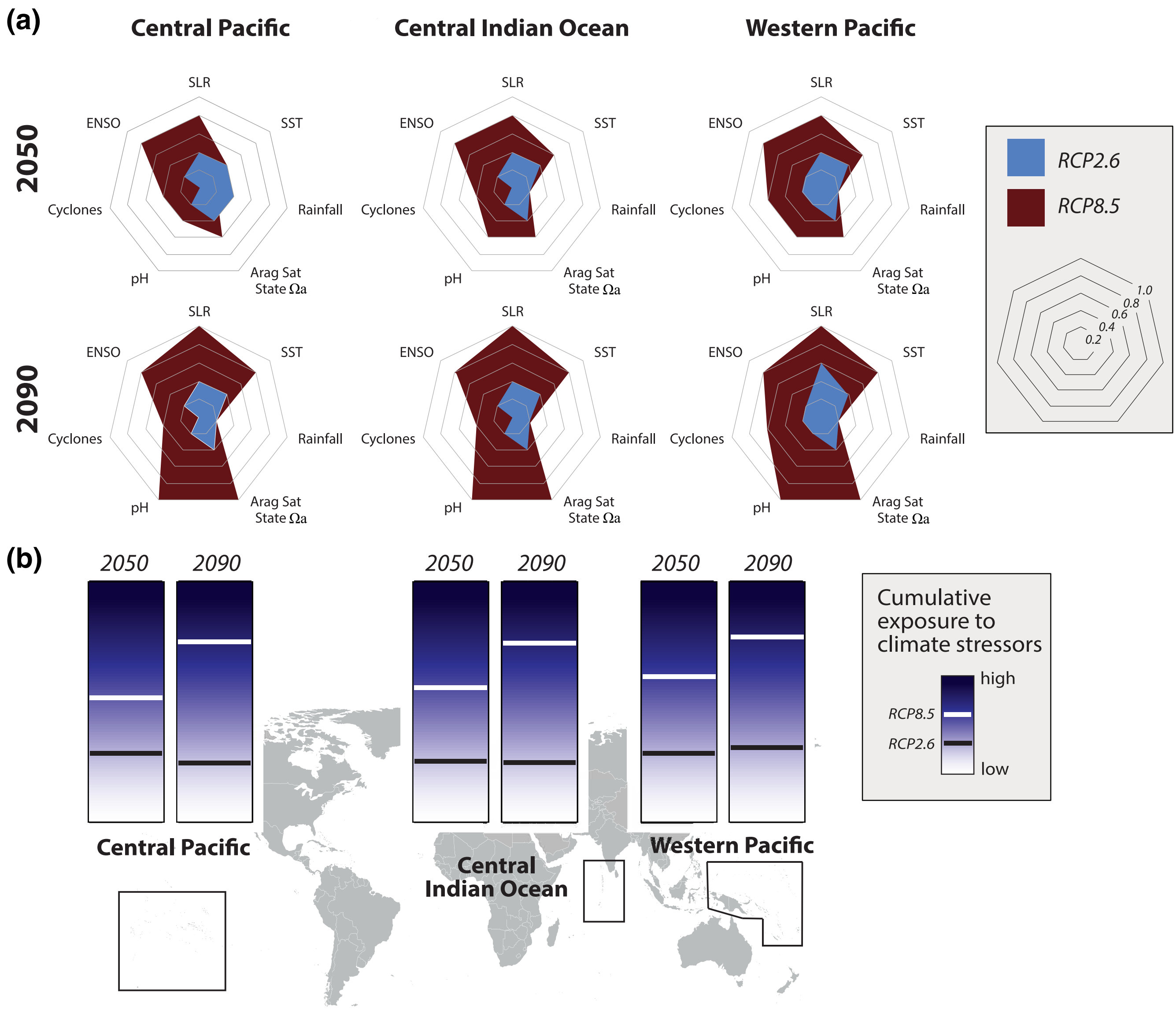


FIGURE 4 Cumulative climate change threats and related exposure of atoll regions, for two emission scenarios in 2050 and 2090, based on mean projected rates of change. SM3.1 provides the full details. Panel a illustrates the cumulative climate and climate-related ocean threats (high = 1.0, low = 0.0) 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 (Canavesio, 2019; Hoeke et al., 2013; 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 (Chand et al., 2013; Walsh et al., 2012). 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, while indirect effects will come from changes in the ecological make-up and structural complexity of reefs (Harris et al., 2018; Perry et al., 2011; Quataert et al., 2015), 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; East et al., 2020; Shope et al., 2017; Shope & Storlazzi, 2019; Storlazzi et al., 2018). Decreased sediment supply would in turn 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 (Duvat & Magnan, 2019; McLean & Kench, 2015; Schuerch et al., 2018). 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 (Hinkel et al., 2018; Naylor, 2015; Wadey et al., 2017), 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) (Figures 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 location-specific, 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 & White, 2020). Qualitatively, these intensifications suggest increased local flooding as groundwater rises to the surface, increased pollution of FGLs (Falkland & 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 (UNICEF and WHO, 2019; White et al., 2007; WHO, 2015).

Increased frequency (and intensity under RCP8.5) of major ENSO and IOD events may challenge water security, especially for rainwater harvesting on urban atolls. Modeling 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 & 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 year^{-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 & 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 & Bailey, 2017). More frequent island overtopping will cause salinization of FGLs (Burns, 2002; Hughes et al., 2020; Storlazzi et al., 2018). Experiences in the Pacific and Indian Oceans and overwash modeling suggest that FGL recovery takes between 1 and 5 years (Bailey, 2015; Bailey & Jenson, 2014; Chui & Terry, 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 & Terry, 2013), as well as the ability of habitable islands to build vertically to adjust to SLR.

However, at least until 2030, nonclimate-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 overfishing of coastal stocks will continue compounding food security challenges by reducing land availability for agriculture and levels of per capita fish consumption, respectively (SM2.3). These challenges will be exacerbated by projected declines in coastal fish abundance and catches in relevant subregions (Asch et al., 2018; Bell, Allain, et al., 2018). For reef fisheries, recent coral bleaching and mortality (e.g., Hughes et al., 2018), and resultant reef structural collapse, have led to declines in commonly targeted fish species (Robinson, Wilson, Jennings, & Graham, 2019).

Minimizing the gap in fish supply is achievable through adequate protection (and restoration) of coral reef and seagrass habitats (Brodie et al., 2020), improved management of coastal fish stocks (Bell, Allain, et al., 2018), increases in the catch of tuna and tuna-like species from nearshore waters (e.g., Maldives; Yadav et al., 2019), as well as by providing 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, Allain, et al., 2018) (SM2.4). Filling the gap in fish supply is all the more crucial given that climate-driven changes to soil moisture and salinization levels, rainfall and land area will increasingly constrain food production on atolls (Barkey & Bailey, 2017; Taylor et al., 2016).

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 (Asch et al., 2018; Pratchett et al., 2011, 2014). 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, Wilson, Robinson, et al., 2019) (SM2.6). Climate change risks to coastal fish productivity, exacerbated by inadequate management, are of particular concern for rural communities (Thow & 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; Bell, Cisneros-Montemayor, et al., 2018). 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, Allain, et al., 2018). Projected decreases in tuna biomass in 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 (Duvat et al., 2013; Speelman et al., 2017; Yamano et al., 2007). 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 1354 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, Magnan, et al., 2017). 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 settlement in marginal low-lying areas, amplifying population exposure to flooding (Duvat, Stahl, et al., 2020; Magnan, Ranché, et al., 2019; Yamano et al., 2007). The expansion of Male' through land reclamation (+67% since the 1970s, mostly <1 m 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 & Strauss, 2019). On Ebeye, Kwajalein Atoll, Marshall Islands, the population annually affected by flooding and erosion will increase from 5000 persons (>50% of its population) to 8800 (10,800) under RCP2.6 (RCP8.5) by 2100; and Expected Annual Damages (EAD) to buildings and infrastructure are projected to increase 2.4–3.8 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 & 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 efforts made to accommodate sea-level rise, including for example floor raising (e.g., Tuamotu; Magnan, Ranché, et al., 2019).

3.2.5 | Economic activities (HP5)

In 2016, revenues derived from tuna-fishing license fees contributed 60%–98% of all (nonaid) government revenue to 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; Bell, Allain, et al., 2018). Under RCP8.5, by 2050, tuna biomass in national waters is projected to decrease by 15% in 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, 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$2742 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 (Bindoff et al., 2019; Fauzel, 2019; Klint et al., 2015; Seetanah & Fauzel, 2019; van der Veeken et al., 2015). SLR, warmer SSTs and extreme events are likely to affect tourism through damage to essential infrastructure (UNFCCC, 2005), loss of beaches and coral bleaching (Koike et al., 2014; Weatherdon et al., 2016; Wielgus et al., 2002). Future COVID-like crises are likely to affect tourism revenues through the reduction of world travel (Filho et al., 2020; Moosa et al., 2020). For example, due to the COVID-19 crisis, the total revenue of the Maldivian government is "expected to fall by 49% in 2020, a drop of approximately US$1 billion. With the increased spending to mitigate COVID-19 impact, the budget deficit for 2020 is projected to reach $841 million" (UNDP & Ministry of Economic Development, 2020, p. 12).

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 & 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 & Pauw, 2016; Musah-Surugu et al., 2018; Nunn & Kumar, 2019). Remittances may also help limit rural exodus and international migration attributable to climate change (Damette & 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 net 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 (Figure 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 (Figure 5). While risk remains undetectable-to-very low in Male′ under both RCPs even in 2090 – because the island mainly relies on desalination – it increases slightly 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 becomes significant under RCP8.5 in 2090.

Risk to food supply (HP3, SM7.3) includes reduced reef fish production, redistribution of tuna and reduced production of crops and livestock. This risk is assessed as very low for all islands under RCP2.6 in 2050 (Figure 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 and livestock productivity 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 high for Fogafale under RCP2.6 in 2090 (Figure 5). Mid-century 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., Brown et al., 2020; Giardino et al., 2018), 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.

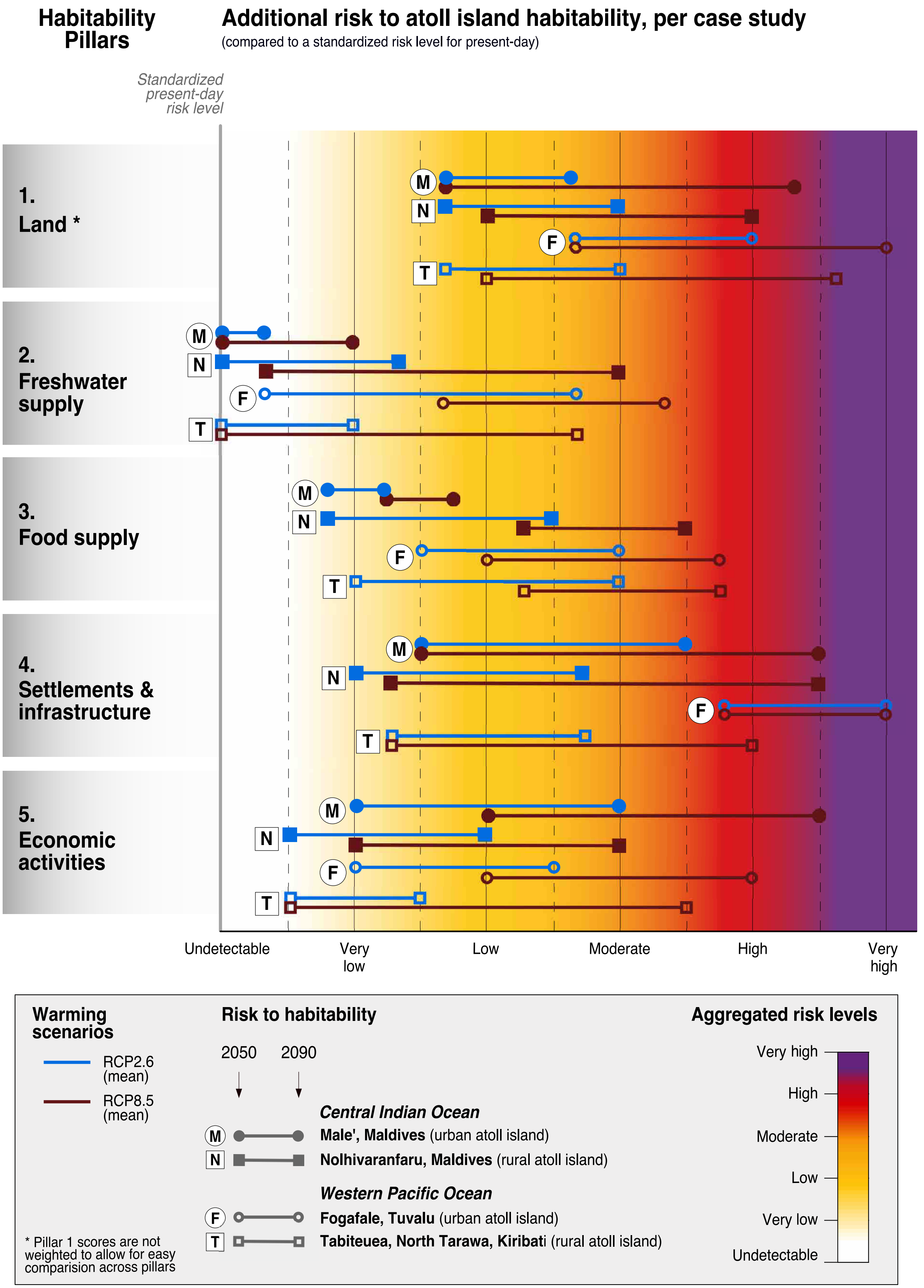


FIGURE 5 Additional climate risks to the five habitability pillars for four atoll islands in the central Indian and Western Pacific oceans. "Additional" means additional risk to habitability compared to a present-day baseline. See Part II of the Supplementary Material for details on the assessment method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

Risk to economic activities (HP5, SM7.5) includes declines in tuna fisheries and tourism revenues (especially in the Maldives for the latter), 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 (Figure 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 Tabiteuea).

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 generally 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).

4.2 | Cumulative risk

Aggregated risk levels (i.e., cross-HP; Figure 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.

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 physical destabilization of islands, 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 (1) a high threat to Land, resulting from the cumulative effects of the highest SLR rates in atoll regions (5.1 and 15.4 mm year^{-1} in 2090 under RCP2.6 and RCP8.5, respectively), and increased tropical cyclone and distant-source wave height; (2) a high threat to both Freshwater supply and land-based Food supply, as a result of increased flooding and frequency of intense droughts; (3) 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 (4) 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 (1) a lower increase in SST and extreme tropical cyclones having more limited impacts on the

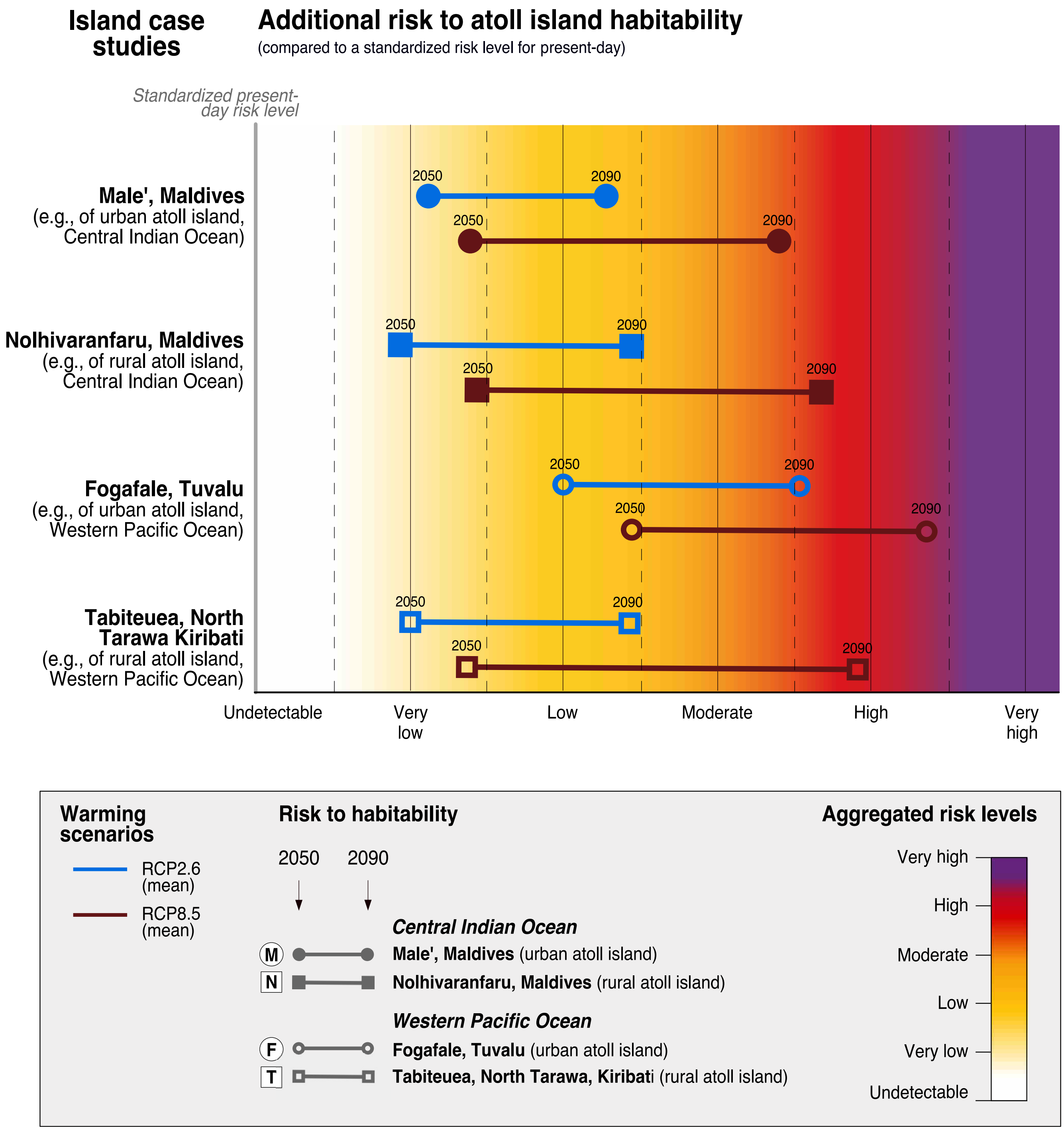


FIGURE 6 Aggregated additional climate risk to habitability for four atoll islands in the central Indian and Western Pacific oceans. See especially SM8 for details on the method

reef ecosystem and therefore on Land and land-dependent HPs, as well as on reef-based Food supply, at least until 2050; and (2) 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 (1) 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 year^{-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); (2) the negative impacts of decline in marine ecosystems 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 (1) lower in 2050 under both RCP2.6 and RCP8.5 compared to urban islands, especially Fogafale (Figure 6); and (2) 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.

6 | 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 subregions 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 subregion, 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 highlights an urgent need for future assessments of risk to atoll habitability to consider not only 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 nonclimatic drivers of risk, in ways that include other resultant habitability dimensions, especially the health of communities.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Duvat VKE, Magnan AK, Perry CT, et al. Risks to future atoll habitability from climate-driven environmental changes. *WIREs Clim Change*. 2021;e700. https://doi.org/10.1002/wcc.700

Le changement climatique : une réalité vécue dans l'Indre

Prise de conscience :

2019, de grands incendies en Brenne et dans le sud de l'Indre :

→ 4 septembre 2019, Commune de Migné, 150 ha de landes, champs et forêts détruits,

→ 18 septembre 2019, Communes de Chalais et Lignac, 800 ha de forêts, brandes et herbes sèches,
(2 incendies simultanés dont un provoqué par les services du Département lors d'une opération d'entretien des accotements routiers par un contact avec un fil barbelé),

→ 2 avril 2021, Commune d'Oulches, 150 ha de forêts et broussailles incendiés.

Photo : SDIS 36
La Nouvelle République
05/09/2019

22 mai 2022, un épisode de grêle traumatisant à Châteauroux

la Nouvelle République.fr

Indre > Martizay > Canicule : des records de température pour un mois de juin battus dans l'Indre

Canicule : des records de température pour un mois de juin battus dans l'Indre

MÉTÉO - INDRE

CANICULE CHALEUR SOLEIL AVEUGLANT TOURS Juin 2022
© (Photo NR, Olivier Pirot)

Par **Bertrand SLEZAK** — Publié le **18/06/2022 à 19:00**, mis à jour le **19/06/2022 à 10:54**

Comme annoncé, le thermomètre a dépassé les 40 °C à plusieurs endroits du département d samedi 18 juin. On a même battu les records de 2019 pour un mois de juin dans certaines co

la Nouvelle République.fr

Vague de chaleur dans l'Indre : quels dispositifs pour protéger les personnes âgées ?

ABONNÉS Cet article est réservé aux abonnés numériques.

SANTÉ - INDRE

Les Ehpad et hôpitaux mettent tout en œuvre pour subvenir aux besoins des résidents, avec notamment l'installation de climatiseurs et de ventilateurs.
© (Photo illustration NR)

Par **Agathe MAILLOT** — Publié le **20/08/2023 à 14:59**, mis à jour le **21/08/2023 à 11:43**

Un pic de chaleur est attendu mardi 22 août 2023 à Châteauroux, avec 37 °C au thermomètre. Face aux fortes chaleurs, les Ehpad, les hôpitaux ou encore les mairies se mobilisent.

la Nouvelle République.fr

A la Une > Canicule : le brevet des collèges reporté au début de semaine prochaine

Canicule : le brevet des collèges reporté au début de semaine prochaine

ÉDUCATION - FRANCE

Les épreuves devaient avoir lieu ce jeudi et ce vendredi.
© Photo d'illustration NR, Patrick Gaïda

Par **Vincent LEBLÉ** — Publié le **24/06/2019 à 16:51**, mis à jour le **25/06/2019 à 10:06**

Le ministre de l'Education nationale a décidé de reporter à lundi et mardi les épreuves du brevet des collèges en raison de la canicule.

Inondations dans l'Indre : "Toutes les baies vitrées ont explosé", 1,50 mètre d'eau dans les maisons à Bélâbre

Dans la nuit du vendredi 29 au samedi 30 mars, la Creuse et l'Anglin sont sorties de leur lit par endroit. À Bélâbre, dans l'Indre, 40 habitants ont dû être évacués en pleine nuit. "C'est du jamais vu'", confie le maire qui a installé les sinistrés dans la salle des fêtes.

Indre

De Selma Riche

Samedi 30 mars 2024 à 12:38

Par France Bleu Berry, France Bleu

Le Blanc > Le Blanc : la foire-expo annulée en raison des crues

Le Blanc : la foire-expo annulée en raison des crues

INTEMPÉRIES - LE BLANC

Fin de matinée, samedi 30 mars 2024, l'eau commence à envahir la bulle...
© (Photo NR)

Par RÉDACTION Publié le 30/03/2024 à 17:32, mis à jour le 31/03/2024 à 10:26

Après les pluies intenses de vendredi 29 mars 2024, le maire et les organisateurs ont décidé, samedi matin, d'annuler la foire-exposition.

Indre > Trois cents maisons inondées à Issoudun

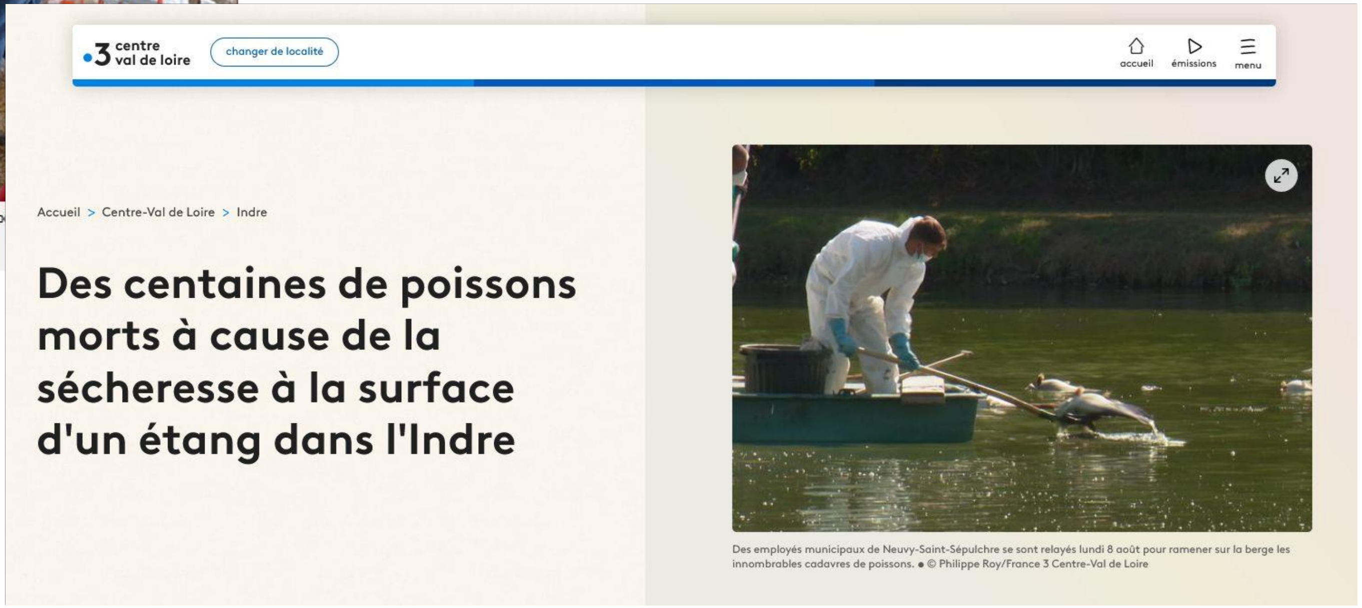
Trois cents maisons inondées à Issoudun

ENVIRONNEMENT - INDRE

> ISSOUDUN. Les fortes pluies ont fait sortir la Théols et son bras, la rivière forcée, de leur lit.
© Photo NR

Par RÉDACTION Publié le 02/06/2016 à 05:38, mis à jour le 02/06/2017 à 03:57

Commune de Bélâbre inondée le 30 mars 2024, le 14 juillet 2021 et 1er juin 2016



- « Pertes sur fourrage » pour la sécheresse :
  4,6 M€ versés pour 2018
  6 M€ versés pour 2019

la Nouvelle République.fr

Indre > Éguzon-Chantôme > Cyanobactéries à Éguzon : le lac fermé à la baignade et à certaines activités nautiques

Cyanobactéries à Éguzon : le lac fermé à la baignade et à certaines activités nautiques

POLLUTION - INDRE

Seuls le canoë, les bateaux à voile et les pédalos restent autorisés au lac d'Éguzon. La baignade et les autres activités nautiques sont désormais interdites.
© Photo archives NR, Thierry Roulliaud

Par Martine ROY — Publié le 19/07/2023 à 16:49, mis à jour le 19/07/2023 à 19:47

Alerte aux cyanobactéries au lac d'Éguzon. Les plages de Cuzion et de Chambon sont fermées à la baignade et à la plupart des activités nautiques depuis mardi 18 juillet 2023. La pêche est autorisée mais il est fortement recommandé de ne pas consommer le poisson.

la Nouvelle République.fr

Indre > Buzançais > Sécheresse : l'eau potable risque de faire défaut à Buzançais

Sécheresse : l'eau potable risque de faire défaut à Buzançais

ENVIRONNEMENT - INDRE

Régis Blanchet, maire de Buzançais, et Valéry Penin, responsable de la régie de l'eau, devant le ruisseau de la Grosse Planche, au débit déjà très faible.
© (Photo NR, Gaspard Mathé)

Par Gaspard MATHE — Publié le 10/05/2022 à 17:21, mis à jour le 11/05/2022 à 08:03

En 2019, le forage principal d'adduction en eau potable a fait défaut trois mois durant, à Buzançais, dans l'Indre. Face à la sécheresse qui se profile, la commune craint un scénario identique cette année.

"J'en ai fait des nuits blanches". À Buzançais, la ressource en eau potable est un casse-tête quotidien pour Valéry Penin, responsable de la régie des eaux. "En 2019, du 17 septembre au 17 décembre, le forage de la Grosse Planche était à l'arrêt, faute d'eau. On a réussi à tenir grâce au forage de secours, celui de la Gare." Un forage à utiliser avec parcimonie, car régulièrement au-dessus des normes en ce qui concerne les nitrates.

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Indre > Poissons morts dans l'Indre : le terrible décompte de la fédération de pêche

Poissons morts dans l'Indre : le terrible décompte de la fédération de pêche

ENVIRONNEMENT - INDRE

Une tonne de poissons morts dans l'étang de Neuvy-Saint-Sépulchre. C'était au début du mois d'août.
© (Photo d'archive NR, Jean-Sébastien Le Berre)

Par Bruno MASCLE — Publié le 25/08/2022 à 06:25, mis à jour le 25/08/2022 à 08:20

Une centaine de tonnes de poissons morts à cause de la sécheresse et de la chaleur ? La Fédération de pêche estime ce chiffre totalement sous-estimé.

Des initiatives d'adaptation à fédérer :

la Nouvelle République.fr

Indre > Incendies, inondations, tempêtes : face aux risques majeurs, les collectivités de l'Indre s'organisent

Incendies, inondations, tempêtes : face aux risques majeurs, les collectivités de l'Indre s'organisent

ABONNÉS Cet article est réservé aux abonnés numériques.

POLITIQUE - INDRE

Les vents violents avaient arraché la cabine de la station essence du sol.
© (Photo NR, Thierry Roulliaud)

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Châteauroux > Les élus locaux de l'Indre formés au changement climatique

Les élus locaux de l'Indre formés au changement climatique

ENVIRONNEMENT - INDRE

Près de deux cent cinquante élus locaux ont participé à la formation, organisée dans la salle des délibérations du Conseil départemental.
© (Photo NR, Gaspard Mathé)

Par Gaspard MATHE — Publié le 28/09/2022 à 10:00, mis à jour le 28/09/2022 à 10:00

C'est une première en France. La préfecture a accueilli près de deux cent cinquante élus locaux pour évoquer l'adaptation des politiques face à l'évolution climatique.

Le changement climatique est là. Pas de doute pour le préfet Stéphane Bredin, "le dérèglement climatique n'est plus une discussion d'experts, ses effets sont déjà là".

la Nouvelle République.fr

Châteauroux > Le Département de l'Indre veut adapter les collèges au changement climatique

Le Département de l'Indre veut adapter les collèges au changement climatique

TRAVAUX - INDRE

Gil Avérous, maire de Châteauroux, et Marc Fleuret, président du conseil départemental, ont visité le collège La Fayette, mardi 6 septembre.
© (Photo NR, Thierry Roulliaud)

Par Gaspard MATHE — Publié le 06/09/2022 à 16:59, mis à jour le 06/09/2022 à 17:16

En visite au collège La Fayette, à Châteauroux, le président du conseil départemental a souligné sa volonté d'aller vers des établissements moins énergivores et adaptés au changement climatique.

la Nouvelle République.fr

Châteauroux > Climat : 250 agents mobilisés à Châteauroux pour trouver les solutions de demain

Climat : 250 agents mobilisés à Châteauroux pour trouver les solutions de demain

ENVIRONNEMENT - INDRE

par petits groupes.

Publié le 12/12/2022 à 17:07, mis à jour le 12/12/2022 à 18:10

s services de l'Etat dans l'Indre ont décidé de s'impliquer dans un projet de ue du climat ", qui vise à trouver des idées pour limiter l'impact du à la Cité administrative.

ici par France Bleu et France 3

Les pompiers de l'Indre dotés de quatre nouveaux camions pour lutter contre les feux de forêt

Quatre nouveaux camions citernes feux de forêt sont opérationnels depuis le mois d'août dans l'Indre. Ils avaient été commandés pour les sapeurs-pompiers après les violents incendies en septembre 2019.

Indre

De Jérôme Collin

Dimanche 8 août 2021 à 17:46

Par France Bleu Berry

Quatre nouveaux camions citerne de feux de forêt vont équiper les sapeurs-pompiers de l'Indre © Radio France - Jérôme Collin

240 000 euros le camion, un investissement total de près d'un million d'euros. Malgré la dépense conséquente, le Conseil départemental de l'Indre n'a pas hésité pour renforcer l'équipement des sapeurs-pompiers de l'Indre. **Quatre camions citernes de feux de forêt** sont arrivés fin juillet. Ils **sont opérationnels** dans les centres de secours de Châteauroux, Argenton-sur-Creuse, Issoudun et Le Blanc depuis début août.

la Nouvelle République.fr

Châteauroux > À Châteauroux, les cours d'écoles se mettent au vert

À Châteauroux, les cours d'écoles se mettent au vert

ABONNÉS Cet article est réservé aux abonnés numériques.

ENVIRONNEMENT - CHÂTEAUROUX

La cour du Grand Poirier était entièrement goudronnée avant la restauration.
© (Photo NR, Benjamin Abgrall)

Par RÉDACTION

Publié le 07/09/2023 à 09:52, mis à jour le 07/09/2023 à 09:53

Alors que les fortes chaleurs touchent la ville pour cette rentrée 2023, certaines cours d'école agissent comme de vrais récepteurs de chaleur. Pour limiter ce phénomène des projets de végétalisation fleurissent dans plusieurs établissements de la ville.

la Nouvelle République.fr

Indre > Éguzon-Chantôme > Climatiseurs, îlots de fraîcheur, repas adaptés : les Ehpad de l'Indre s'adaptent à la canicule

Climatiseurs, îlots de fraîcheur, repas adaptés : les Ehpad de l'Indre s'adaptent à la canicule

ABONNÉS Cet article est réservé aux abonnés numériques.

SENIORS - INDRE

Aurélien Joubert, directeur du Hameau d'Éguzon, offrant un verre d'eau fraîche à Françoise Alexandre, l'une des résidentes de son établissement, âgée de 90 ans.
© (Photo NR, Jean-Sébastien Le Berre)

Par Jean-Sébastien LE BERRE

Publié le 23/08/2023 à 19:44, mis à jour le 23/08/2023 à 20:21

la Nouvelle République.fr

Indre > Saint-Maur > Indre : face au changement climatique, les forêts s'adaptent

Indre : face au changement climatique, les forêts s'adaptent

ABONNÉS Cet article est réservé aux abonnés numériques.

ENVIRONNEMENT - INDRE

De plus en plus d'arbres issus de forêts indriennes sont en situation de dép
essences, comme le chêne rouge d'Amérique ici, fait partie des solutions p
© (Photo NR, Matthieu Renard)

Par Matthieu RENARD Publié le 18/10/2023 à 20:36, r

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Indre > Bommiers > Contre le changement climatique, des arbres plantés dans le massif de Chœurs-Bommiers

Contre le changement climatique, des arbres plantés dans le massif de Chœurs-Bommiers

ABONNÉS Cet article est réservé aux abonnés numériques.

ENVIRONNEMENT - INDRE

Arnaud Rodriguez, forestier à l'ONF, scrute les massifs forestiers de l'Indre et alerte face au dérèglement climatique.
© (Photo NR, Alice Rouger)

Par Alice ROUGER Publié le 07/01/2023 à 06:30, mis à jour le 07/01/2023 à 06:30

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Indre > Changement climatique : la chambre d'agriculture de l'Indre se penche sur une inéluctable adaptation

Changement climatique : la chambre d'agriculture de l'Indre se penche sur une inéluctable adaptation

ABONNÉS Cet article est réservé aux abonnés numériques.

ENVIRONNEMENT - INDRE

Le changement climatique se fait déjà ressentir, tous les ans, dans les champs de l'Indre, soumis à des sécheresses de plus en plus intenses et régulières.
© (Photo d'archive NR, Jean-Sébastien Le Berre)

Par Jean-Sébastien LE BERRE Publié le 12/03/2024 à 18:40, mis à jour le 12/03/2024 à 20:41

la Nouvelle République.fr

Indre > Indre : face aux changements climatiques, les vins de valençay adaptent leur cahier des charges

Indre : face aux changements climatiques, les vins de valençay adaptent leur cahier des charges

ABONNÉS Cet article est réservé aux abonnés numériques.

AGRICULTURE - INDRE

depuis la fin novembre, dans le vignoble du valençay. Avec le nouveau cahier des charges, les
aisser un œil (futur bourgeon) de plus sur les coursons.

Stratégie Climat 36

Lien internet : https://www.indre.gouv.fr/Actions-de-l-Etat/Environnement/Strategie-Climat-36-une-demarche-departementale-et-partenariale

INDRE
LE DÉPARTEMENT

ADEME
AGENCE DE LA TRANSITION ÉCOLOGIQUE

PRÉFET DE L'INDRE
Liberté
Égalité
Fraternité

RÉPUBLIQUE FRANÇAISE
Liberté Égalité Fraternité

DATA CHALLENGES
ADAPT'ACTION :
LA DONNEE AU SERVICE DE L'ADAPTATION

METEO FRANCE
À VOS CÔTÉS, DANS UN CLIMAT QUI CHANGE

Le changement climatique en France : Où en est-on ? Quel climat dans une France à +4°C ?

Réponses avec les portails Climat^{HD} et DRIAS

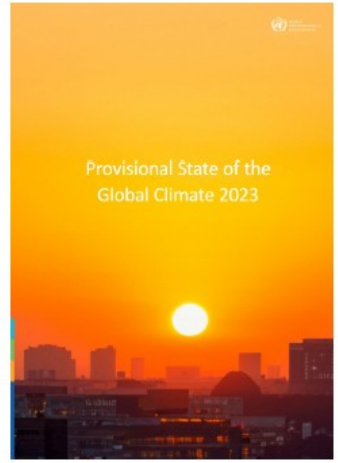
Jean-Michel Soubeyroux

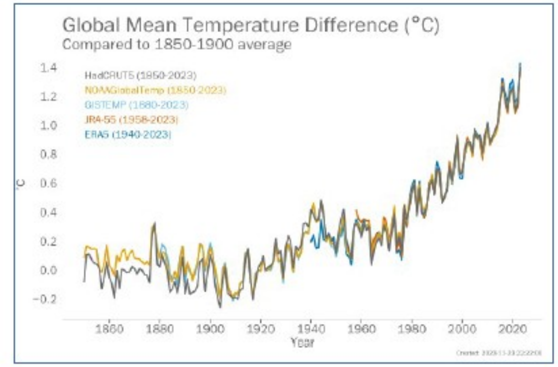
Directeur Adjoint Scientifique de la Climatologie et des Services Climatiques

Où en est-on du changement climatique ?

- S'adapter au changement climatique nécessite de pouvoir mesurer sa climato-sensibilité et de connaître quelle est la situation actuelle.

- Au niveau planétaire, l'OMM publie des rapports annuels venant compléter les rapports de synthèse du GIEC





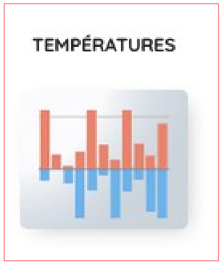
Température moyenne mondiale annuelle record en 2023 : +1,45°C (1850-1900)

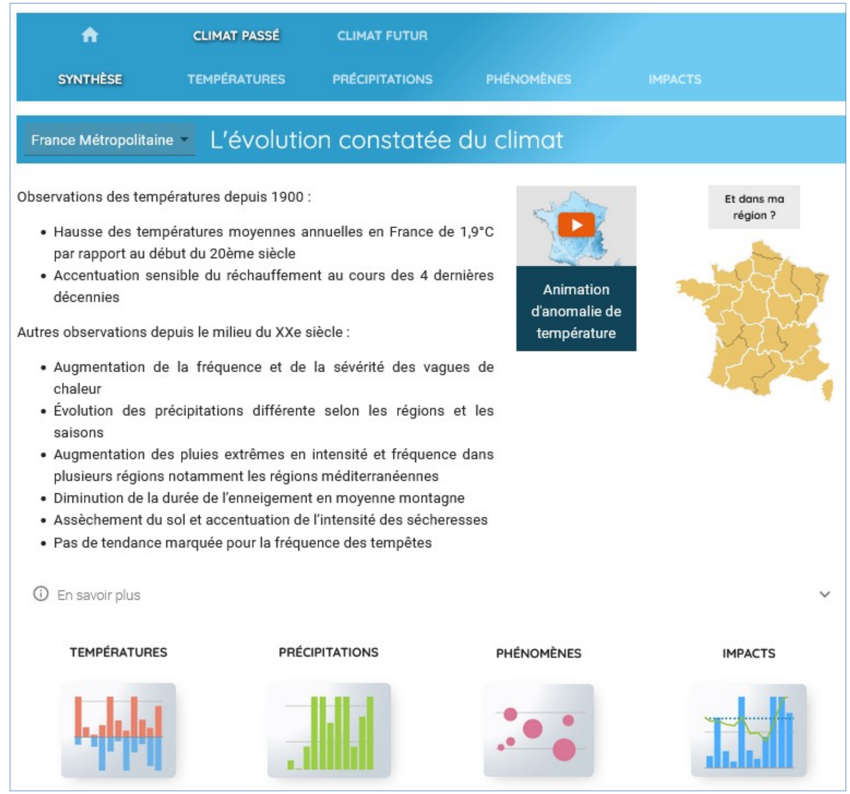
- Au niveau national, Météo-France met à jour annuellement une application, nommée Climat^{HD} pour décrire le changement climatique en œuvre et à venir, à l'échelle régionale (largement utilisée par les Collectivités pour leur PCAET)

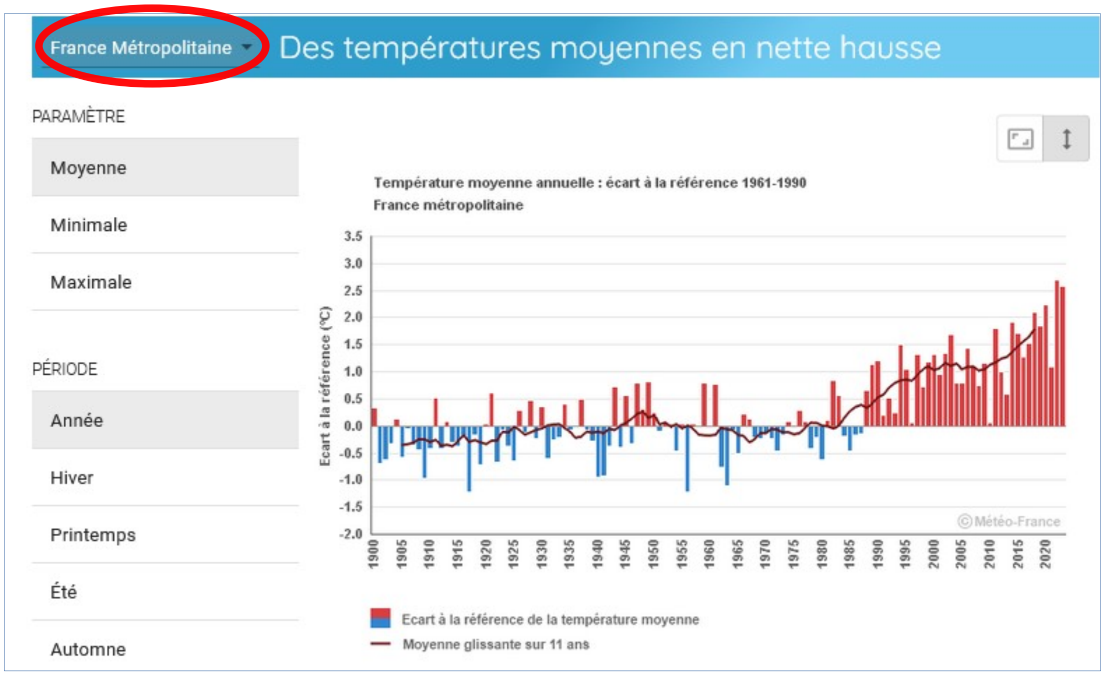
https://meteofrance.com/climathd

Quel constat du changement climatique ?

- Températures, précipitation, phénomènes, impacts, toute une gamme d'indicateurs simple à comprendre et commenter

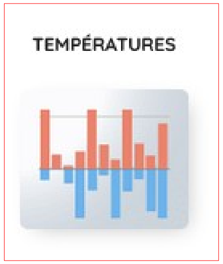


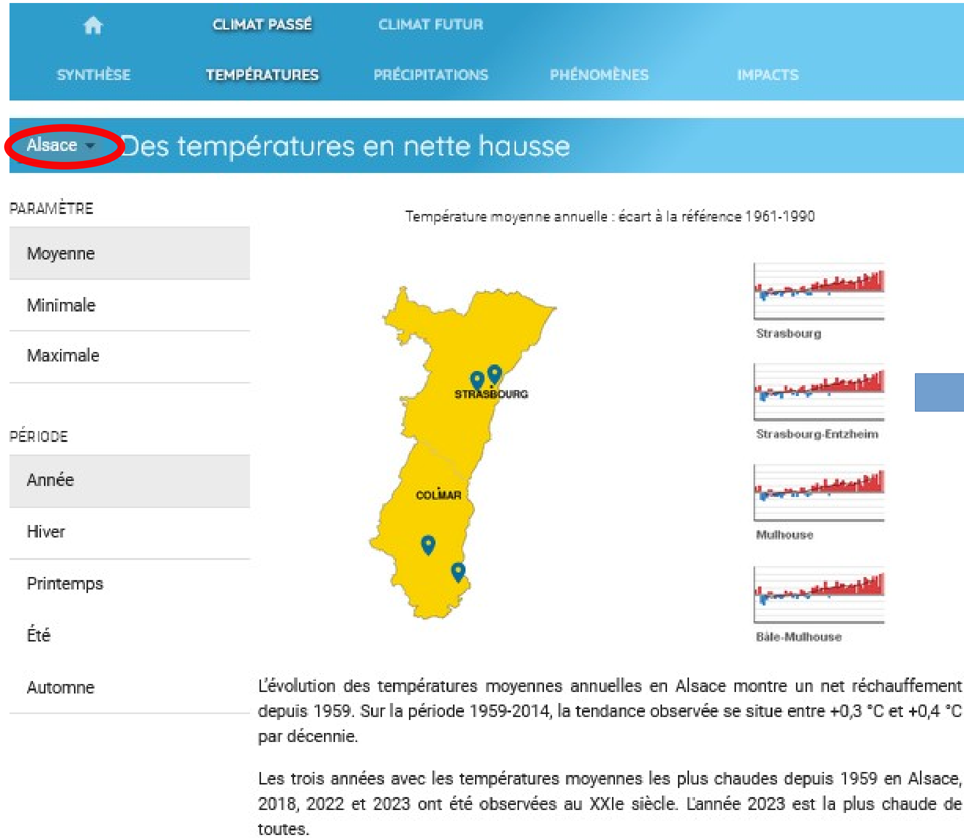


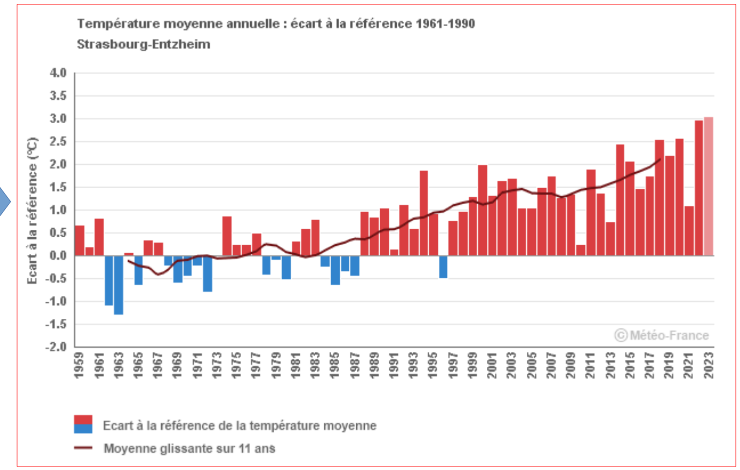


A l'échelle nationale et annuelle, une hausse de température de +1,9°C sur la dernière décennie par rapport au début du XXe siècle

Quel constat du changement climatique ?

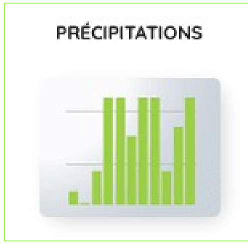


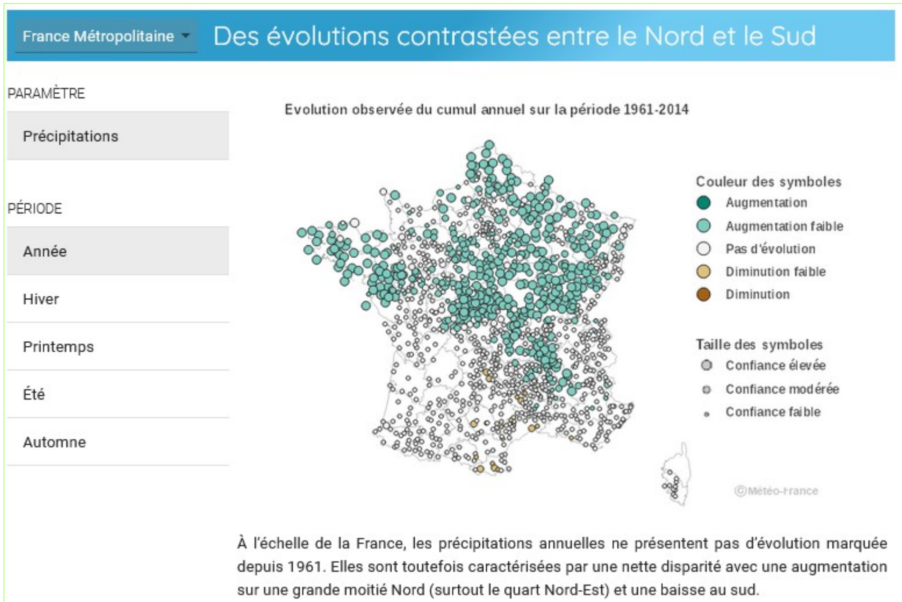




A l'échelle régionale, ici en Alsace et notamment à Strasbourg, le réchauffement est encore plus marqué qu'à l'échelle nationale et atteint déjà +2°C depuis les années 60

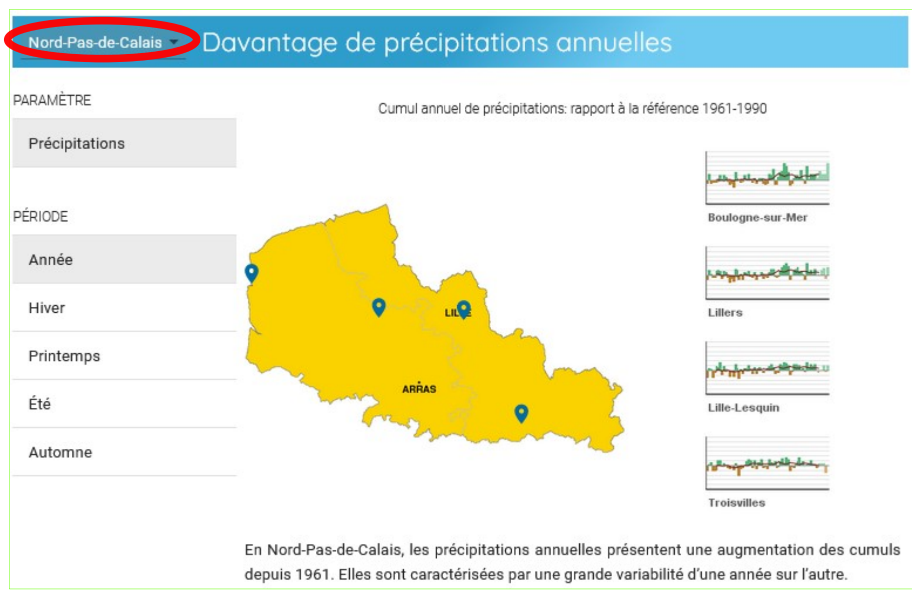
Quel constat du changement climatique ?

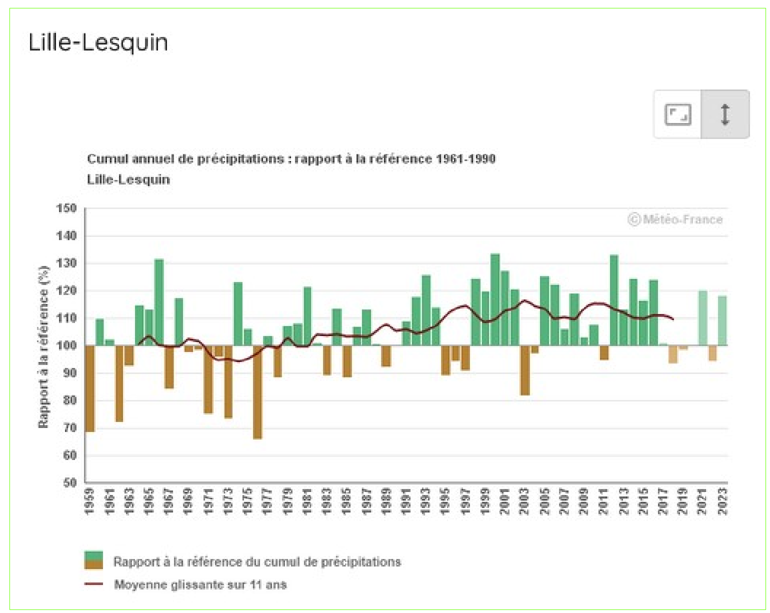




En matière de cumul annuel de précipitation, l'évolution observée depuis les années 1960 est contrastée sur le pays entre le Nord et le Sud

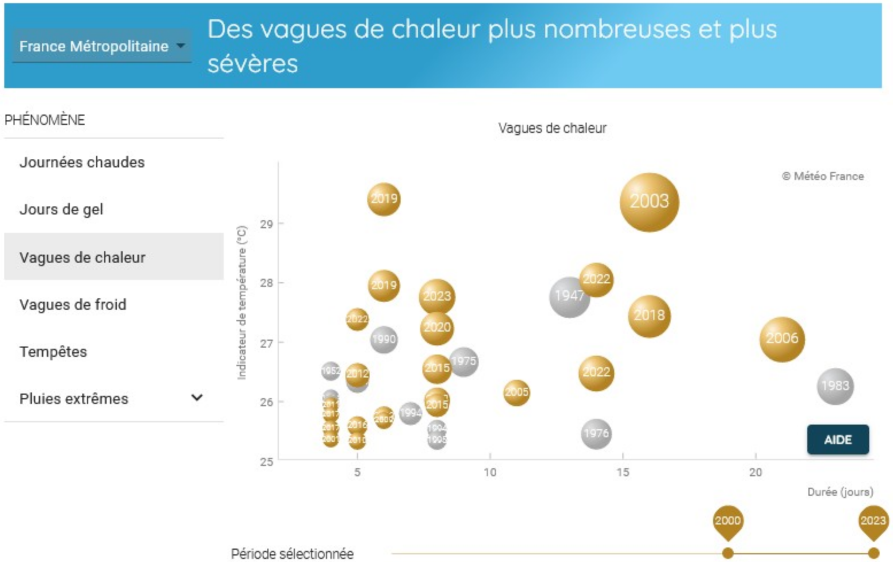
A Lille, le cumul annuel est en hausse de +10 % depuis les années 1960





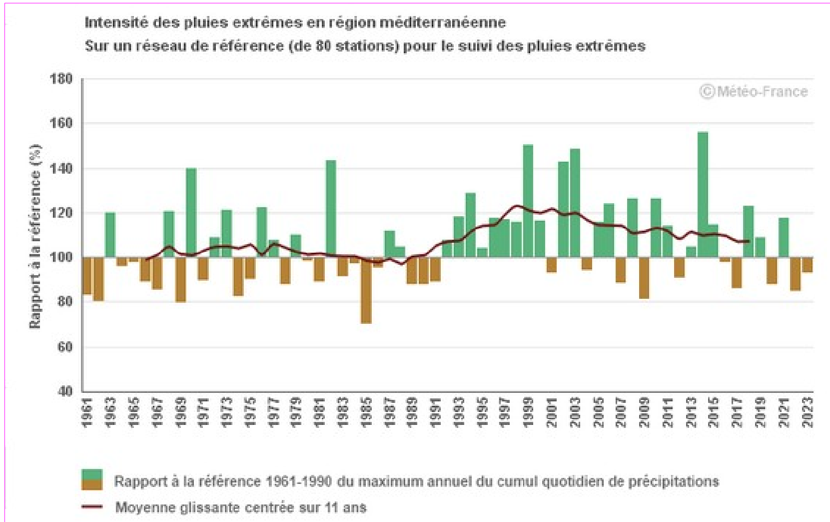
Quel constat du changement climatique ?

PHÉNOMÈNES



Les extrêmes sont des marqueurs du changement climatique en cours. Les vagues de chaleur sont 4 fois plus nombreuses à l'échelle nationale depuis 2000

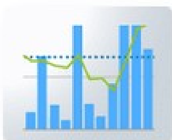
Les précipitations extrêmes sont en hausse sur les régions méditerranéennes

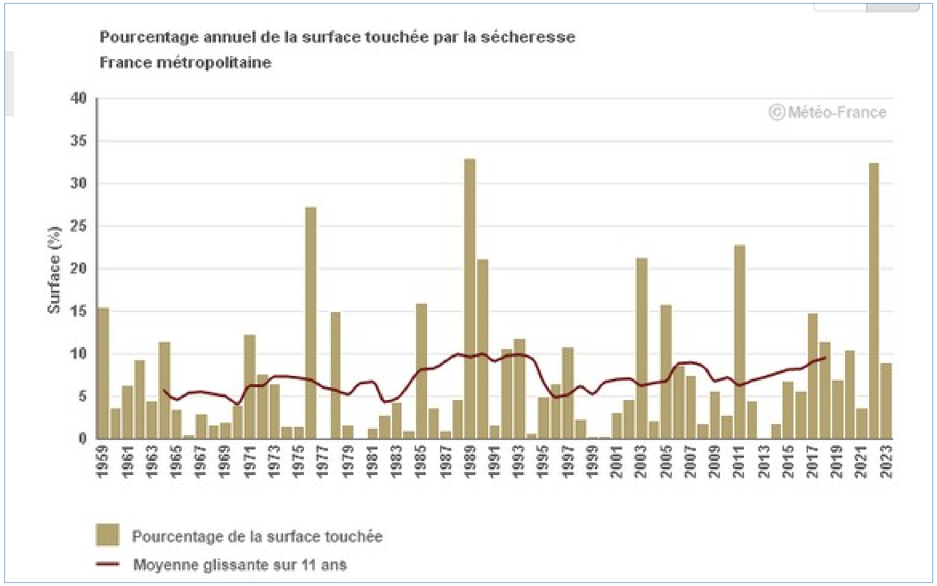


Les pluies extrêmes quotidiennes sur le pourtour méditerranéen sont de plus en plus intenses. Elles sont également caractérisées par une grande variabilité d'une année sur l'autre.

Quel constat du changement climatique ?

IMPACTS

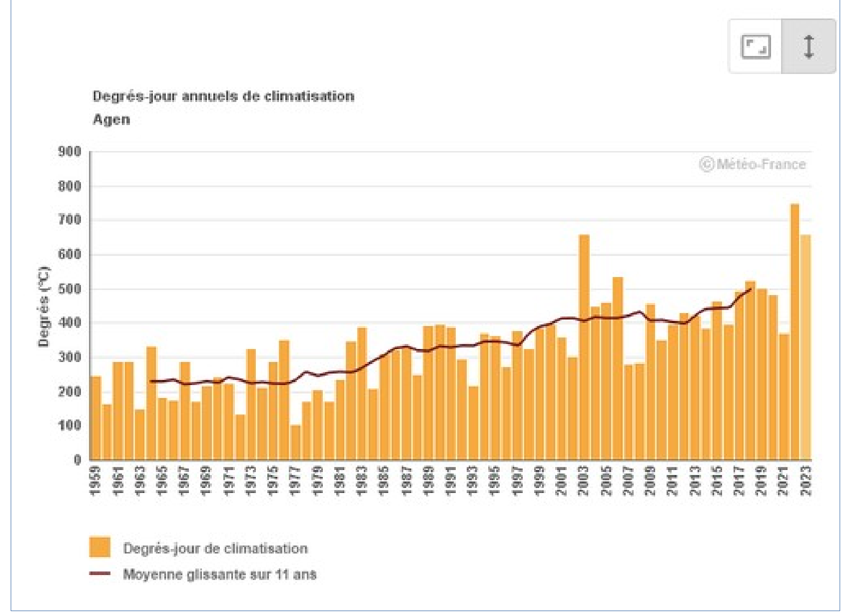




Les sécheresses du sol sont deux fois plus fréquentes que dans les années 1960

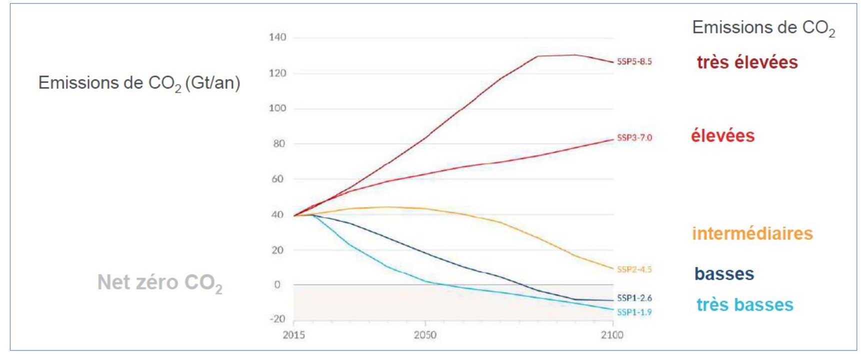
Avec la hausse des températures, les besoins en climatisation s’accentuent rapidement (ici à Agen)

Agen

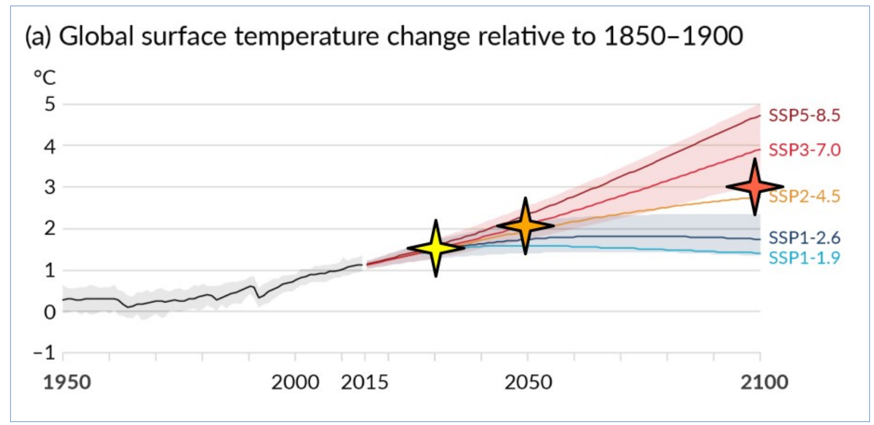


A quel climat se préparer demain ?

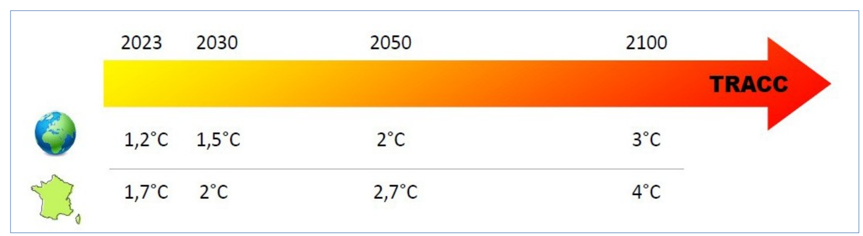
- En climat futur, tout dépend de notre capacité planétaire à limiter nos émissions de GES



- Les projections climatiques modélisent ainsi plusieurs futurs climatiques



- La France s'est dotée en 2023 d'une trajectoire de réchauffement de référence pour l'adaptation au changement climatique (TRACC) basée sur des niveaux de réchauffement planétaires et leur correspondance sur la France Hexagonale



- Météo-France a préparé sur le portail DRIAS un jeu de données climatiques (17 simulations) pour caractériser le climat (avec ses incertitudes) auquel collectivement s'adapter.

https://www.drias-climat.fr/

Quel climat dans une France à +4°C ?

Accompagnement

- Concept & méthodes
- Description des jeux de données et indicateurs
- Aide à la prise en main des données
- Retour d'expérience sur l'utilisation des données
- Fiches diagnostics

Données, Produits

- Accès aux données et indicateurs dans différents formats
- outil de sélection des données

Découverte

Outil cartographique pour la visualisation de certains indicateurs, repères géographiques, fonctions d'import

Quel climat dans une France à +4°C ?

Explorer les 3 horizons de la TRACC

Simulations climatiques pour la métropole

Thème de la modélisation	Domaine géographique	Famille de paramètres	
Métropole - TRACC-2023	Métropole	Indicateurs TRACC	Actualiser le formulaire

Indicateurs: Écart de la température moyenne annuelle - °C

Horizons / Niveaux de réchauffement: --- Choisir les horizons / niveaux de réchauffement ---

Niveaux de réchauffement retenus :
- Référence
- Horizon 2030 / réchauffement +2°C France
- Horizon 2050 / réchauffement +2,7°C France
- Horizon 2100 / réchauffement +4°C France

Modèles et produits multi-modèles: --- Choisir les modèles et/ou produits multi-modèles ---

Modeles retenus :
- médiane de l'ensemble multi-modèles

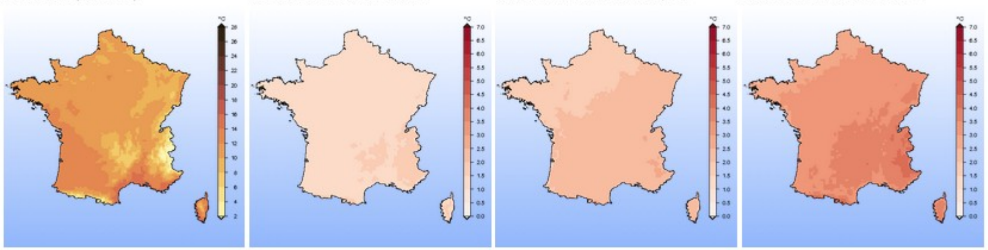
Valider

Simulations climatiques pour la métropole

Température moyenne annuelle : valeur de référence et écart à cette valeur par horizon
Moyenne sur la période autour des horizons

Produit multi-modèles de TRACC-2023 : médiane de l'ensemble

Référence (1976-2005)	Horizon 2030 / France +2°C	Horizon 2050 / France +2,7°C	Horizon 2100 / France +4°C



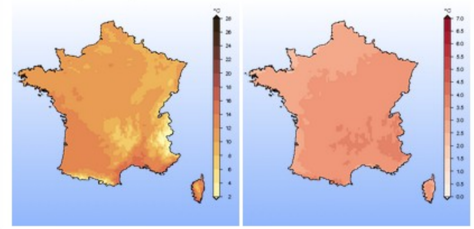
Explorer les incertitudes dans le climat à +4°C

Simulations climatiques pour la métropole

Température moyenne annuelle : valeur de référence et écart à cette valeur par horizon
Moyenne sur la période autour des horizons

Produit multi-modèles de TRACC-2023 : minimum de l'ensemble

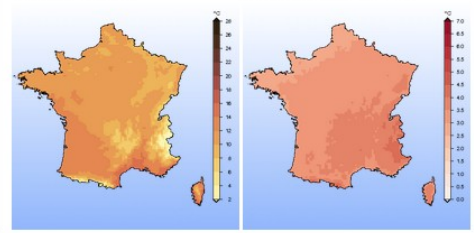
Référence (1976-2005) | Horizon 2100 / France +4°C



Minimum de l'ensemble

Produit multi-modèles de TRACC-2023 : médiane de l'ensemble

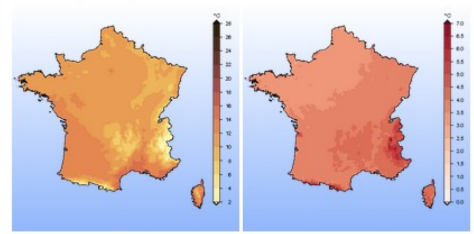
Référence (1976-2005) | Horizon 2100 / France +4°C



Médiane de l'ensemble

Produit multi-modèles de TRACC-2023 : maximum de l'ensemble

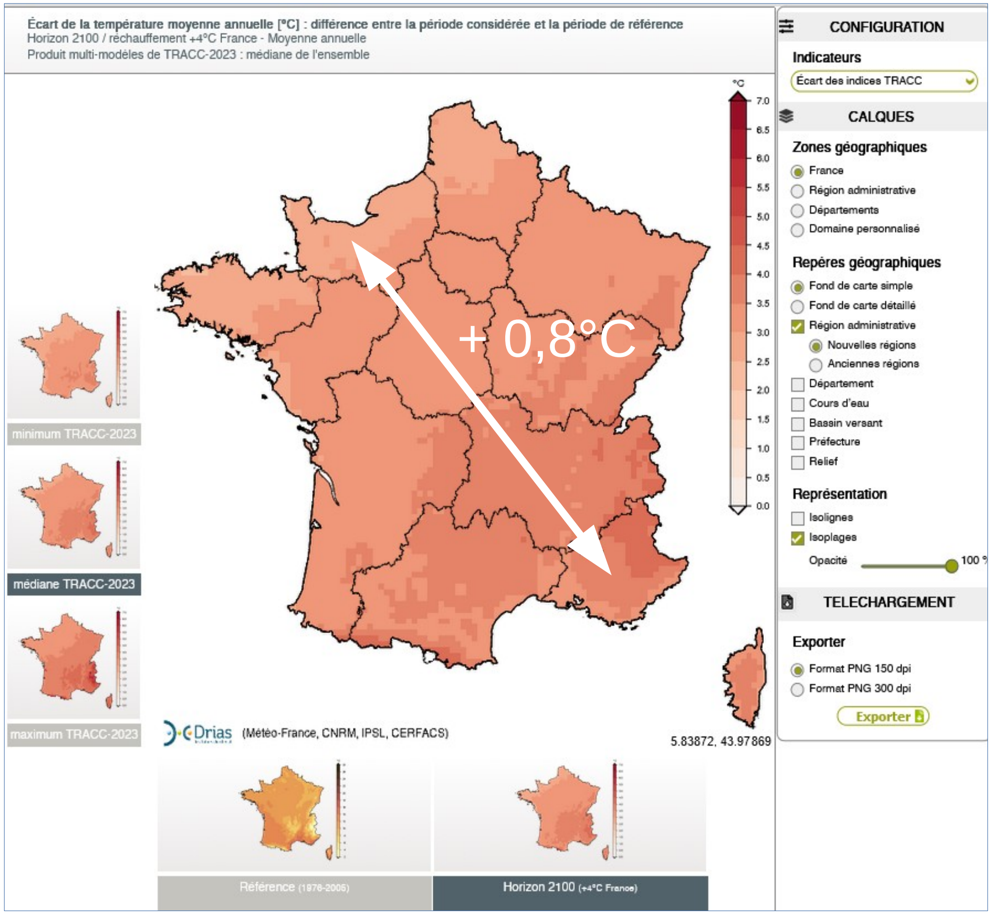
Référence (1976-2005) | Horizon 2100 / France +4°C



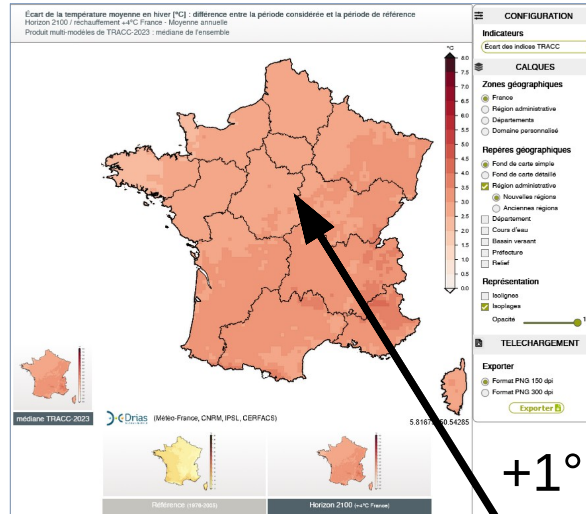
Maximum de l'ensemble

Quel climat dans une France à +4°C ?

Variabilité régionale et saisonnière des températures

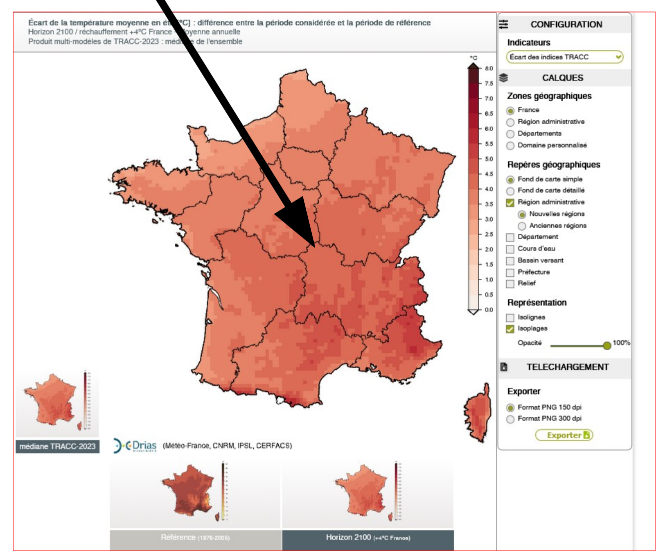


Température moyenne annuelle (médiane)



Température moyenne hiver (médiane)

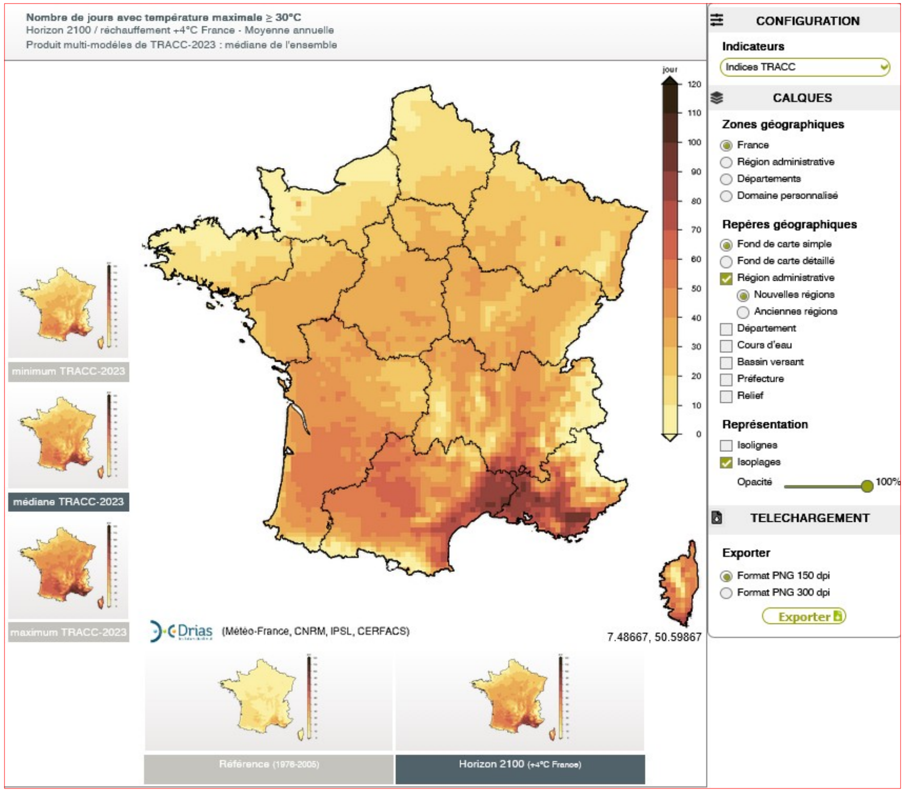
+1°C

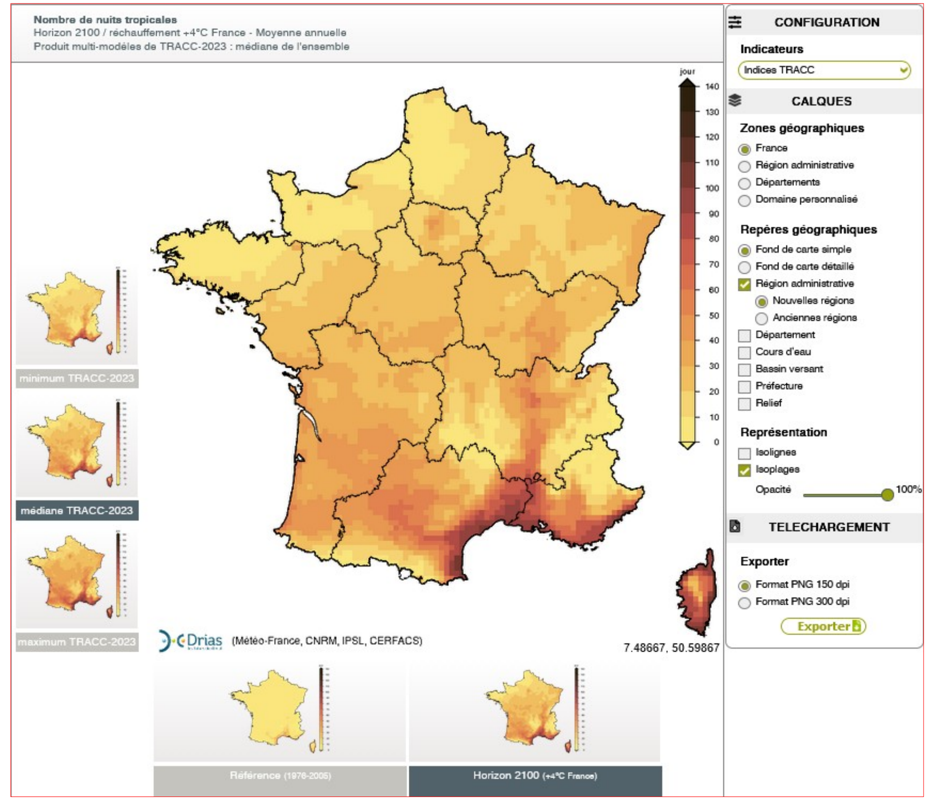


Température moyenne été (médiane)

Quel climat dans une France à +4°C ?

Evolution des extrêmes de température

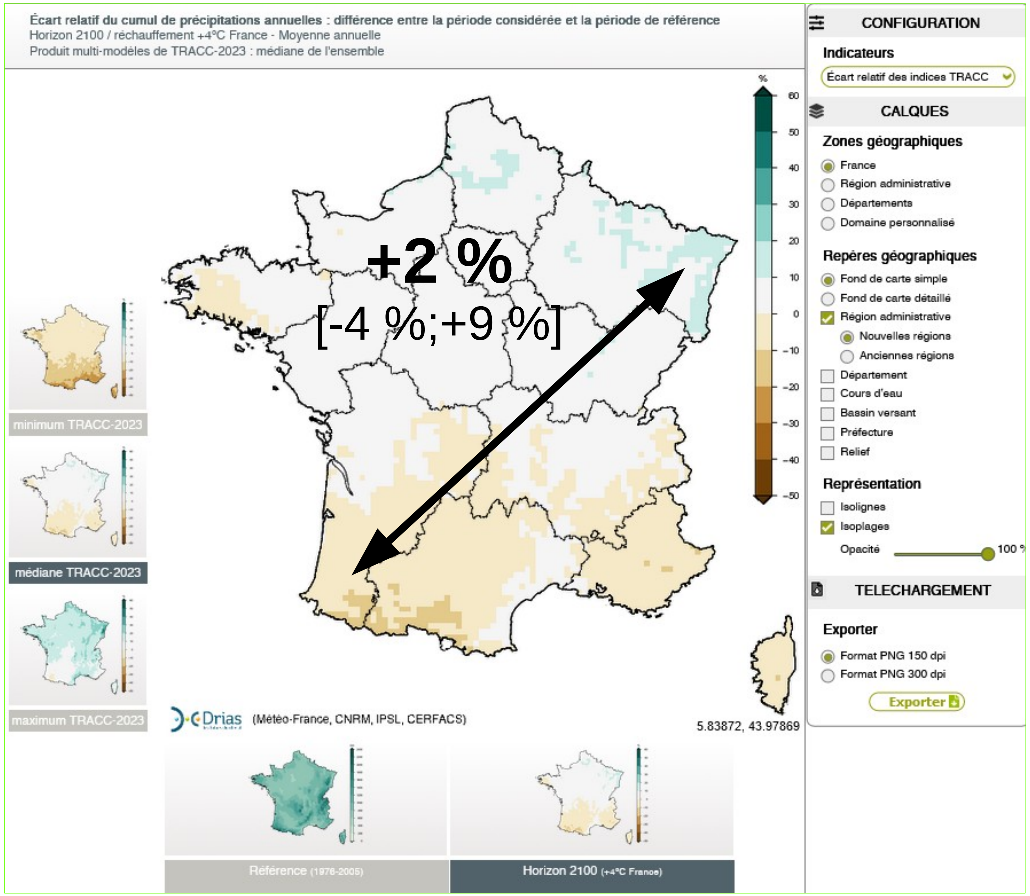


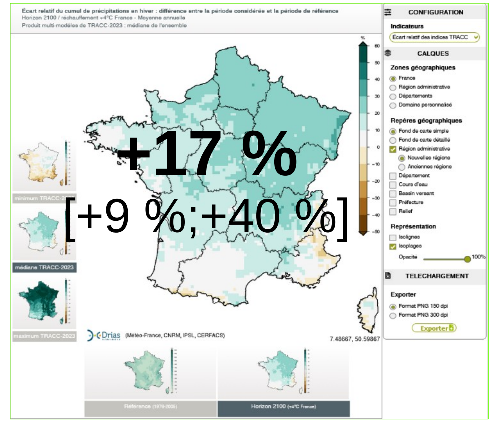


Les conditions de confort thermique évoluent fortement dans la plupart des régions :
- le nombre de journées très chaudes atteint 15 à 40j sur la moitié nord et jusqu'à 90j sur le sud
- le nombre de nuits tropicales atteint 25 en moyenne sur la France et jusqu'à plus de 100 nuits dans les régions méditerranéennes

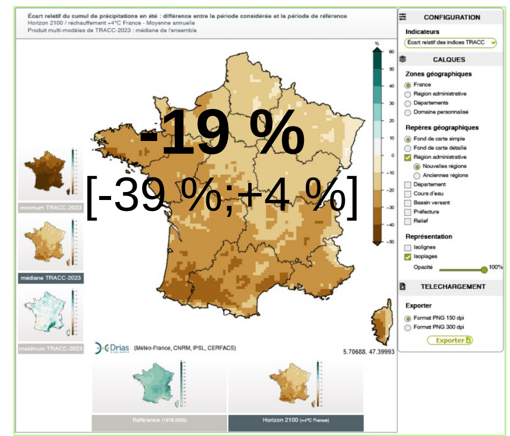
Quel climat dans une France à +4°C ?

Evolution du cumul de précipitation (année, hiver et été)





Evolution du cumul hivernal

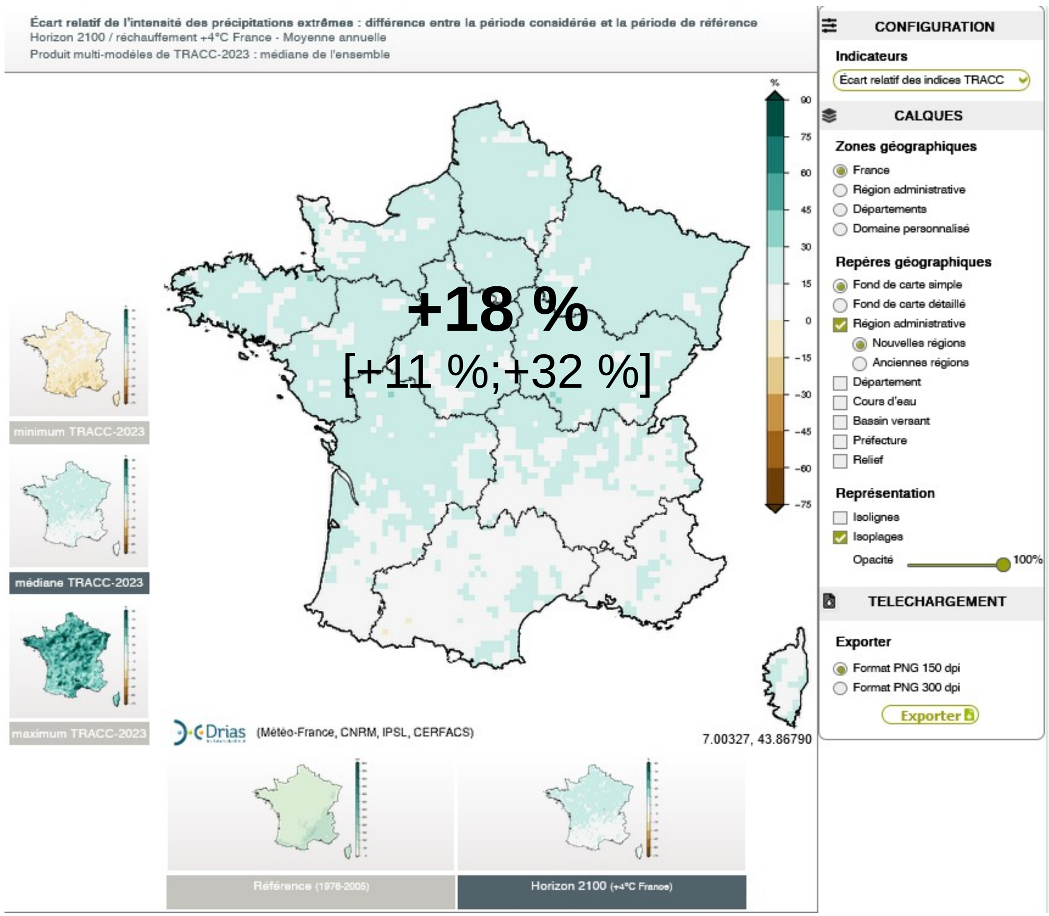


Evolution du cumul estival

L'évolution du cumul annuel de précipitation présente un gradient Nord Est/Sud Ouest mais reste d'une amplitude faible. Le contraste saisonnier des précipitations se renforce

Quel climat dans une France à +4°C ?

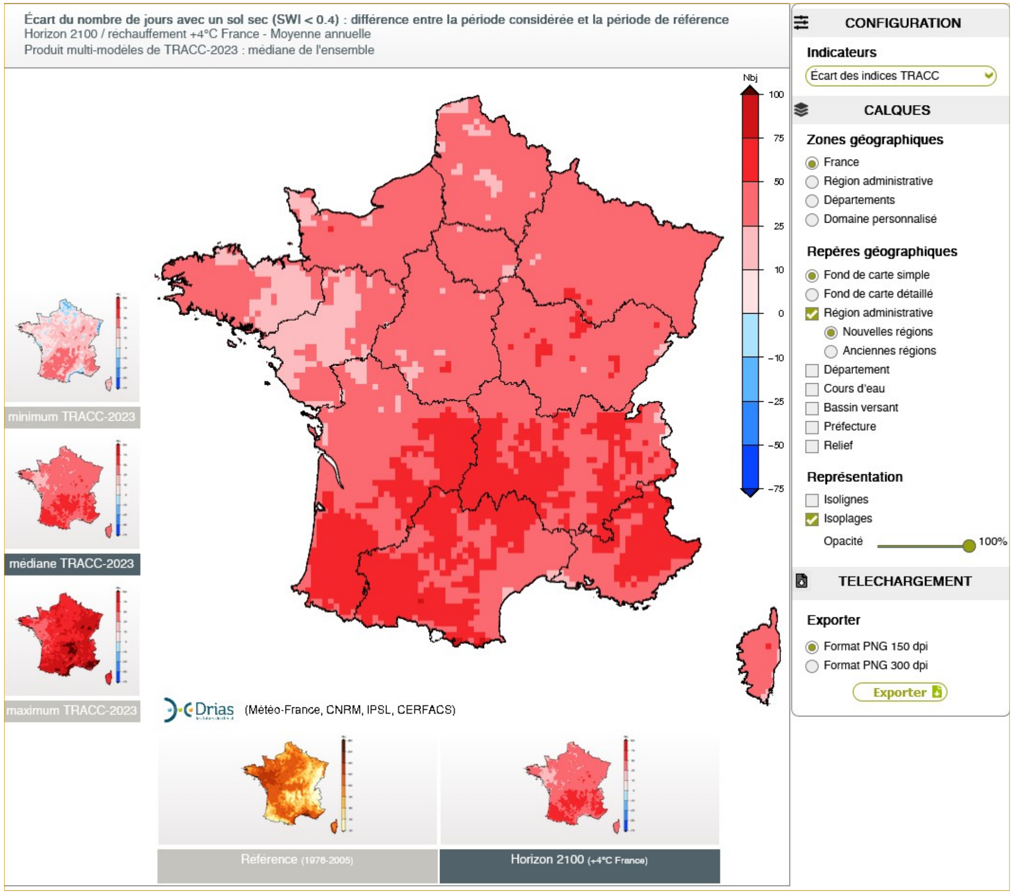
Evolution des extrêmes de précipitation



L'intensité des pluies quotidiennes maximales annuelles se renforce significativement d'environ 20 % en moyenne et plus encore sur la moitié nord.

Quel climat dans une France à +4°C ?

Evolution de la sécheresse des sols

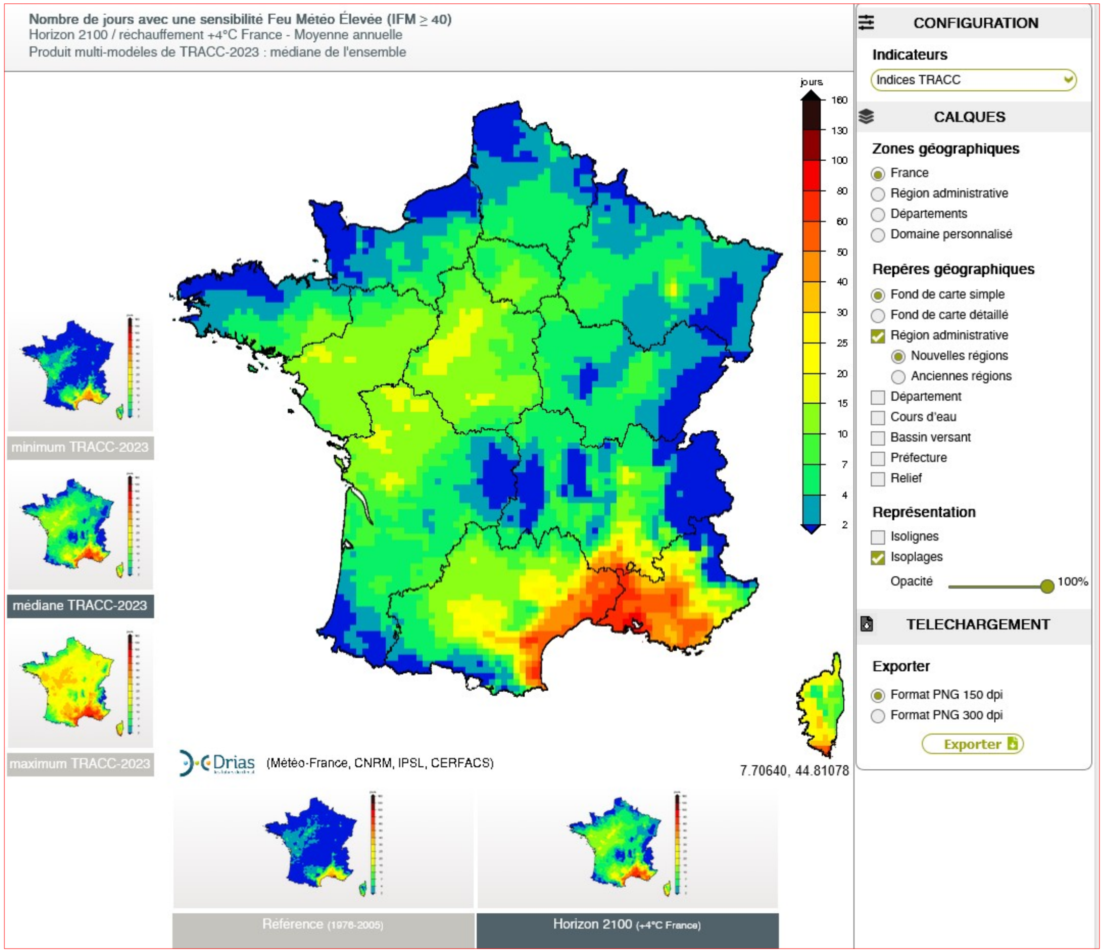


La sécheresse du sol se renforce également avec autour de 30j supplémentaires de jours de sol sec dans la moitié nord et jusqu'à 60j dans la moitié sud

METEO FRANCE
À VOS CÔTÉS, DANS UN CLIMAT QUI CHANGE

Quel climat dans une France à +4°C ?

Evolution du risque de feux



Le nombre de jours de sensibilité feu météo élevée s'étend à l'ensemble du pays (5 à 10j sur la moitié nord) et double sur la moitié sud (jusqu'à 60j)

METEO FRANCE
À VOS CÔTÉS, DANS UN CLIMAT QUI CHANGE

Quel climat dans une France à +4°C ?

Climadiag Commune

https://meteofrance.com/climadiag-commune

L'application climadiag commune permet d'accéder facilement à l'information sur l'évolution du climat dans ma commune selon la TRACC (pour une vingtaine d'indicateurs adaptés aux risques locaux)

Merci de votre attention

https://meteofrance.com/climathd

https://www.drias-climat.fr/

https://meteofrance.com/climadiag-commune

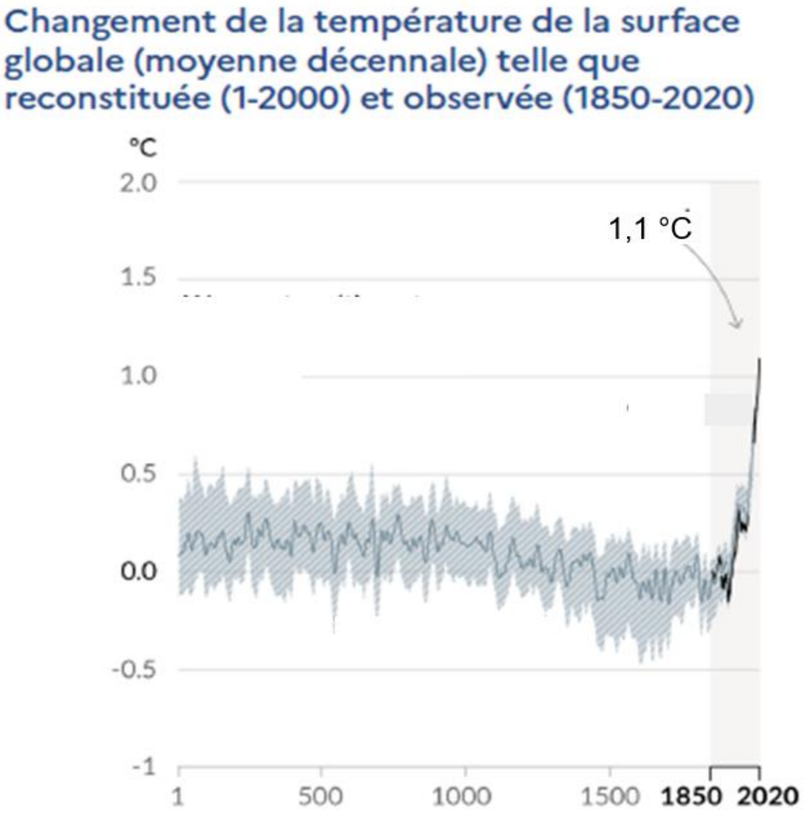
MINISTÈRE
DE LA TRANSITION
ÉCOLOGIQUE,
DE L'ÉNERGIE, DU CLIMAT
ET DE LA PRÉVENTION
DES RISQUES

Liberté
Égalité
Fraternité

CYCLE « L'ADAPTATION : ENJEUX, DÉMARCHES, DONNÉES ET OUTILS »

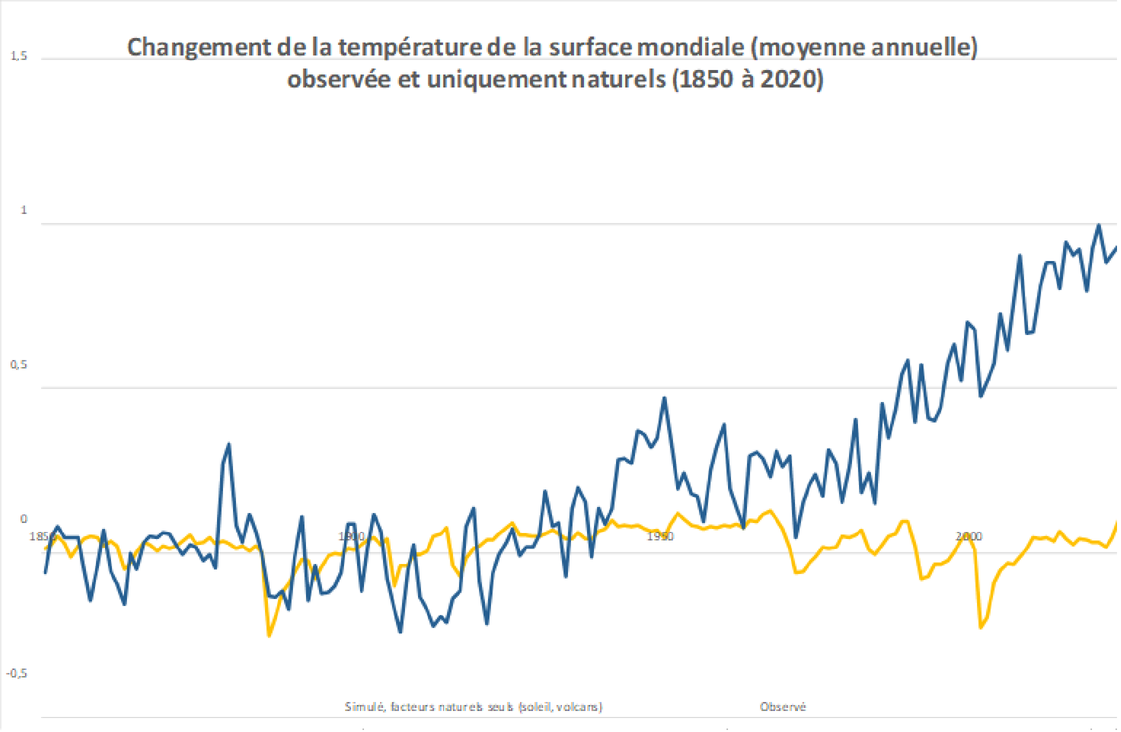
RAPPELS DU WEBINAIRE 1

Des changements sans précédents depuis plusieurs milliers d'années



Source : GIEC, 2022

Des changements non naturels



Source : GIEC, 2022

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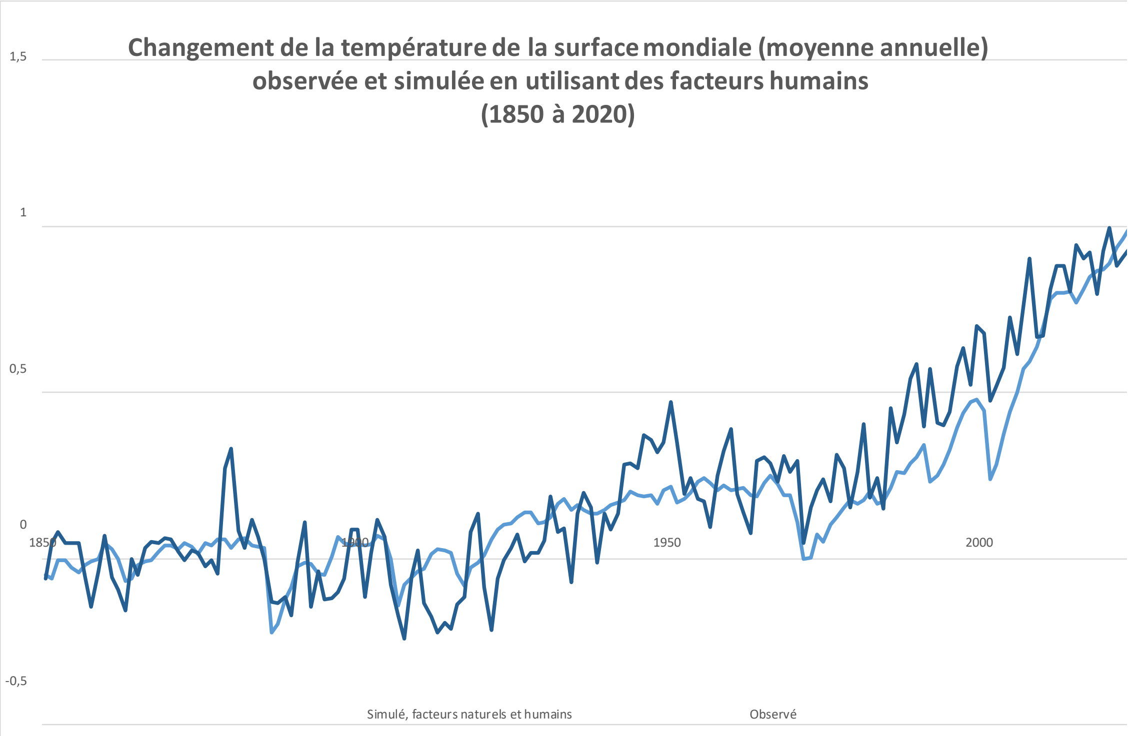
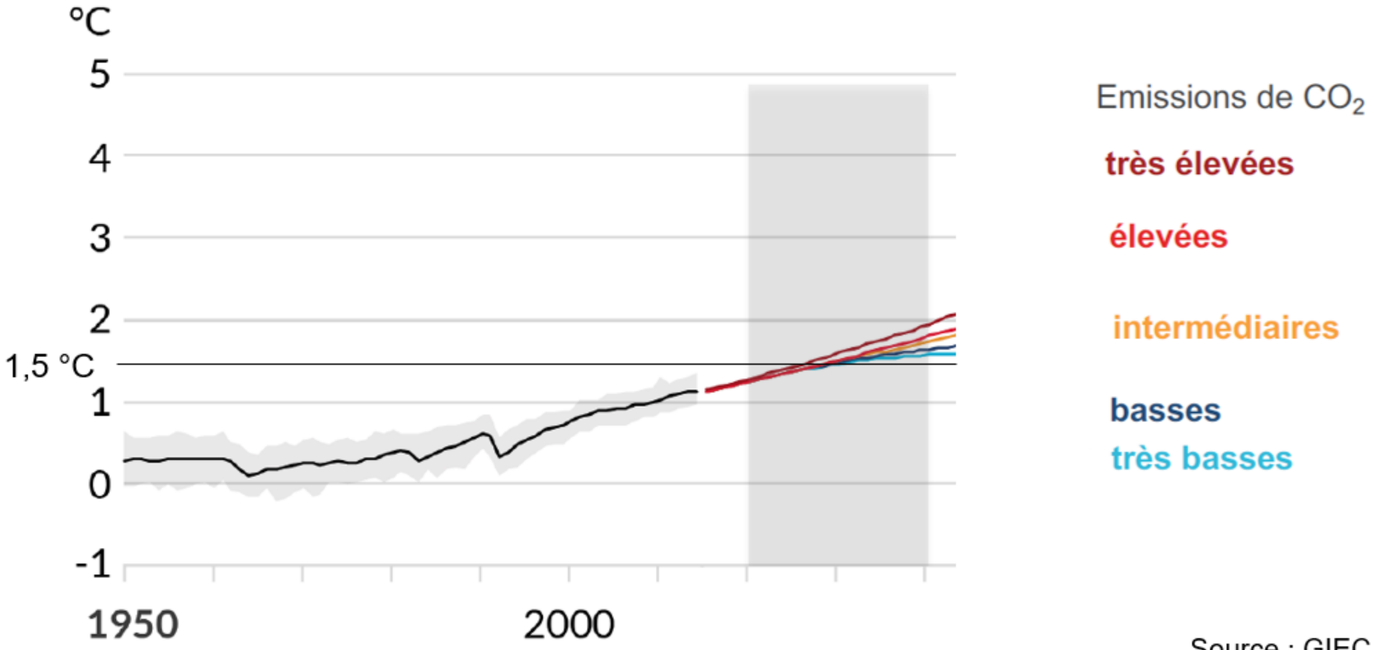
mais anthropiques

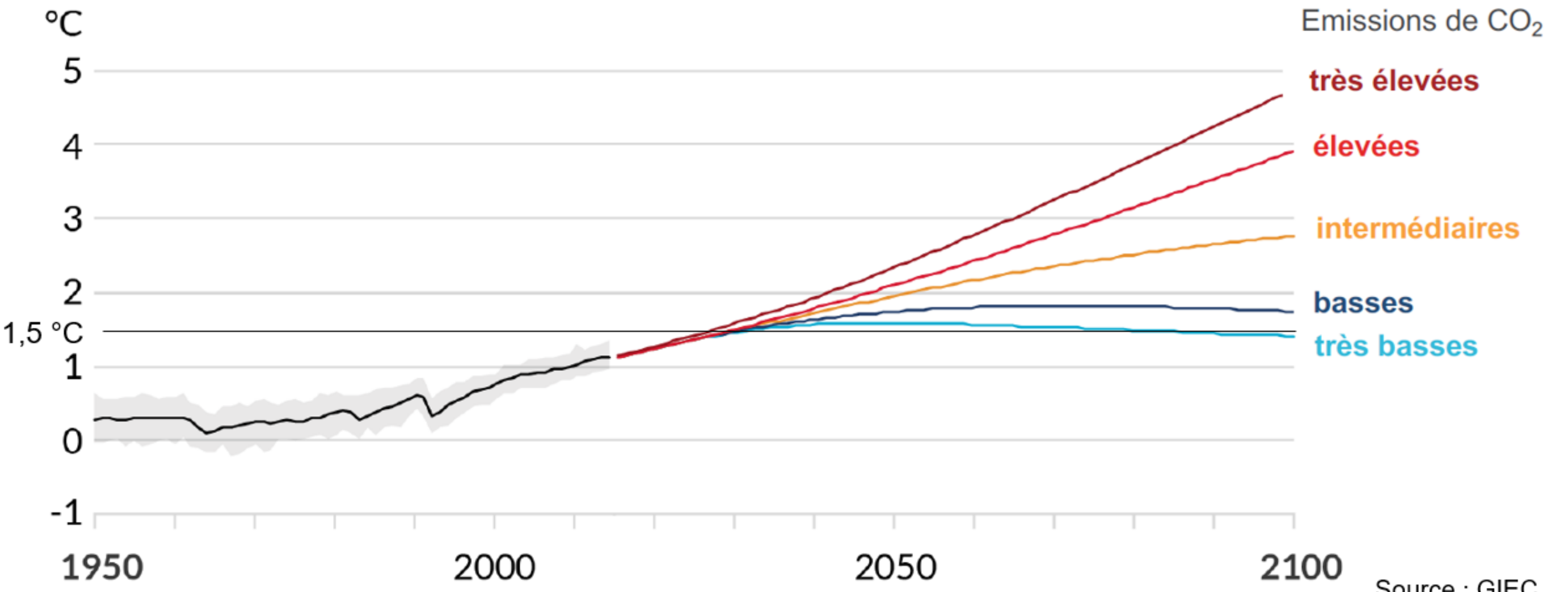


Source : GIEC, 2022

Quel sera le climat futur ?



Source : GIEC, 2022



Source : GIEC, 2022

Les tendances actuelles

- Le réchauffement climatique mondial atteindra +1,5°C dès le début des années 2030
- Limiter le réchauffement climatique mondial à +2°C implique de très fortes réductions des émissions mondiales dès la décennie 2021-2030
- Les engagements des Etats annoncés avant octobre 2021 conduisent à un réchauffement médian de 2.8°C en 2100. Les politiques mondiales en place fin 2020 conduisent à un réchauffement médian de 3.2°C en 2100
- Les scénarios à très fortes émissions sont devenus moins probables

→ Proposition de retenir pour trajectoire de réchauffement de référence :

- +1,5°C en 2030, +2°C en 2050, +3°C en 2100 au niveau mondial
- Soit +2°C en 2030, +2,7°C en 2050, +4°C en 2100 en France hexagonale

L’INTÉRÊT DU CONCEPT D’HABITABILITÉ POUR S’ADAPTER AU CHANGEMENT CLIMATIQUE

L’intérêt d’une démarche d’évaluation interdisciplinaire pour dépasser les frontières scientifiques et soutenir l’action publique

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virginie.duvat@univ-lr.fr

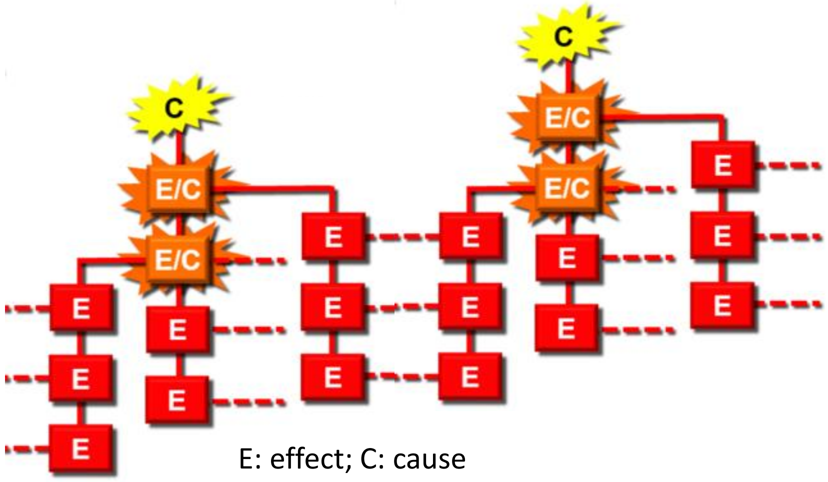
SUBMERSION DUE AUX HOULES D’ORIGINE LOINTAINE DE JUILLET 1996
Atoll de Tikehau, Polynésie française (© B. Marty)

Introduction : évolution du risque climatique et rôle de l’adaptation au changement climatique

À l’heure des risques combinés
Facteurs d’Impact Climatique ou CID

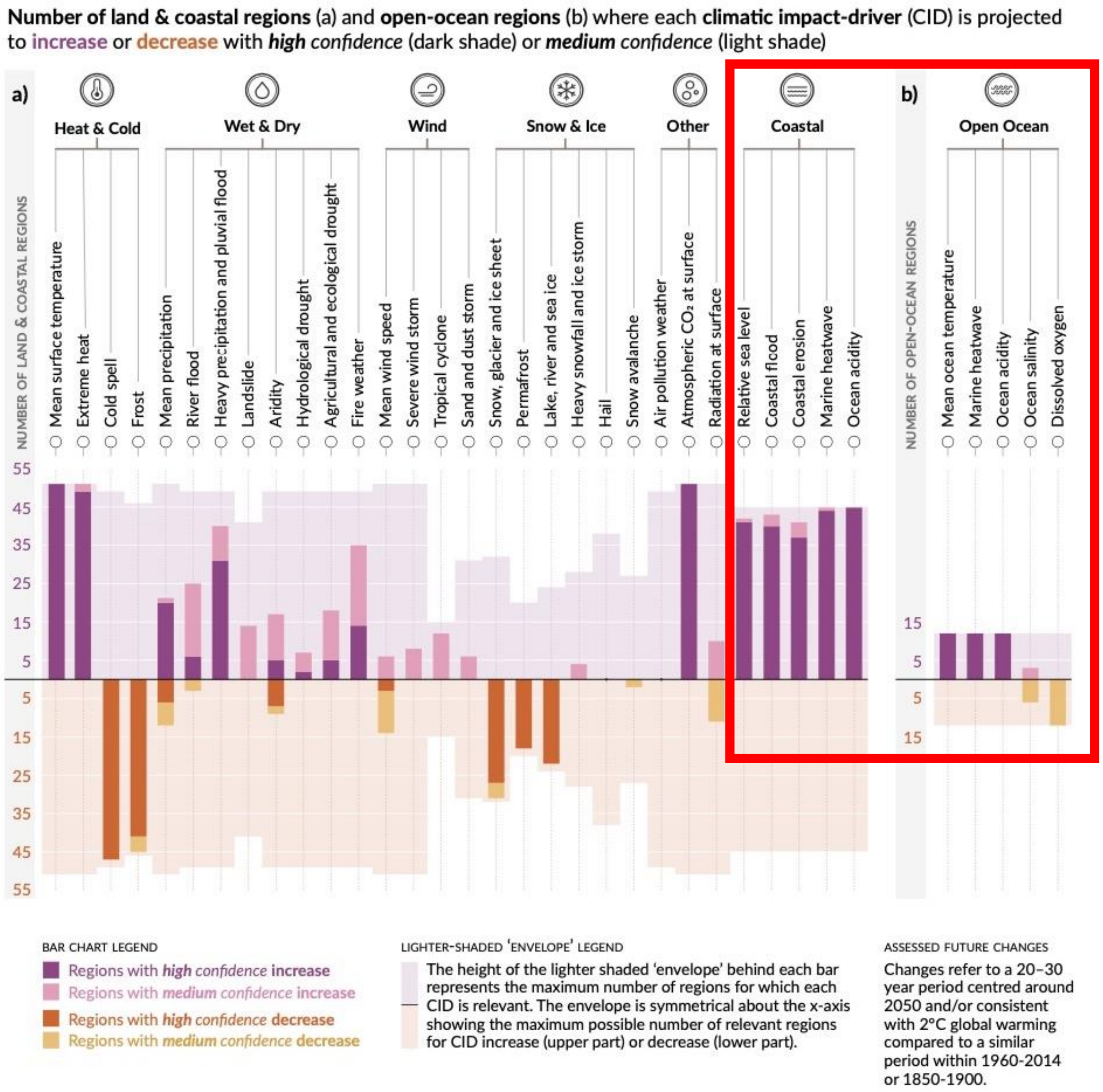
- Dans 96 % des régions du globe, plus de 10 paramètres climatiques sont affectés par le changement climatique

Complexification, accumulation et amplification des impacts



E: effect; C: cause

Pescaroli & Alexander, 2015



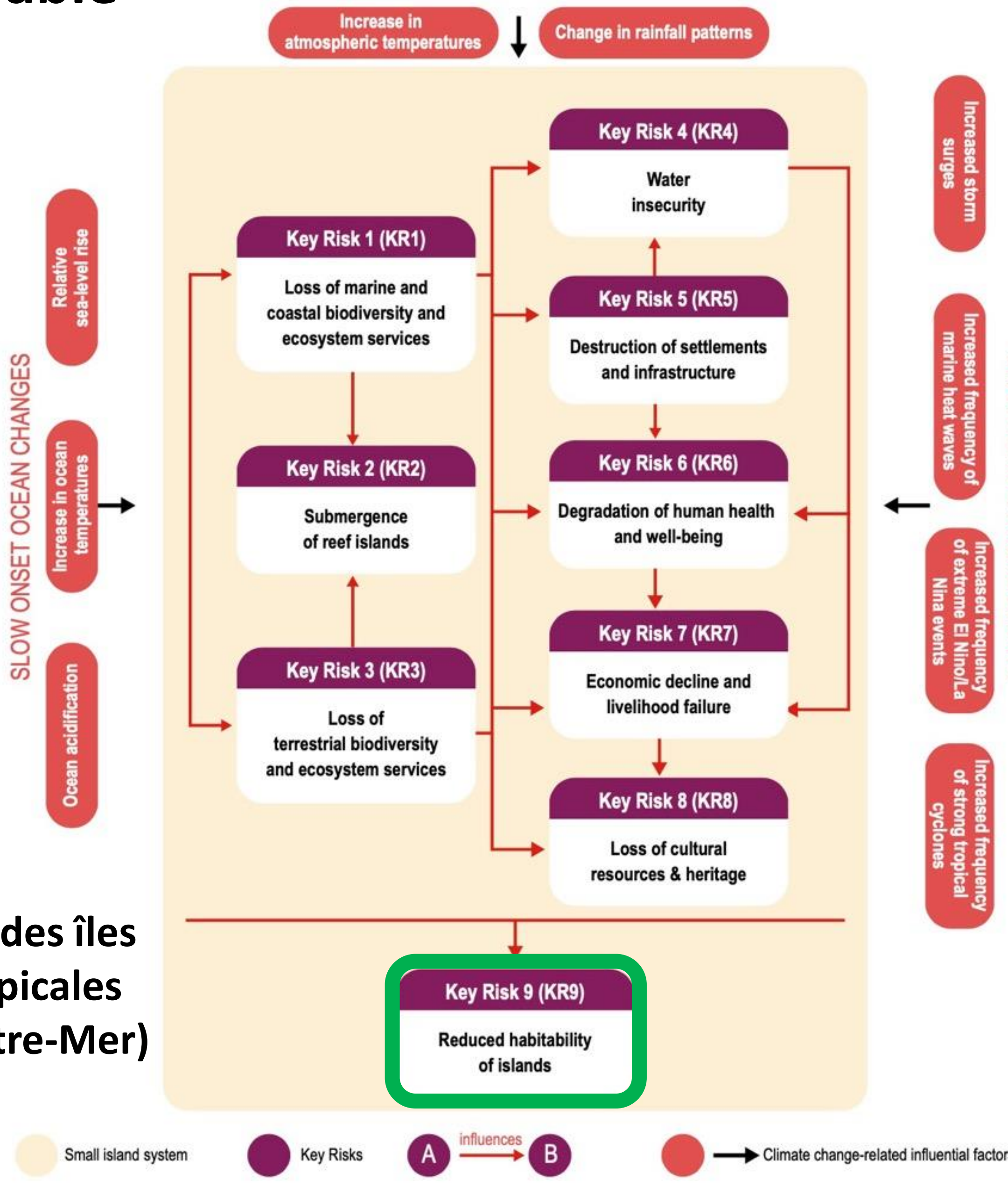
Vers une crise climatique aiguë, totale et durable

- ➔ Risques **combinés**
- ➔ Risques **majeurs**
- ➔ Risques **émergents**
- ➔ **Risque systémique** générateur d'une dégradation significative des conditions de vie sur les territoires

Perte d'habitabilité des Territoires

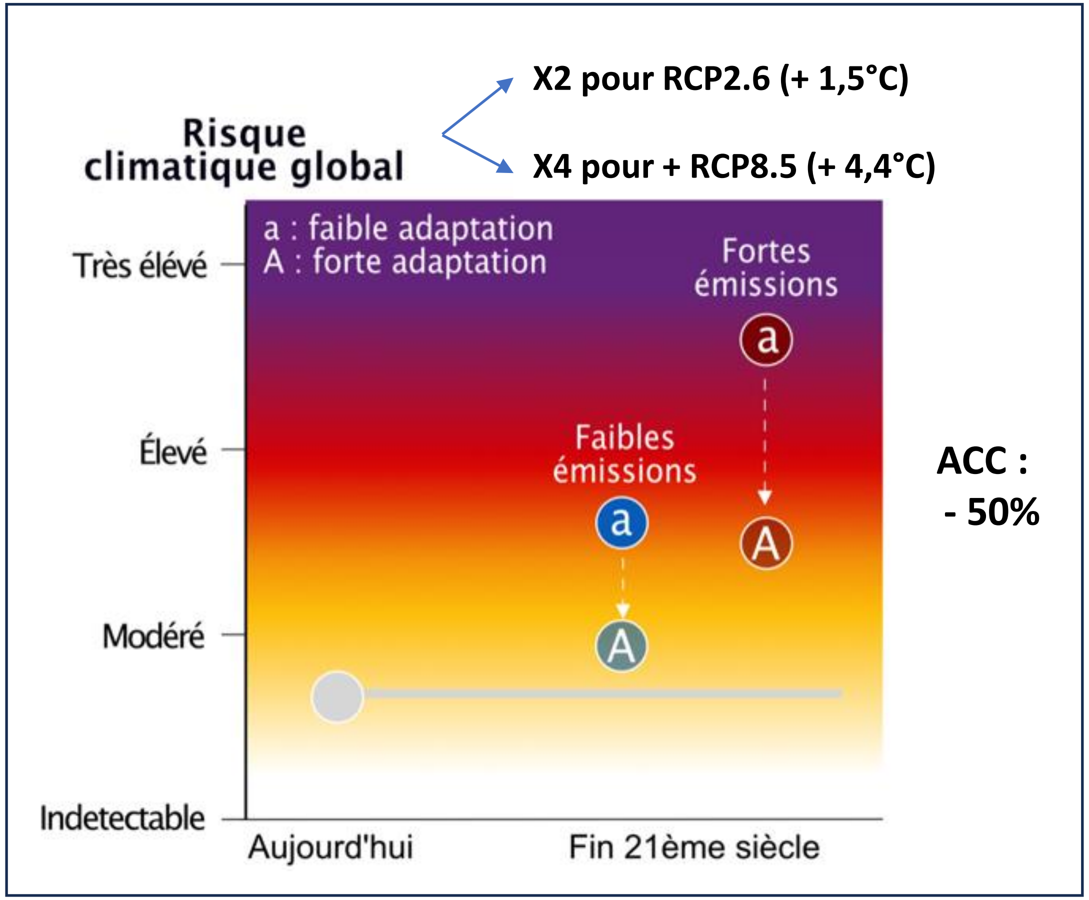
Ex : littoral, îles basses

Ex. des îles tropicales (Outre-Mer)



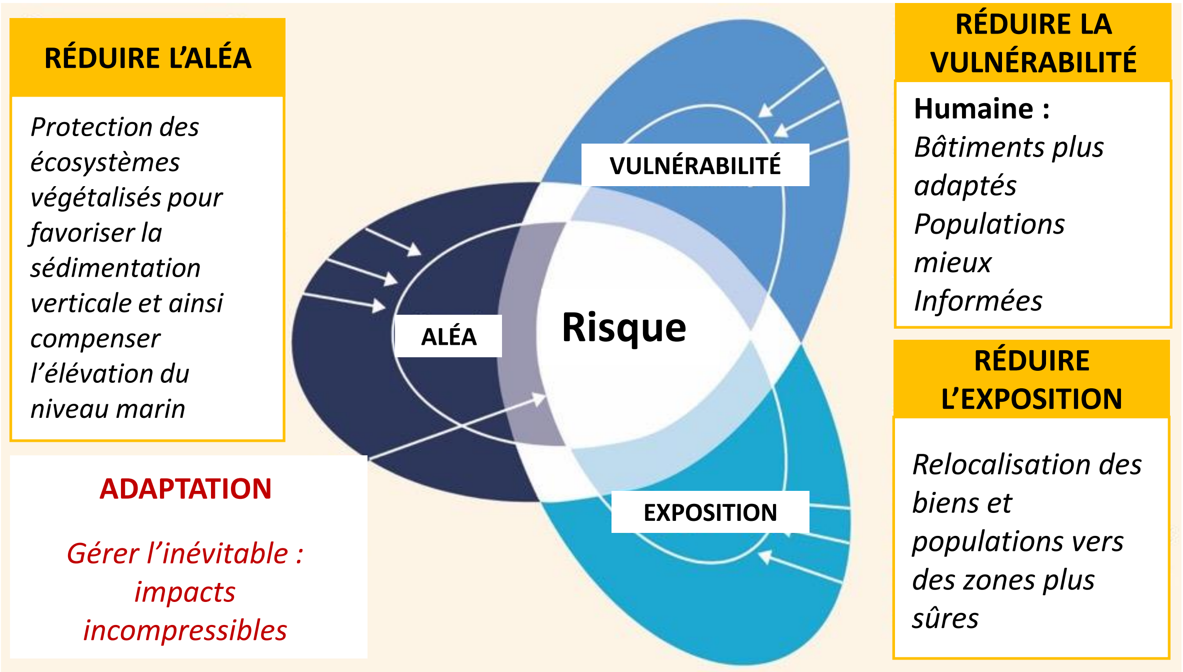
AR6, Mycoo et al., 2022

Le risque climatique global va doubler à quadrupler d'ici à 2100 !



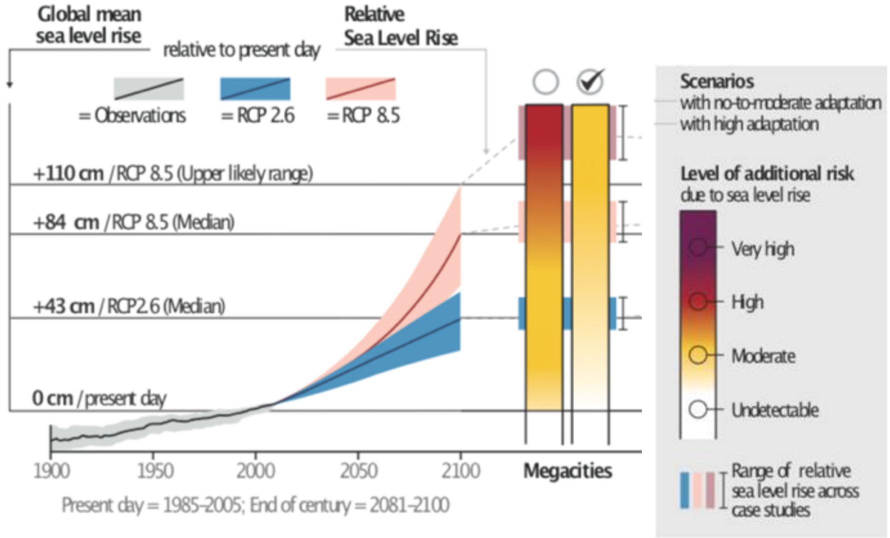
Magnan et al. 2021. Estimating the global risk of anthropogenic climate change. Nature Climate Change. https://doi.org/10.1038/s41558-021-01156-w

L'ACC réduit le risque climatique de 50%



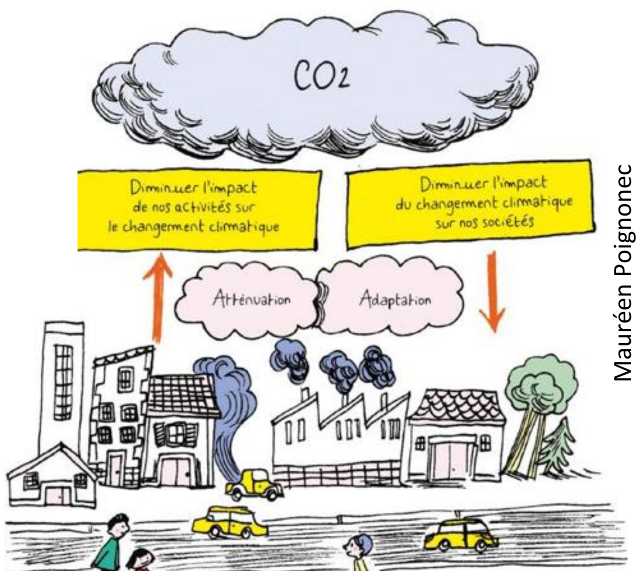
D'après GIEC, 2019

Ex. des villes côtières



⇒ L'adaptation (transformationnelle) est cruciale, d'autant que l'adaptation accuse un retard important !

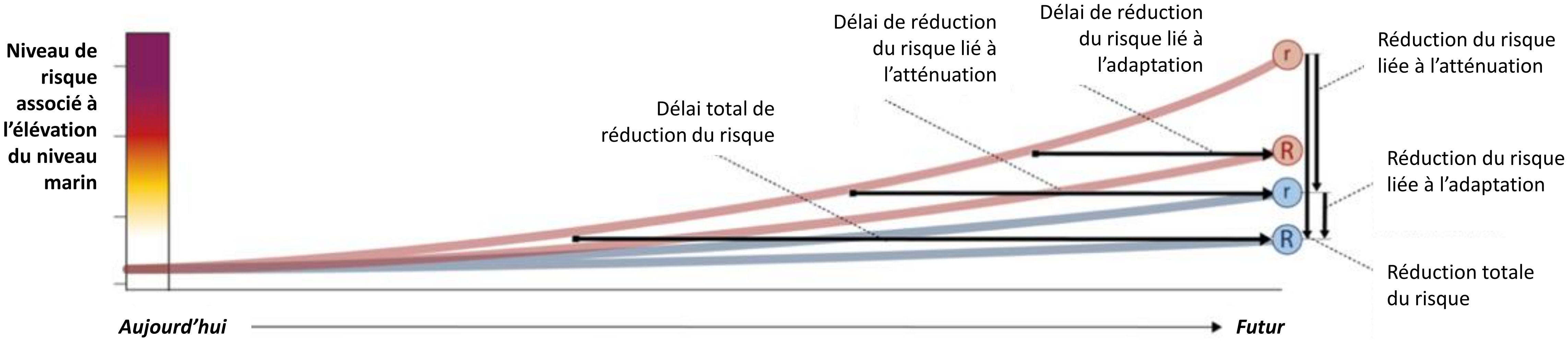
Exploiter les effets de synergie entre atténuation & adaptation



Mauréen Poignonec

1. Adaptation = délai de réduction du risque < atténuation
2. Adaptation = contribution significative à la réduction du risque

Bénéfices comparés de l'adaptation et de l'atténuation



r: réponse nulle à modérée
R: réponse optimale

En rouge : Scénario climatique à fortes émissions (RCP 8.5)
En bleu : Scénario climatique à faibles émissions (RCP 2.6)

IPCC, SROCC, 2019

⇒ Mais justement, quelle approche pour faire face aux défis de l'adaptation transformationnelle à des risques climatiques majeurs, évolutifs et systémiques ?

De l’intérêt du concept d’HABITABILITÉ pour s’adapter au changement climatique

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ADVANCED REVIEW

WIREs CLIMATE CHANGE WILEY

Risks to future atoll habitability from climate-driven environmental changes

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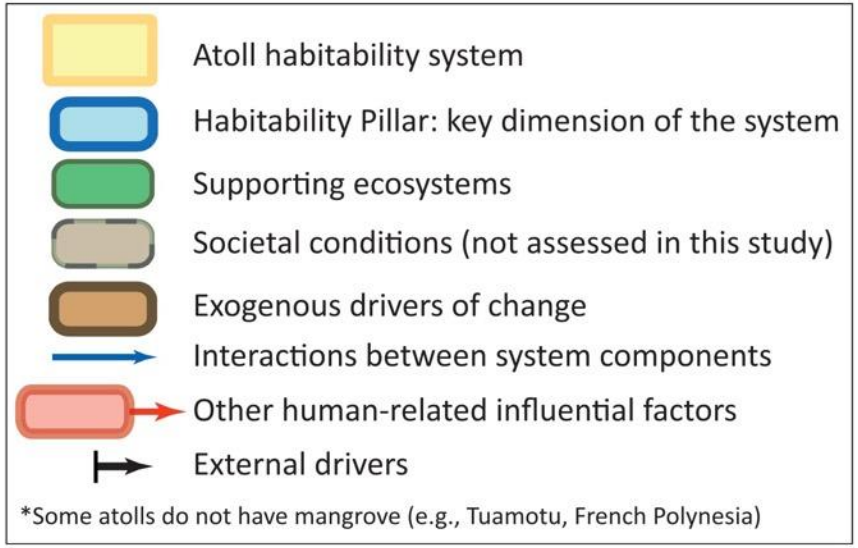
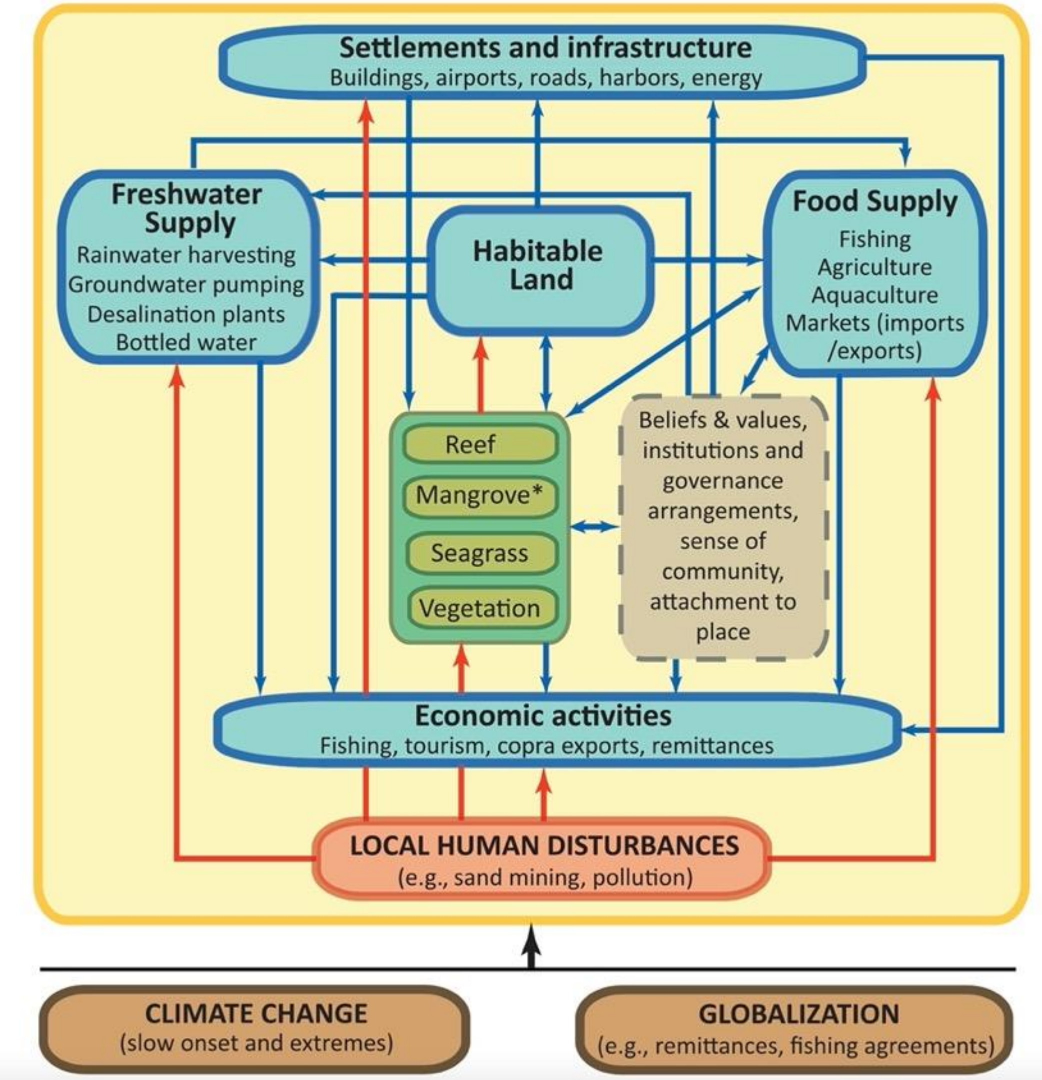
Un concept récent dans le champ de la science climatique

Définition de l’habitabilité (*Duvat et al., 2021*)

Capacité d’un territoire à fournir durablement à une société donnée :
- Des terres émergées suffisamment étendues et sûres
- Un environnement bâti et infrastructurel adéquat
- Les ressources vitales nécessaires (eau, alimentation)
- Des opportunités de développement économique
Pour contribuer à la santé et au bien-être humain, en s’appuyant sur et en préservant les écosystèmes, tout en prenant en compte les valeurs et modes de gouvernance de la société concernée



Modèle conceptuel de l’habitabilité (ex. atoll)



Duvat et al., 2021

Démonstration de l’intérêt de ce concept pour évaluer le risque de perte d’habitabilité des territoires

Exemple des atolls, mais réplicable à tout type de territoire

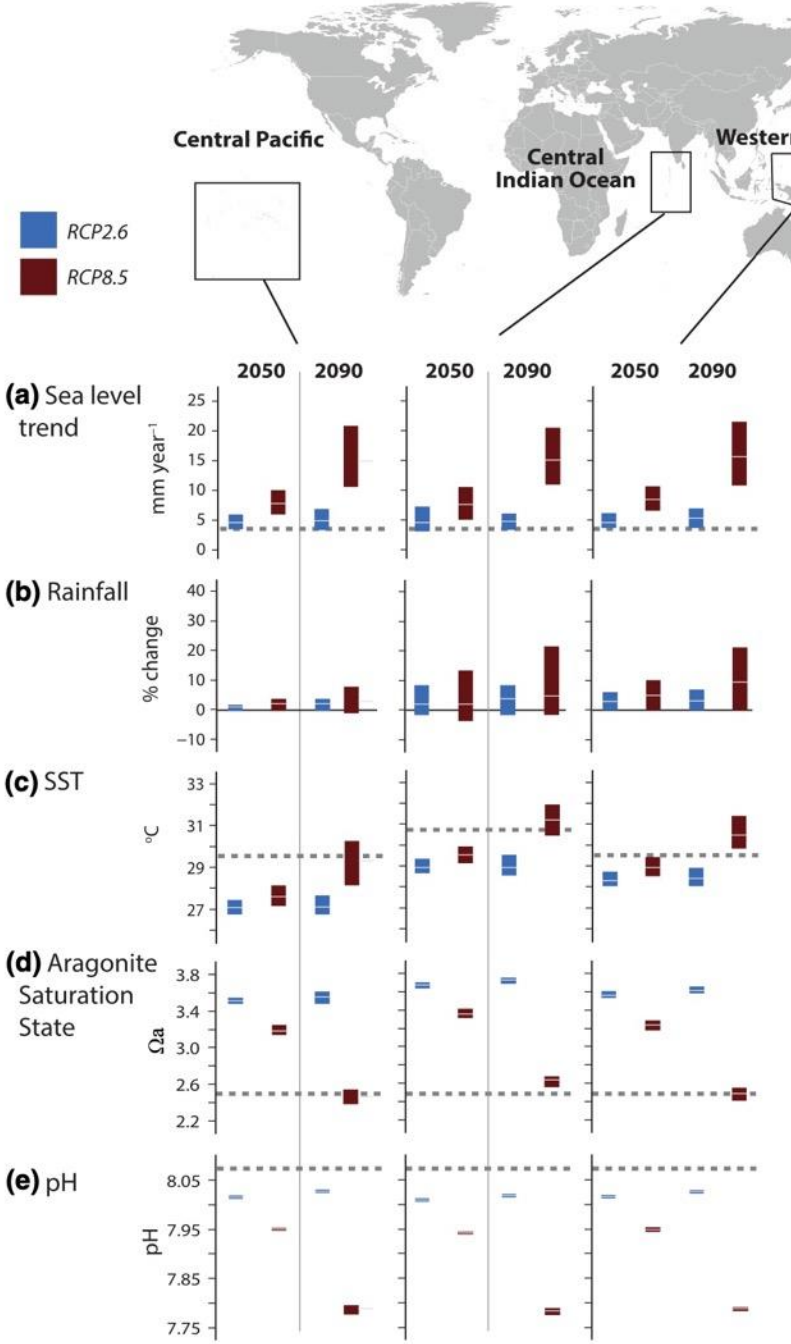
Étape 1 – Mobiliser les projections relatives à l’évolution des conditions climatiques et océaniques…

-> Ne pas considérer que l’élévation du niveau de la mer, mais l’ensemble des pressions climatiques et océaniques et leurs interactions

-> Considérer la variabilité régionale de ces pressions et de leur évolution

-> Considérer deux pas de temps (2050 + 2090) et pas seulement la fin de siècle

-> Considérer plusieurs scénarios climatiques et pas seulement le scénario pessimiste RCP8.5



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

… pour calculer un indice régional d’exposition au risque climatique

Avantage : offrir une vision régionale du niveau de pression climatique à deux pas de temps et selon deux scénarios climatiques

-> Permettrait des comparaisons entre régions au sein de l’Hexagone et entre les Outre-Mer

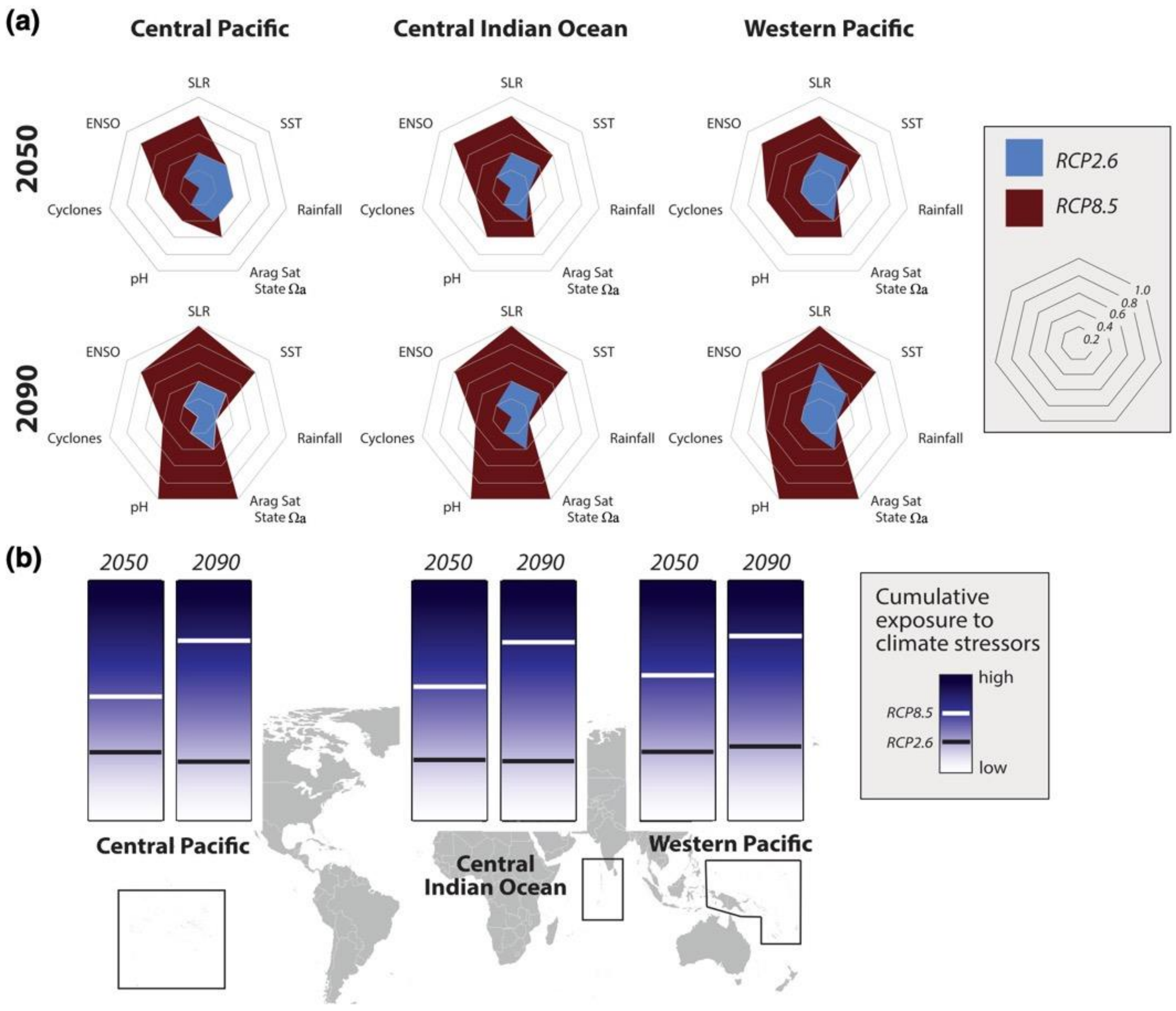
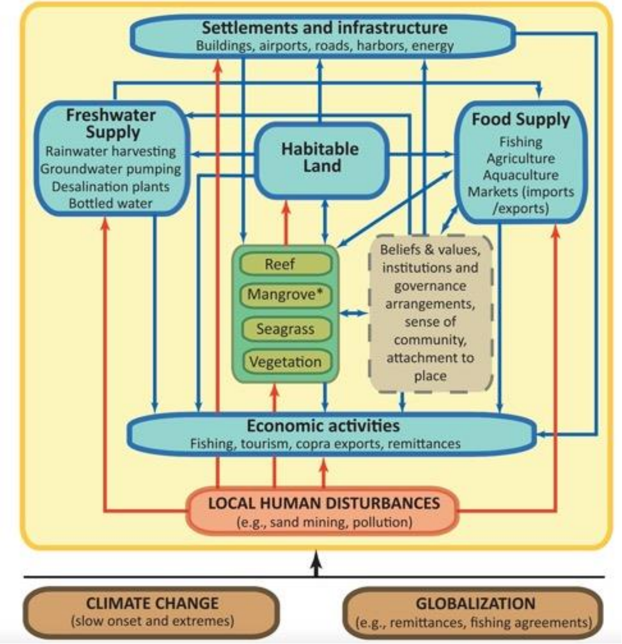


FIGURE 4 Cumulative climate change threats and related exposure of atoll regions, for two emission scenarios in 2050 and 2090, based on mean projected rates of change. SM3.1 provides the full details. Panel a illustrates the cumulative climate and climate-related ocean threats (high = 1.0, low = 0.0) 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)

Évaluation du risque climatique futur ($21^{ème}$ siècle) pesant sur chaque pilier de l'habitabilité



14 variables pour évaluer le risque de perte d'habitabilité

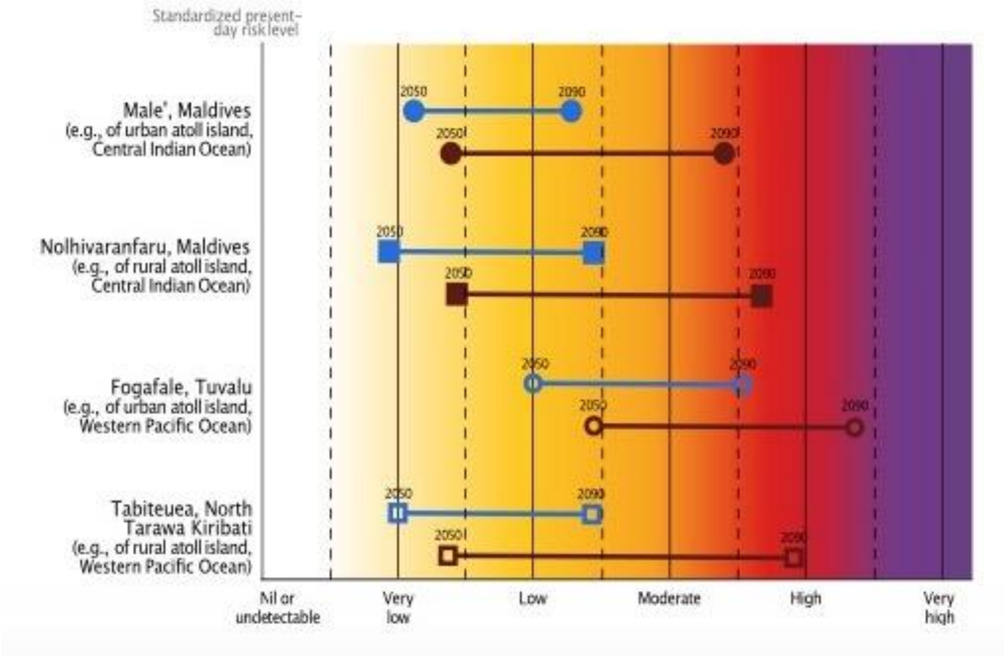
Step 1

- Risk criteria identification for each Habitability Pillar (HP)
- Design of the assessment method

- Land (HP1): coastal erosion, marine flooding
- Freshwater supply (HP2): fresh groundwater salinization, decrease in rainwater harvesting, decrease in desalination
- Food supply (HP3): reduced reef fish production, redistribution of tuna, reduced crops and livestock production
- Settlements and infrastructure (HP4): loss of settlements, critical infrastructure and transport connectivity
- Economic activities (HP5): reduction in tuna fisheries revenues, tourism revenue, and other revenue streams

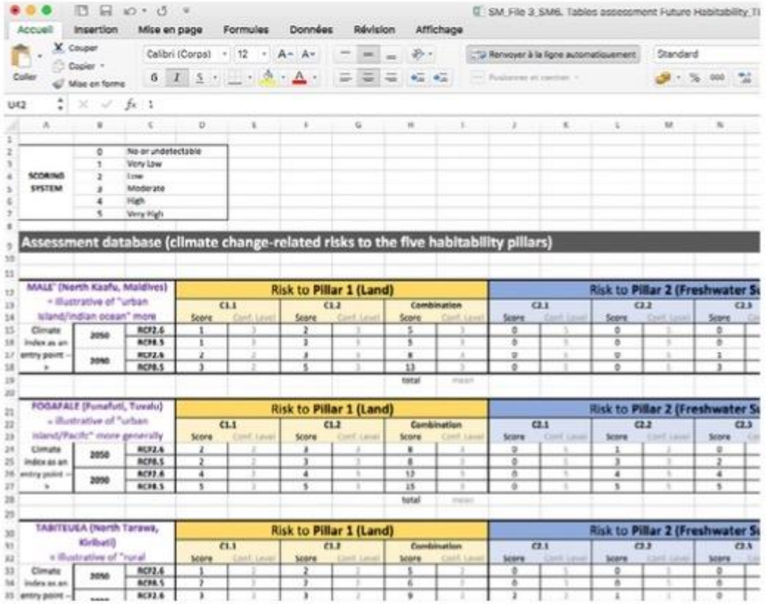
Step 2

- Scoring system, from 0 (“undetectable” additional risk from climate stressors) to 5 (very high contribution)
- Under RCP2.6 and RCP8.5
- In 2050 and 2090
- Application to the 4 case studies
- Expert judgment (set of 2–4 authors), based on case study-oriented papers, available datasets, review of the general literature, and authors' own expertise

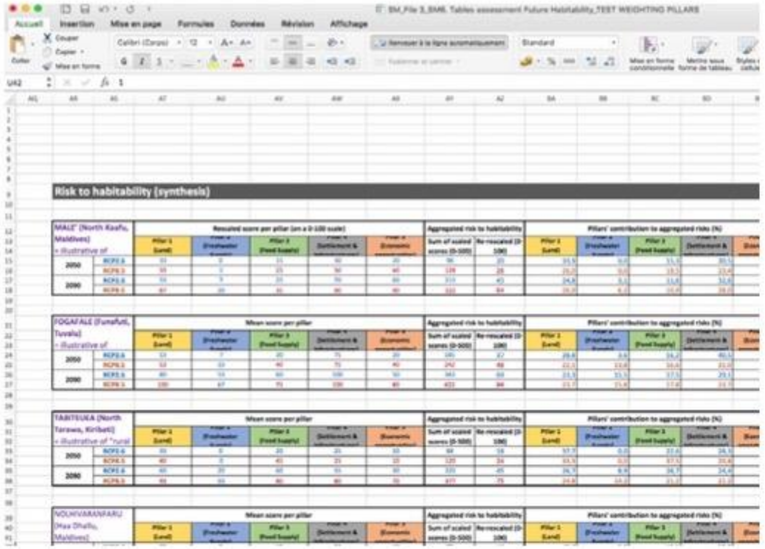


Excel database *(SM_File 3_SM6)*

Risk criteria level



HP level



Step 3

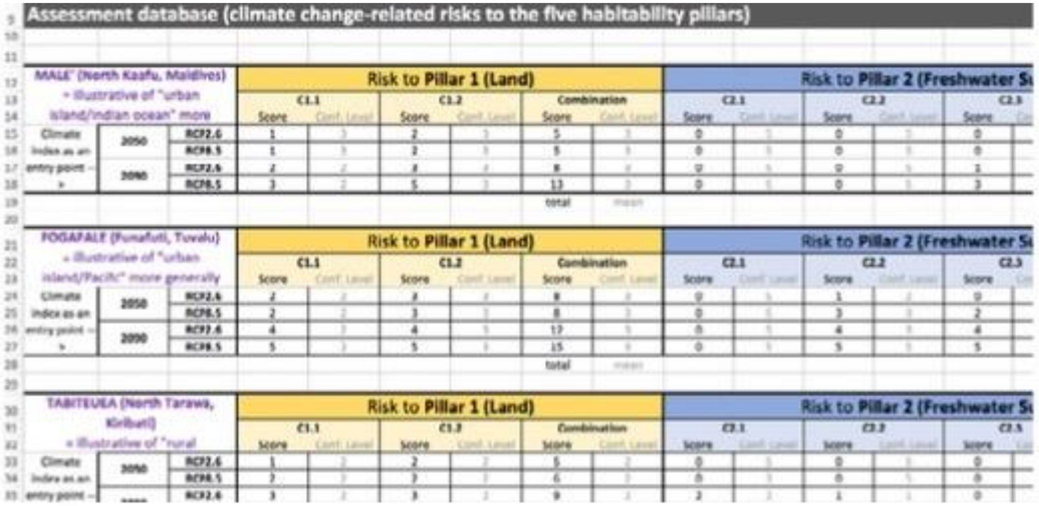
- Confidence level, from low (1) to medium (2) and high (3)
- For each criteria score
- Expert judgment

Step 4

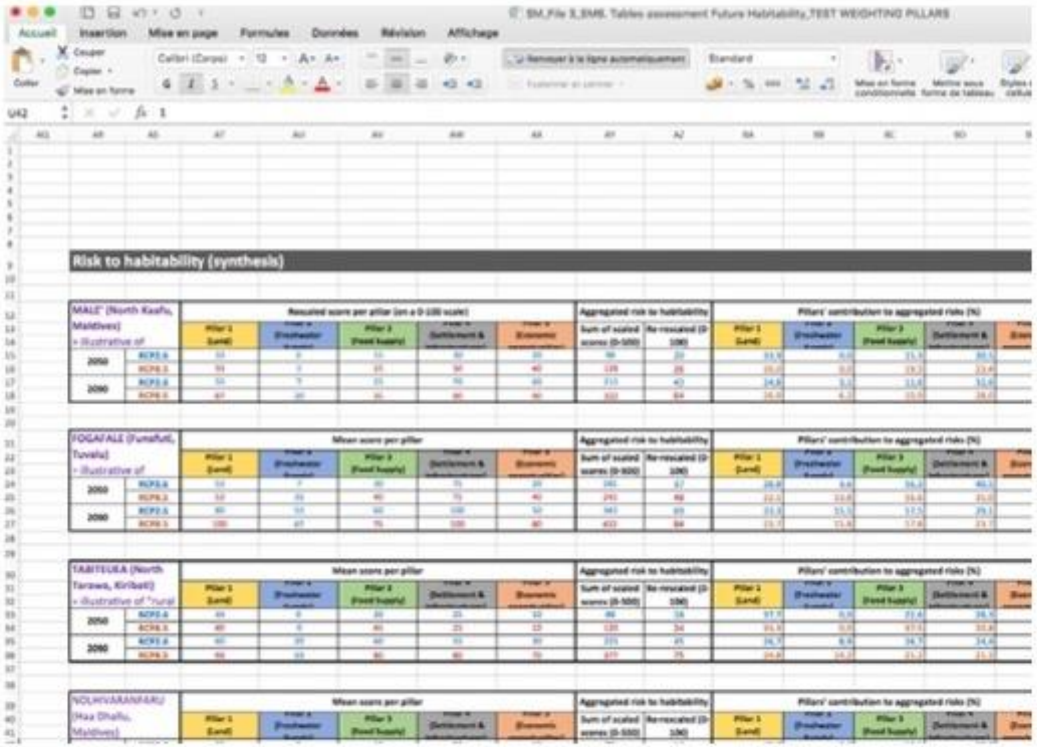
- Aggregation of criteria scores for each habitability pillar
- Weighting of criteria scores for each habitability pillar

Step 5

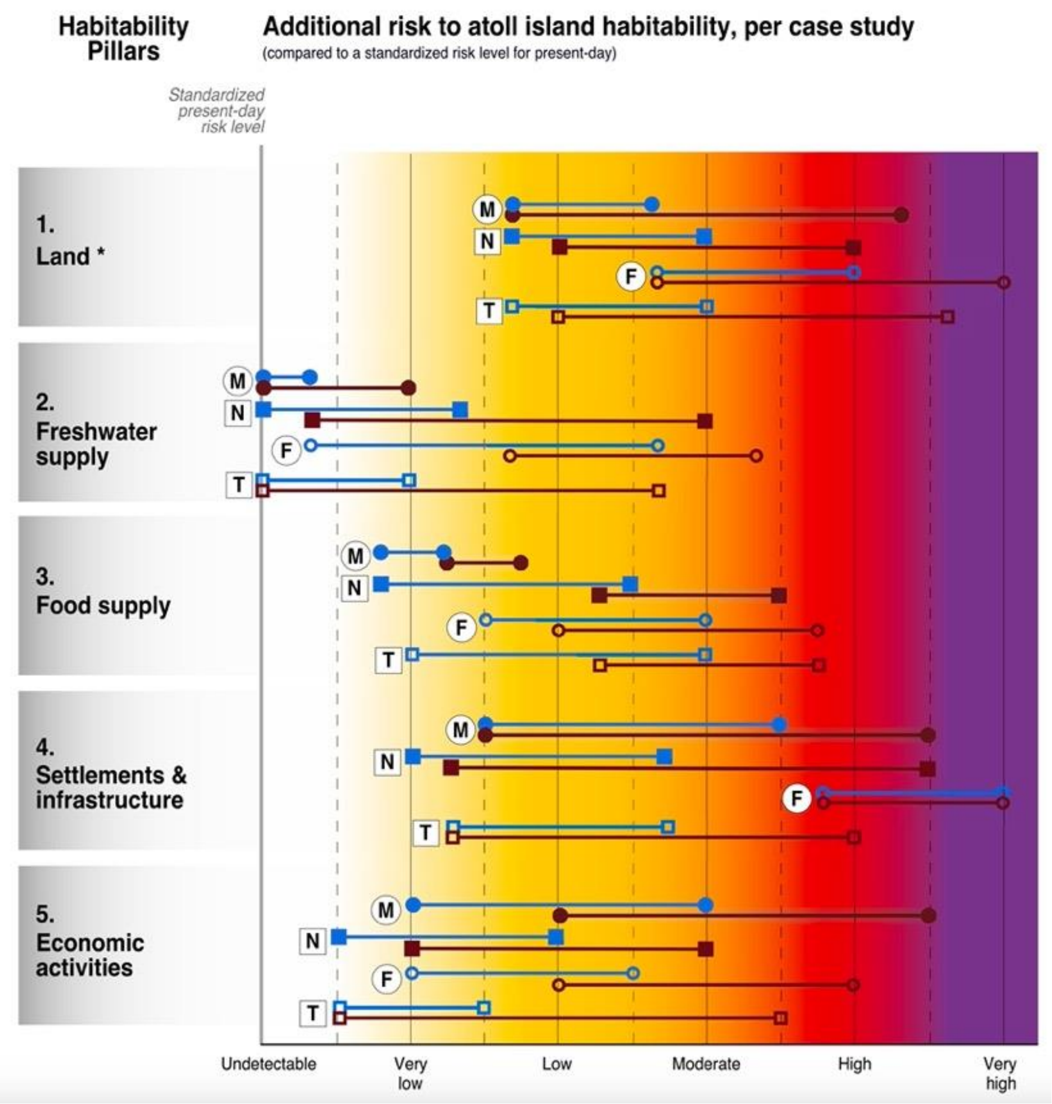
- Combination of aggregated scores for each habitability pillar
- Weighting of HP1 aggregated score (x2) compared to the other HP aggregated scores (x1)
- Final analysis across HPs
- Final analysis across case studies



HP level



Résultat 1 : Risque futur pesant sur chaque pilier de l'habitabilité



Intérêt : prioriser la recherche et l'action publique/privée en ciblant bien les piliers menacés

Dans les atolls : abandonner l'idée que la perte d'habitabilité sera principalement déterminée par le pilier « terres émergées » (érosion et submersion) et intégrer le risque sur le bâti et les infrastructures + le risque pesant sur les activités économiques

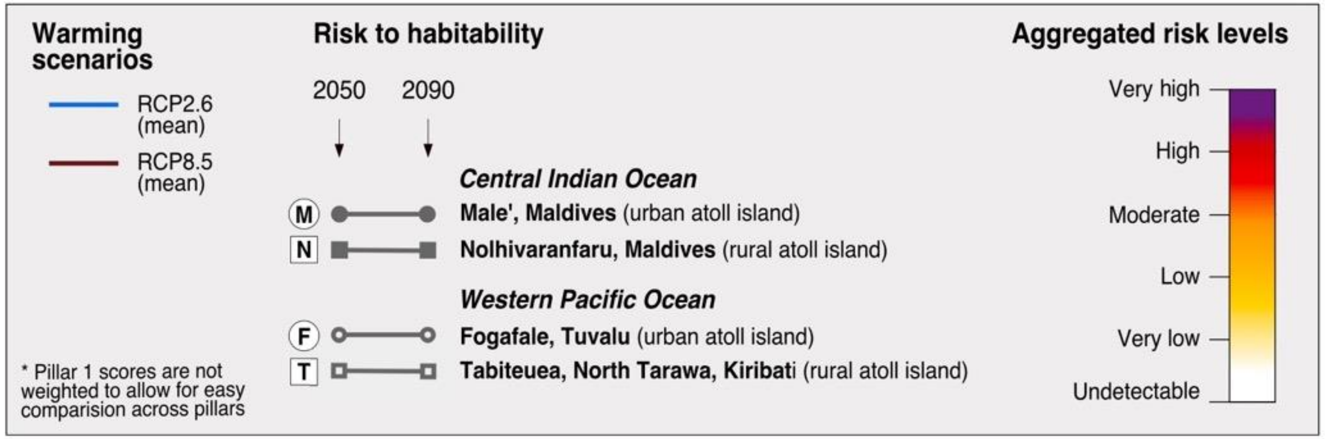
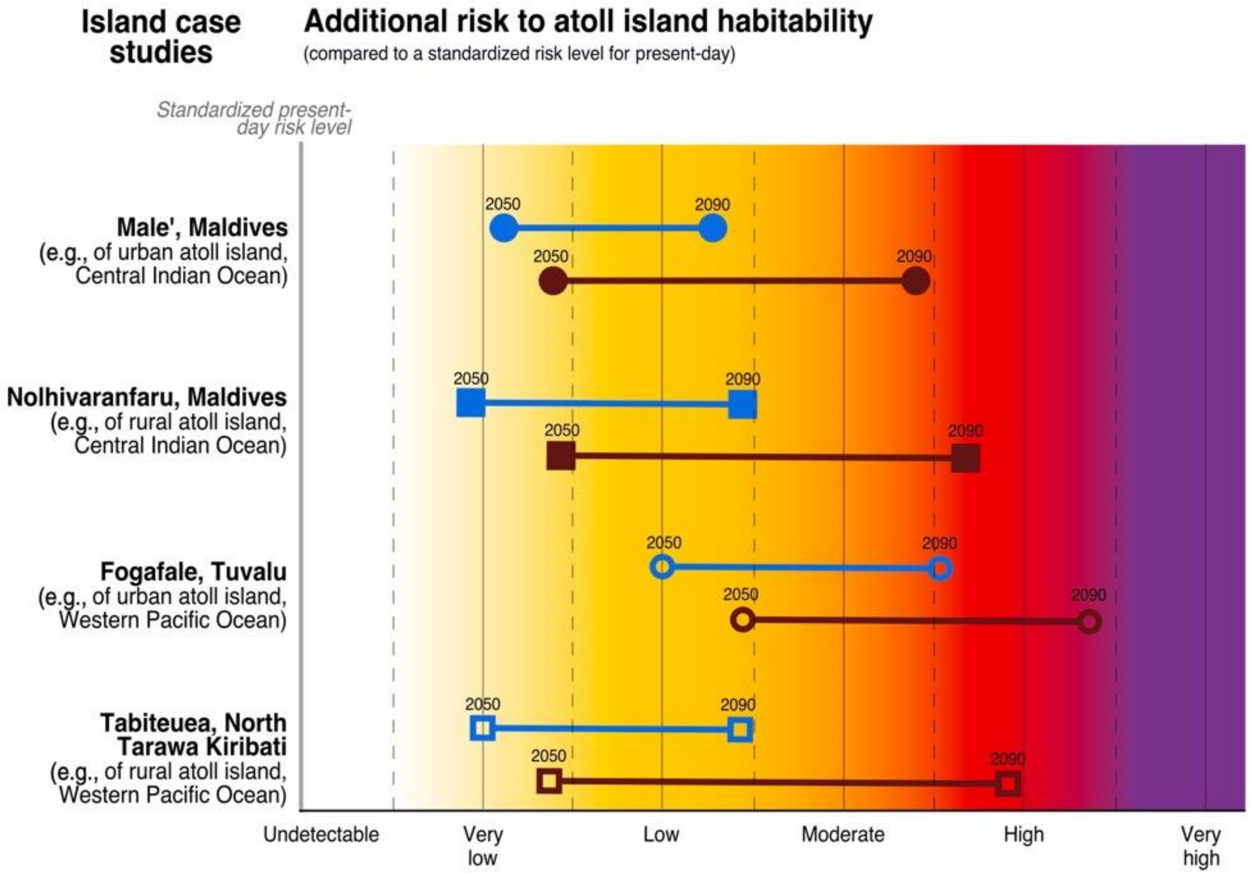


FIGURE 5 Additional climate risks to the five habitability pillars for four atoll islands in the central Indian and Western Pacific oceans. "Additional" means additional risk to habitability compared to a present-day baseline. See Part II of the Supplementary Material for details on the assessment method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

Résultat 2 : Risque futur pesant sur chaque archétype territorial



Intérêt : capturer et traduire en action (de recherche et opérationnelle) la variabilité régionale du risque de perte d'habitabilité

Dans les atolls :

- Forte variabilité entre territoires urbains (la capitale de Tuvalu deviendra inhabitable avant celle des Maldives)
- Faible variabilité entre territoires ruraux

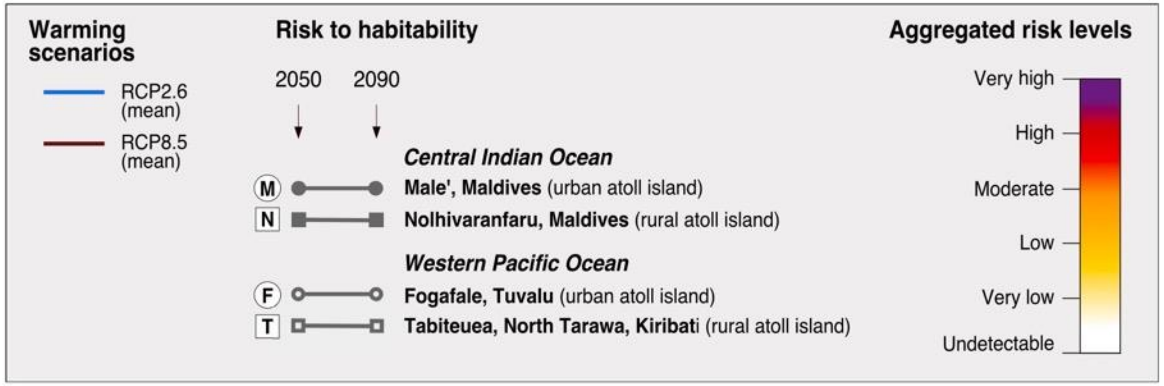


FIGURE 6 Aggregated additional climate risk to habitability for four atoll islands in the central Indian and Western Pacific oceans. See especially SM8 for details on the method

Les étapes suivantes ou l'agenda scientifique

1. Évaluer l'efficacité potentielle de différentes solutions d'adaptation pour chacun des piliers de l'habitabilité

En cours, toujours à partir d'un démonstrateur « atolls »

2. Mieux intégrer les facteurs non environnementaux/biophysiques de l'habitabilité dans l'évaluation

Facteurs socioculturels :

- Ce qui fait menace (perception des types et niveaux de pressions climatiques)
- Ce qui fait habitabilité (perception de ce qu'est un territoire inhabitable)
- Ce qui peut faire solution face au risque de perte d'habitabilité

En cours, démarrage d'une thèse avec comme terrain d'application les Outre-Mer du Pacifique (intégrer des indicateurs socioculturels à l'outil TACT de l'ADEME)

L'INTÉRÊT DU CONCEPT D'HABITABILITÉ POUR S'ADAPTER AU CHANGEMENT CLIMATIQUE

L'intérêt d'une démarche d'évaluation interdisciplinaire pour dépasser les frontières scientifiques et soutenir l'action publique

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