Met Office
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Guidance for Understanding Climate-Related Risks to Development in Maritime Environments

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Contents

1. Introduction

Maritime environments have already changed due to anthropogenic climate change and will continue to change in the future – the IPCC [1] reports that it is virtually certain that the global ocean has warmed since 1970 and has taken up over 90% of excess heat in the climate system. Understanding how marine climate change will impact society is crucial for effective adaptation and to increase resilience for coastal communities (as well as communities further from the coast who will be impacted indirectly by marine climate change). Marine climate change will especially impact the hotspots of high human vulnerability including coastal regions of South and Southeast Asia and Small Island Developing States (SIDS). It is projected that by 2050, close to 1 billion people will be living in low-lying coastal regions with 65 million people currently inhabiting SIDS [1].

This report provides guidance for understanding climate-related risks to 4 priority maritime climate risk areas identified by FCDO: key marine ecosystems, nationally important fishing territories, coastal inundation hazards and coastal and offshore energy production.

Methodological approaches developed for regional assessments of climate risk with a focus on terrestrial characteristics such as the ‘Climate in Context’ methodology[1] (from herein CiC methodology) may not capture characteristics which are important in coastal and ocean settings (see Section 2). In this report, the important characteristics of coastal regions, seas, and oceans are identified, and a synthesis of available datasets and analysis approaches for maritime climate-related risk assessments is provided.

Within the report, we define maritime environments as all ocean environments which can be categorised into exclusive economic zones (EEZs) and the high seas. EEZs include coastal regions (waters immediately adjacent to the coastline), territorial seas and contiguous zones which extend 12 and 24 nautical miles (nmi) respectively from a country’s coastal baseline. EEZs can extend up to 200 nmi (equivalent to 370 km) from a country’s coastal baseline, or further if including extents of continental shelves (see Figure 1-1). The shelf seas refer to the shallow oceans that lie over the continental shelf. Beyond the shelf seas are the high seas, areas outside of EEZs which are generally deep ocean.

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[1] The CiC methodology ‘brings together climate and socio-economic analysis to better understand climate risks through a socio-economic development lens’ [97] and establishes good practice in guiding the production of tailored climate information for understanding climate risk, primarily in terrestrial environments, to inform and support adaption and resilience for development planners and policy makers. The methodology was developed for regional assessments of climate risk (initially in Africa) with a focus on terrestrial characteristics and does not explicitly conduct bespoke analysis of coastal and ocean settings. The CiC methodology has been applied successfully in the recent FCDO Climate Risk Reports, lead and developed by the Met Office.

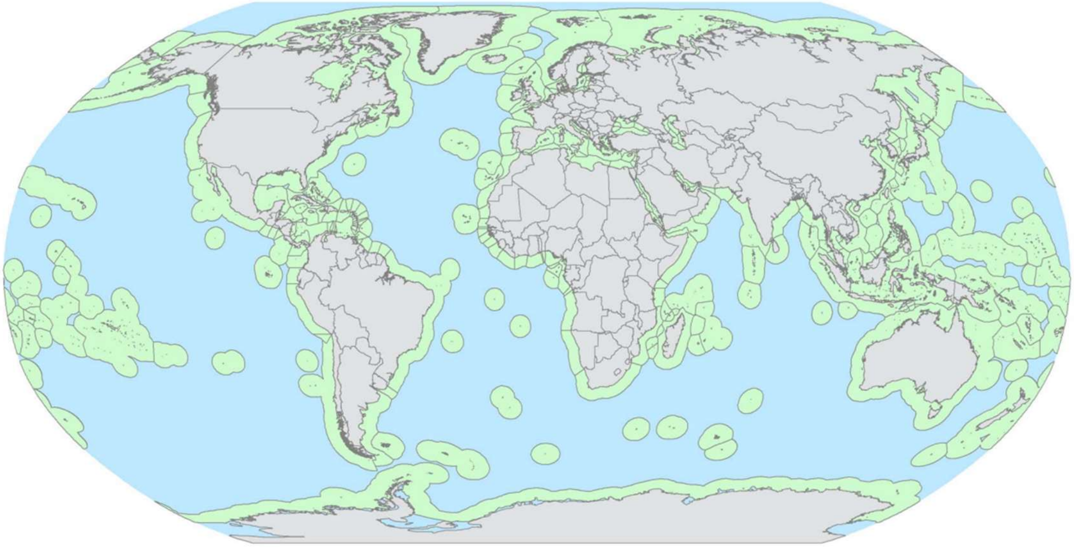

Figure 1-1 - Map of global EEZs (green) and high seas (blue) [2].

2. Approach to Development of Guidance

The approach taken to developing this guidance has been a focus on 4 priority areas for maritime regions with an aim to provide guidance on understanding climate information relevant to:

1. **Marine ecosystems,** including the location and health of mangroves, sea grass, coral reef systems and other key marine ecosystems which support lives and livelihoods.
2. **Nationally important fishing territories**, including fishing grounds, areas where these fish live, conditions for breeding, etc.
3. **Coastal hazards,** including coastal inundation events, tropical cyclones, storm surges, wind-driven waves, sea level rise.
4. **Coastal and offshore energy production/ wealth extraction** including gas fields, offshore wind etc.

It should be noted that the priority areas are highly interconnected. Climate risks to nationally important fishing territories are inherently linked to the response of marine ecosystems to climate change which are in turn impacted by coastal hazards. The direct impacts of coastal hazards are also important in determining risks to fishing infrastructure and infrastructure of coastal and offshore energy production and mineral/ wealth extraction. Many climate impacts are compound both within the marine environment and across marine and terrestrial systems, for example the compound effect of storm surges and rainfall contributing to greater projected flood risk to coastal areas [3], [4].

2.1. Where to apply this guidance

For understanding climate risks in terrestrial environments, part of methodologies like the CiC methodology (outlined in Section 1) is undertaking tailored climate analysis in bespoke sub-regions. In CiC, this is primarily by assessing baseline climate and then mid-century projections of temperature and precipitation from Global Climate Models (GCMs, namely those from the CMIP5 and CMIP6 groups of models) and regional climate models (RCMs, namely those from the CORDEX modelling initiative) within the bespoke analysis zones.

For SIDS located in open oceans[2], i.e., not located on relatively shallow (generally <200m depth) continental shelves), the use of climate analysis established in methodologies like CiC is appropriate as GCMs and RCMs can represent broad scale processes in open oceans. This

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[2] Open ocean SIDS only (non-definitive list compiled by the Met Office): **Pacific Ocean**: Kiribati, Cook Islands, French Polynesia, Palau, Fiji, Tuvalu, Tonga, Niue, American Samoa, Samoa, Nauru, Marshall Islands, Fed. States of Micronesia, Guam, Northern Marianas Islands; **Atlantic Ocean:** Cape Verde, São Tomé and Príncipe; **Indian Ocean:** Comoros, Mauritius, Seychelles, Maldives

is the reason global-level projections of sea surface temperatures (SSTs) have been used in reports such as the IPCC. In this case, tailored climate analysis using similar approaches to CiC can take place in marine regions containing open ocean islands (see Box 2.1 for principles for defining spatial analysis zones for open ocean regions).

Examples of SIDS not on continental shelves are a number of Pacific islands such as Cook Islands or French Polynesia which are located to the east of the New Zealand shelf and the Kermadec Ridge. The Maldives in the Indian Ocean are another example. These atolls were formed through volcanic activity an exist outside of the shallow continental shelves.

[BOX 2.1] Principles for defining bespoke spatial analysis zones for the open ocean

The methods for defining bespoke spatial analysis zones in terrestrial environments (as part of the CiC methodology) is used to spatially aggregate gridded climate data over climatologically similar regions in order to better assess the scale and direction of projected climate trends. It considers both baseline and projected climate information and climate type (as defined by the Köppen-Geiger climate classifications) as well as additional information to ensure climate analysis would also capture relevant socio-economic information (such as livelihood zones). In the open ocean, an alternative approach is required.

We recommend 5 considerations to define bespoke analysis zones for the open ocean surrounding relevant SIDS:

1. **Analysis region size –** The analysis region should be of sufficient size to capture a number of climate data grid boxes to ensure a robust representation of climatology.
2. **Baseline climate** – similar to CiC, baseline and projected SSTs should be used to identify any regional asymmetries or hotspots.
3. **EEZs and fishing territories** – as shown in Figure 1-1, EEZs should be used to guide analysis zones as well as any additional local information about national fishing territories which may extend beyond EEZs.
4. **Physical oceanography and surrounding bathymetry** – nearby continental shelves (generally depth <200m) should be avoided (datasets of global bathymetry such as GEBCO or satellite layers in Google Maps can be consulted) and analyses should follow the edge of the shelf where possible; considerations should also be given to the location of oceanographic features such as currents or large-scale eddies which may impact climate analysis.
5. **Offshore infrastructure** – the locations of relevant offshore energy or mining infrastructure should be considered (see Section 4).

Since most maritime regions important for understanding climate risks to development are located in shelf seas, this report focuses on guidance for understanding these regions rather than the open ocean.

In coastal and shelf seas, the analysis approach noted in Box 2.1 cannot be used as the complex hydrography of these regions cannot be resolved by the relatively coarse resolutions of GCMs and RCMs. Importantly, GCMs and RCMs do not incorporate ocean tides so cannot resolve important shelf sea processes including mixing and stratification regimes, which means these models cannot produce realistic projections of multiple climatic variables including SSTs and productivity. These variables are key to assessing climate risks in many important maritime (in costal and shelf) regions. Therefore, this report instead provides broader guidance for understanding climate risks in maritime environments which can be used to complement the CiC methodology. This includes exploration of additional and alternative datasets that must be considered for these maritime regions.

This report is structured into first an overview of key literature for each of the priority areas, summarising the major observed and projected changes, impacts, risks and methods of assessment from literature (Section 3). Section 4 gives further guidance on relevant datasets (more details provided on these in a non-exhaustive table in the appendix) and variables required to understand these priority areas. Section 5 summarises these into key recommendations and notes research gaps and opportunities for future work.

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Image location: Solomon Islands

3. Literature Overview of Climate Risks in Maritime Environments

The following section gives an overview of key literature describing climate information relevant to 1) marine ecosystems, 2) nationally important fisheries, 3) coastal hazards and 4) marine coastal and offshore energy production and mineral extraction. This overview is not exhaustive and does not include regional detail but summarises climate information, key climate risks and methods of assessment at a global level which can be used for regional risk reports.

3.1. Risks to marine ecosystems

Recent research that mapped future climate risks to marine life (Figure 3.1) notes that ecosystems most at risk reside in the tropics (30° S–30° N), some polar regions (>60° N or S) and closer to shore. Under a high emissions scenario (SSP5-8.5), 84% of marine species are at high risk by the year 2100 [5].

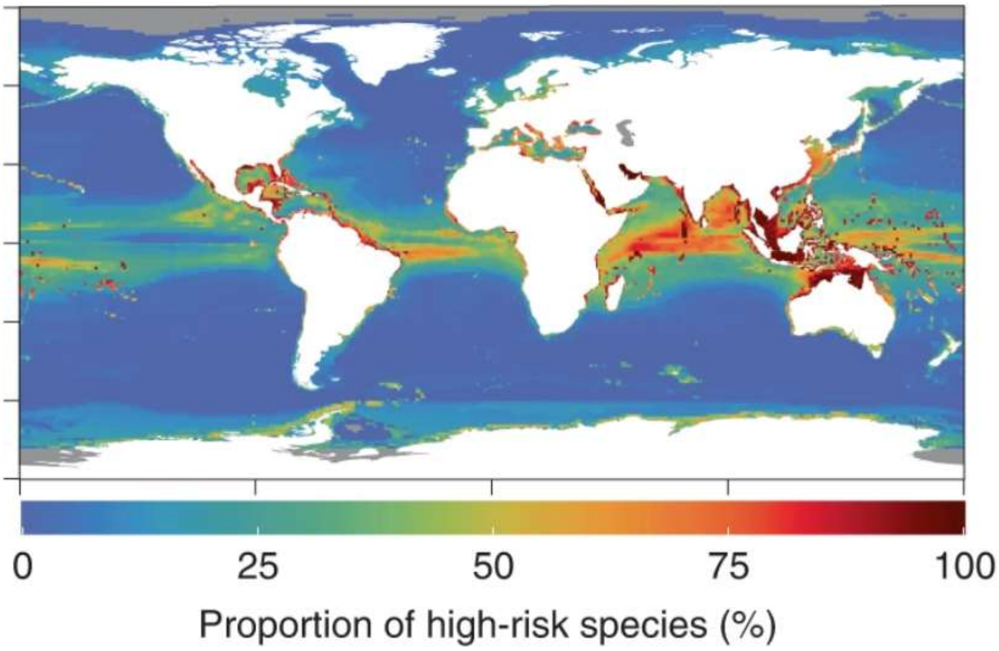

Figure 3-1. The proportion of high or critical risk species under the high-emission scenario (SSP5-8.5) for 2100 for all species [5].

Some of the most at-risk marine ecosystems include mangrove forests, sea grass meadows, and coral reefs. These ecosystems are often co-located due to their interconnection and interdependence (Figure 3.2) and are of huge importance to coastal communities providing food, income (from fishing and tourism), and protection (as a form of coastal defence) to hundreds of millions of people worldwide. However, as the climate changes, so does the environment in which these fragile ecosystems thrive, making monitoring and adaptation highly important. The ecosystems themselves are also interconnected (Figure 3.2) making future climate impacts difficult to project as well as being complicated by other human impacts such as pollution, overfishing and coastal development that affects coastal ecosystems.

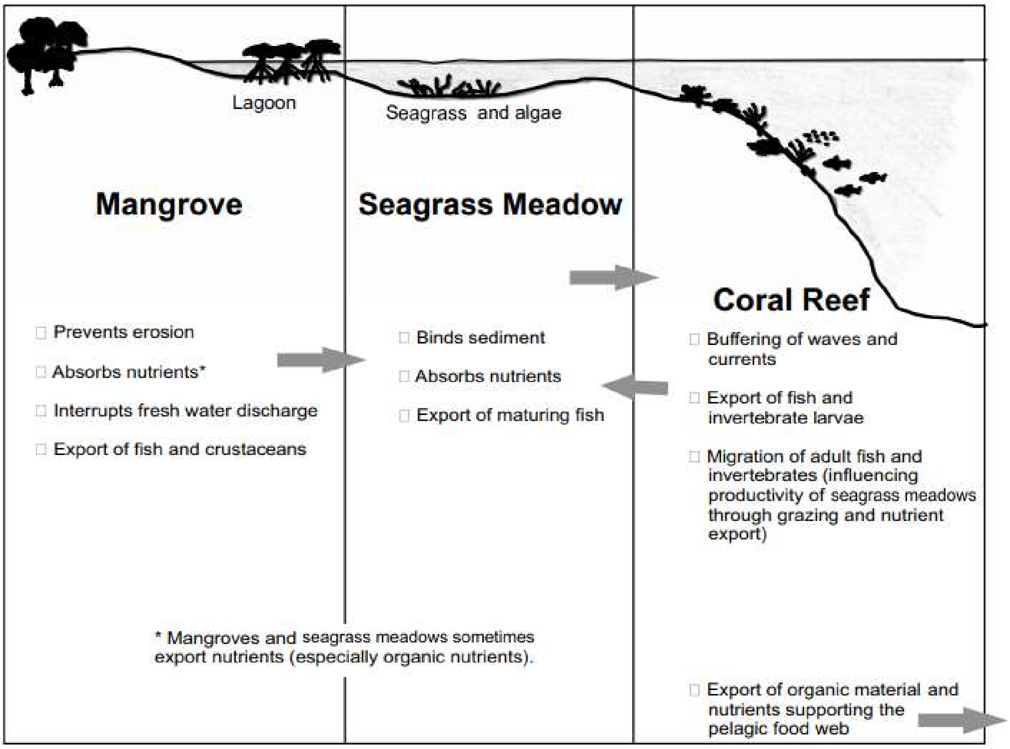

Figure 3-2. Interactions between mangroves, seagrass meadows and coral reefs, highlighting their interdependence [6].

3.1.1. Mangroves

- Mangroves contribute at least $1.6 billion to the global economy [3], [4] and are critical in protecting coastlines from storms and hurricanes with the ability to dissipate 76% of wave energy and reduce wind velocity by 50% [7].
- Estimates of losses of mangroves during the last 25 years range from 35-80% [8].
- Mangrove forests are predominantly located in intertidal areas of tropical-subtropical regions with 75% concentrated in 15 countries: Indonesia, Brazil, Australia, Mexico,

Nigeria, Malaysia, Myanmar, Bangladesh, Cuba, India, Papua New Guinea, Guinea Bissau, Mozambique, Madagascar, and Philippines [9].

- Climate change is likely to have a substantial impact on mangrove ecosystems as demonstrated in Figure 3.3.
    - On one hand, increasing atmospheric CO2 concentrations and temperatures are expected to enrich growth and productivity of mangrove biomass (with a reduction in arid areas), but rising sea levels are expected to reduce growth in intertidal areas shifting growth to upper intertidal zones [10].
- Inundation (see more in Section 3.3) is the key driving factor behind mangrove loss until 2100 [6]. One of the greatest threats to mangroves is sea level rise (SLR) where mangrove communities located in micro-tidal areas (i.e. where tidal range is small) are generally at greater risk from SLR than those situated in regions where tidal range is large (macro-tidal) [8], [10].
- Temperature ranges for each mangrove species are important in defining the extent of range expansion [11], with reduction in cold events (days colder than -4°C which is defined as an ecological threshold [12], promoting range expansion, although photosynthesis declines above 32°C [13], [14].
- At present, the location of mangrove forests is limited latitudinally, confined by minimum air temperature of the coldest month (16°C) [14], with evidence that the extent of mangroves has expanded [9], [12].
- Range changes can be measured using remote sensing data and field observational data. Future impacts of climate change on mangroves (and especially mangrove range changes) have been modelled by combining biological thresholds with climate model data (e.g. [12]) or using biophysical models such as the Sea Level Affects Marshes Model (SLAMM) which has been used to determine future losses in e.g. Vietnam [4].
    - More spatial information on mangrove habitats such as their current distribution and extent would benefit management practises for long-term mangrove conservation.

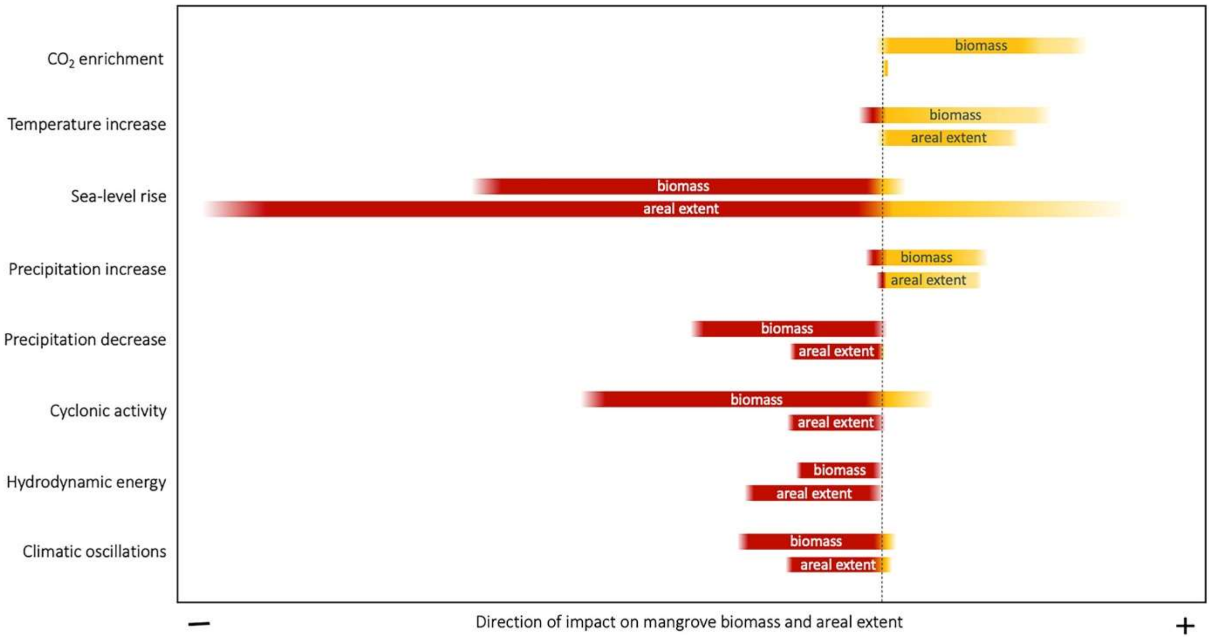

Figure 3-3. Impacts on the biomass and areal extent of mangrove forests under 2.0°C warming [10].

3.1.2. Seagrass and macroalgal forests

- Both seagrasses and brown macroalgae (which includes kelp) are key species that determine ecosystem structure and create a stable habitat for other species that comprise some of the most productive and diverse coastal marine ecosystems on the planet [15].
- Seagrasses exist from temperate to tropical latitudes on sandy shores [16], whereas and macroalgal forests are predominantly located on rocky shores in temperate to polar regions [17], [18].
- Macroalgal forests are in decline globally with between 19-29% lost since 1940s [19], [20], but particularly in the Mediterranean [21].
- There are multiple climate change-related stressors on these organisms with ocean warming considered to be the most severe threat [15].
- The thermal tolerance of macroalgae can be potentially enhanced by other environmental variables such as nitrate, but more research is needed to determine if this is species and biogeographic-specific [22].
- Increasing SST is the most severe threat to seagrass communities, affecting distribution and physiological functions [16], [23].
- The predicted rise in ocean CO2 concentration is likely to have a positive effect on sea grass, though in the tropics where species live close to thermal limits (32-38°C depending on the species) this may not be the case [23].

3.1.3. Coral reefs

A comparative analysis of risks faced by coral reefs conducted by the UNAM-The Nature Conservancy [24] found numerous risks to corals, some of which are likely to be exacerbated by a changing climate. Risks to corals were calculated using ‘Risk Sets’ which are defined as an ‘event’ occurring at a site alongside the condition of the coral before and after the event.

The Global Coral Reef Monitoring Network[3] is the operational arm of the International Coral Reef Initiative which has been reporting on the condition of coral reefs for 2 decades, operating in 10 regional nodes: Australia, Brazil, Caribbean, East Asia, Eastern Tropical Pacific (ETP), Pacific, Red Sea and Gulf of Aden (PERSGA), Regional Organization for the Protection of the Marine Environment (ROPME) Sea Area, South Asia, Western Indian Ocean. They produce periodic reports (the latest was published in 2020), which compile global datasets of 2 million observations in incorporate Essential Ocean Variables[4] to robustly assess reef health. Coral Reef Watch which is operated by NOAA[5] also offers a number of 5km satellite products to monitor reef health.

- Coral reefs are worth billions to the global economy and yet their coverage has decreased by 30-50% since the 1980s [25].
- Coral reefs are predominantly located in tropical-subtropical waters, particularly the Indo-Pacific region.
- When corals are stressed by e.g., temperature, light, or nutrients, they expel the symbiotic algae living in their tissues which causes them to turn white.
- Bleaching events do not kill the coral outright but it can take between 9-12 years for them to recover[6].

Increases in SSTs

- On seasonal to interannual timescales, 1-2°C increases above the long-term summer SST maxima can trigger mass coral bleaching and mortality [24], [26], [27]. Meta-analysis on global climate change impacts on coral reefs in five locations found that coral coverage decreases when annual mean SST exceeds 26.85°C. When annual mean SSTs increase by 1% coral cover declines by 2.3% [28].
- Increasing SSTs due to climate change have exacerbated marine heatwaves (MHWs, defined as localised SSTs >90th percentile for five continuous days, [29]), a distinct class of ‘thermal stress events’ which can cause widespread bleaching in more thermally tolerant corals [30] such as Porties sp. [31]. There

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[3] https://gcrmn.net/about-gcrmn/
[4] https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114
[5] https://coralreefwatch.noaa.gov/product/5km/index.php#data_access
[6] https://www.jcu.edu.au/news/releases/2019/february/how-long-does-it-take-coral-reefs-to-recover-from-bleaching#:~:text=%E2%80%9CWe%20found%20that%20the%20time,coral%20varied%20across%20the%20species.

is currently no universal metric for estimating the proportion of thermally tolerant corals on any given reef.

- The working group on MHWs[7] produce an annual review of the biological impacts of marine heatwaves including the impacts on coral reef systems and report that MHWs are projected to increase in intensity and frequency [32], [33].
- Increases in water temperatures up to 30°C may increase the incidence and abundance of coral predators such as the Pacific Crown of Thorns starfish (Acanthatser) (Indo-Pacific), but survival of this predator is expected to be compromised at water temperatures >32°C [34].
- Corals are more likely to be susceptible to disease, pathogen abundance and virulence with increasing temperature, but there is large variation spatially in the projected timing of these disease-favouring conditions [35].
- Higher water temperatures can be associated with algal blooms which can cause temporary hypoxia causing a reduction in dissolved oxygen causing the death of corals, fish and other marine organisms e.g., Gulf of Mannar in South East India [36].
- Tropical water corals present in surface waters (0-30m) are at the greatest risk from increasing SSTs, and deeper (>40 m) (mesophotic) coral reefs may be less susceptible to offer a refuge against rapid changes in temperature, storm intensity, and ocean water chemistry.
    - This is known as the “Deep Reef Refugia” hypothesis where deeper corals have provided limited refuge in the Caribbean [37] and the Great Barrier Reef [38] from thermal stress events.
    - However, recent research has shown that even these refugia are under threat from climate change with none projected to exist with 2°C in global warming [39].
- There are varieties of heat-tolerant corals which have been shown to be adaptive to thermal stress in e.g., the Great Barrier Reef [40] and Palau reef, South East Asia [41], but it is currently unknown about the extent of genetic variation across different reefs.

Anthropogenic Ocean Acidification (OA)

- Dissolution of atmospheric carbon dioxide into the oceans causing a reduction in the ocean pH manifested for corals (through a reduction in the aragonite saturation) – this can make it more energetically costly for corals to build their calcareous skeletons [42].
    - Mass coral bleaching can increase the susceptibility of corals to ocean acidification [43] with experiments suggesting ocean acidification can directly cause coral bleaching in some coral reef builders [44].

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[7] http://www.marineheatwaves.org/

- Corals at higher latitudes are more susceptible to ocean chemistry changes as higher latitude waters absorb more CO_2 than lower latitudes [45].

Other Anthropogenic stressors

- Overfishing and destructive fishing practises affects up to 55% of the world's reefs, especially in South East Asia (up to 95%) [8] and can deplete the reef of herbivorous fish which graze on harmful algae, leaving the reefs susceptible to overgrowth and disease.
- Coral disease can also be caused/exacerbated by nutrient enrichment caused by changes in precipitation causing increased runoff, coastal development, agriculture, and industry [46], which can amplify the damage caused by heat stress [47]. Quantifying the individual impact of anthropogenic OA on coral ecosystems is complicated by multiple co-occurring environmental variables which all affect marine ecosystem responses [48], e.g., increasing SSTs and associated impacts, as well as other anthropogenic stressors listed above.
- Coral reef structure can be destroyed by increased intensity of cyclones [49] and more frequent storms.

3.2. Risks to nationally important fishing

The future of food from the sea depends on a range of ecological, economic, policy and technological factors [50]. The fishing industry faces multiple threats from climate change, including:

- Direct impacts of sea level rise (see Section 3.3), ocean warming, ocean acidification and extreme weather events such as storms [51], [52].
- Indirect changes to seasonality of biological processes and aquatic habitats leading to modifications in the distributions and productivity of fish species [51], [52].
    - Such indirect changes are of particular concern to endemic species which are restricted to small areas with highly specific (and often unknown) habitat requirements [52].
    - There are also many uncertainties concerning these threats on marine species and their habitats [53].
- Both direct and indirect changes are also often compounded by external pressures including overfishing, pollution, and poor management [51], [52] and other aspects of the industry including infrastructure and production chain processes [54].
- Natural variability in the climate system, particularly driven by ENSO, is known to be strongly related to annual fish catches [50], [55].

Global climate risk assessments (CRAs) have been fundamental in assessing global fisheries and aim to:

- Evaluate risk at the species level, for example Barange et al. (2014) [56] evaluate climate risk for 24,975 marine species.
- Assess the relative importance of fisheries to national economies, diets, and societal capacity to adapt to potential impacts and opportunities [57].
- Evaluate management effectiveness and trade practices as influences on global fish production [56].
- Calculate a relative vulnerability index for multiple countries. E.g., Blasiak et al. (2017) [58] create an index for 147 countries drawing on data related to climate impacts on marine fisheries using 12 primary variables (Figure 3.4).

One of the most comprehensive CRAs has been carried out for European fisheries and coastal communities [59], consisting of multiple external datasets and databases forming the basis of the five stages of analysis (Figure 3.5). They conclude that future CRAs should aim to be carried out well below the national level to ensure the diversity of risk faced by coastal communities and fishing fleets is not obscured. The challenge remains in creating, finding and collating the large amounts of required data.

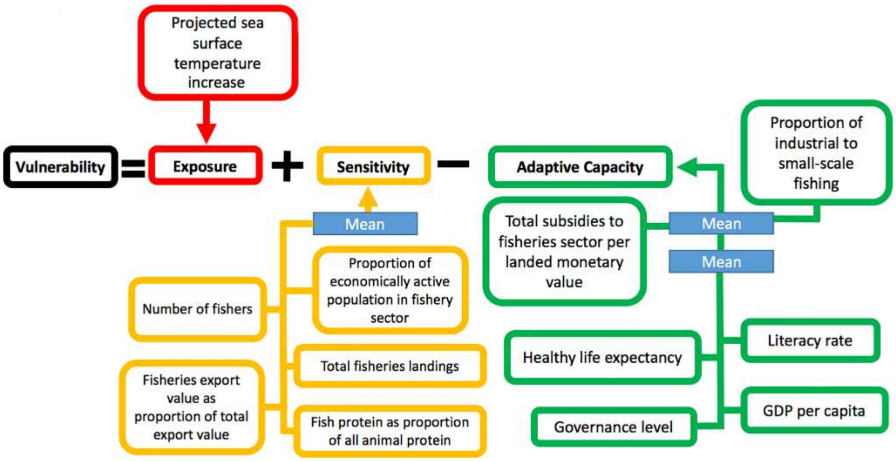

Figure 3-4 - Overview of variable construction and calculation of the vulnerability index in Blasiak et al. 2017 [58].

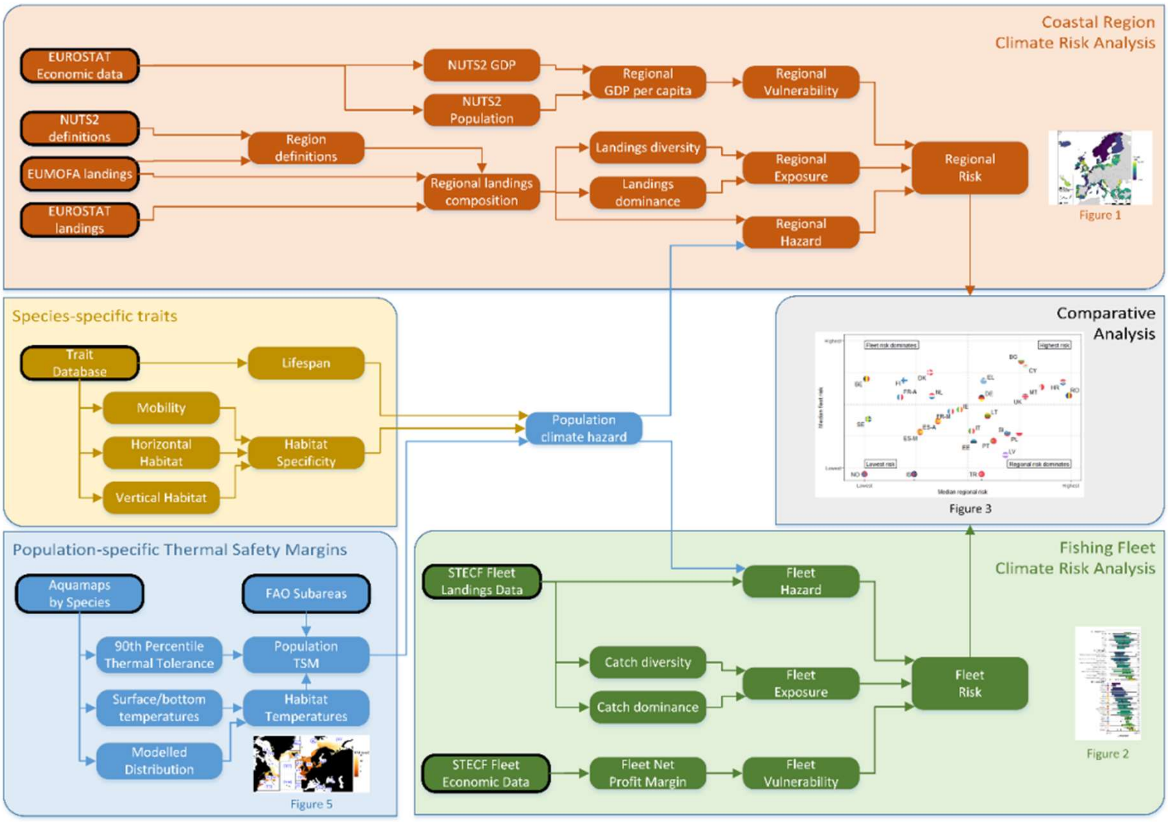

Figure 3-5- Flowchart of the CRA process carried out by Payne et al. 2021 [59] comprising of a species-specific trait analysis, a population-specific thermal safety margin analysis, a separate coastal region CRA, a fishing fleet CRA and finally a combined comparative analysis. External datasets are highlighted in black.

Three key ecological responses to ocean warming have been researched in recent decades: distribution of species, changes in the timing of life events (phenology) and effects on body size. Some limited information on the effects of ocean acidification on fish physiology and early survival is also available in the literature [53]. Species distribution models (SDMs) are typically used to study the projected impacts of climate change on terrestrial and marine species:

- Statistical or theoretical methods are used to relate current climate variables to the current distribution of a species to define a “bioclimatic envelope” where future changes in the species distribution are found through projecting the new range of the bioclimatic envelope under different climate scenarios.
- SDMs have been criticised as being over-simplistic but are becoming more sophisticated and using multiple SDMs, particularly when combined with ensembles of driving climate models, can overcome some of their shortcomings [60].
- SDMs also rely on comprehensive presence and absence datasets which are frequently not available, leading to restricted and biased results. Jones et al (2012) [60] conclude that expert understanding of the data sources and model limitations is vital for an insightful analysis.

Key papers which utilise SDMs to assess future changes relevant for fishing include:

- Cheung et al. (2016) [61] used a marine SDM to express impacts to fisheries by changes in maximum catch potential against degree of warming between 1950 and 2100 and discuss changes to other oceanographic variables that drive changes in marine ecosystems (see Section 3.1.2).
    - They find that, over large marine ecosystem scales, global warming scales nearly linearly with global mean SST, surface oxygen and net primary production at the sea surface under both RCP2.6 and RCP8.5.
    - This suggests that while climate models may not be able to produce realistic local scale SSTs, useful change signals can be found for larger scales relevant to whole ecosystems.
- Hodapp et al. (2023) [62] projected changes in global marine biodiversity to 2100 through integration of geo-references species occurrence data for 33,518 marine species using GCM simulations and an SDM to assign probabilities of occurrence for every species for 0.5° grid cells of the global oceans.
- Tittensor et al. (2021) [63] analysed how projected climate change will affect future ocean ecosystems using a suite of nine global marine ecosystem models from the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP), forced by two CMIP6 generation GCMs.
    - Their projections show steep global biomass declines and greater climate risks for marine ecosystems than previous CMIP5 studies.
    - They stress the need for scenarios of future fleet behaviour, economics and changes in target fish species that are not yet available and not included in Shared Socioeconomic Pathways.

There are several limitations to ecological modelling for marine CRAs, for example:

- It is generally not possible to associate a driver of change, such as ocean warming, to a change such as declining stocks, given the current state of knowledge of the complex social-ecological system and the many unknowns and uncertainties concerning species, their habitats, and their threats [52].
- Ecological modelling is useful, but results must be considered within the wider context including the response of producers to incentives, changes in demand, technological developments, and operational costs [60].

3.3. Risks from coastal hazards

Coastal hazards are risks from individual and combined physical processes. These hazards threaten coastal infrastructure, can cause environmental degradation and endanger the lives of those living in coastal regions, e.g., through coastal inundation. This section will give an overview of the key coastal hazards including sea level rise and sea level extremes, storms, waves and surges. Note than these physical processes rarely occur in isolation.

3.3.1. Sea level rise

Sea-level rise over the coming centuries presents an existential threat for many small island states and low-lying coastlines, with impacts to communities, livelihoods, infrastructure, and ecosystems from inundation, salination of water supplies, and destruction of coastal protections (mangroves, reefs, as described above).

Sea level rise occurs due to two key effects, often referred to as steric effects - these are water level increases through water addition to oceans (i.e., via ice melt) and through thermal expansion (water volume expands with increasing temperature)).

- The IPCC has reported that it is virtually certain that global mean sea level (GMSL, also referred to as relative sea level) is rising and accelerating in all ocean basins.
- It is also expected that GMSL will continue to rise and accelerate under all emission scenarios [64].
    - However, sea level is not rising uniformly and has substantial regional variability. Factors including ocean dynamics, Earth's uneven gravity field as well as regional differences in winds, heat and freshwater fluxes, atmospheric pressure and ice melt which all contribute to uneven sea level rise ([65]; Figure 3.6).
- The earliest detected impacts of increasing sea-level rise rates includes chronic flooding at high tide, salinisaton of wetlands and ecosystem changes, and increasing damages due to coastal flooding and erosion [66].

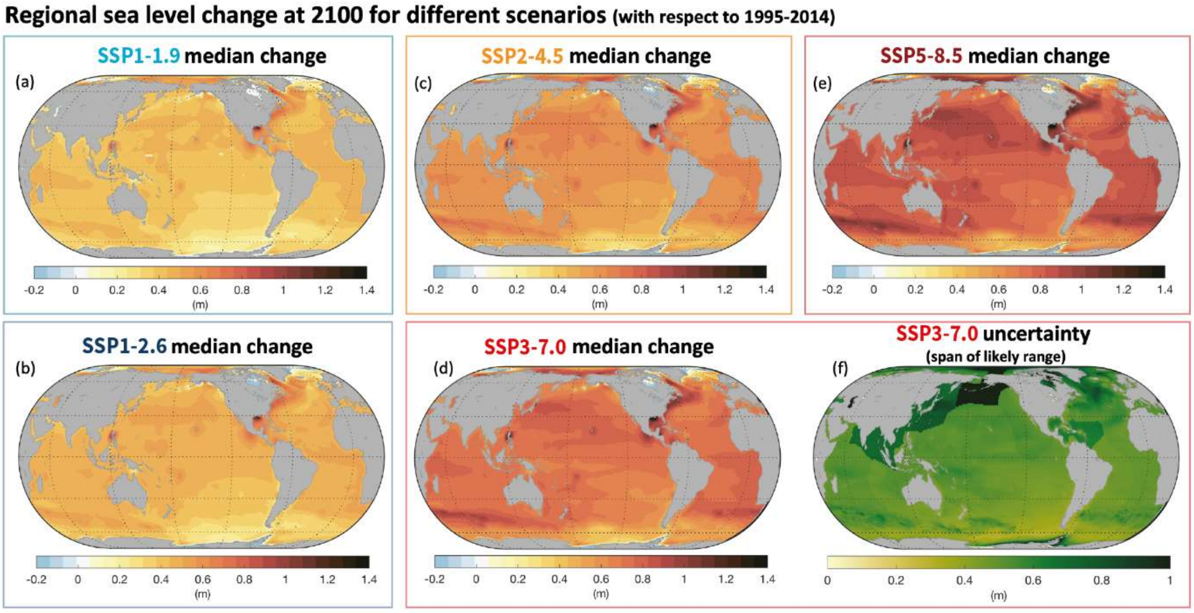

Figure 3-6 - Regional Sea Level Change at 2100 for different scenarios [64].

3.3.2. Extreme sea level

Extreme sea levels (ESL) are water level heights in addition to mean sea level and triggered by storm surges, waves and tides. At most locations across the world, changes in sea level relative to land is the primary driver of changes in sea-level extremes, setting a new base water level from which such events occur, as well as changing the depth for the propagation of tides, waves and surges [64].

Extreme sea level is often assessed in through measures of two metrics: extreme still water level (ESWL, inclusive of storm surges and tides but not waves) and extreme total water level (ETWL, inclusive of wind-driven waves) [64], [67]. Future extreme sea-levels are projected using two distinct methods [68], [69] – the static approach and the dynamic approach.

1. **Static approach**
    - This approach uses historical tidal, surge and wave component distributions to generate future extreme sea level then distributions for relative mean sea level rise.
    - The approach has been employed to present projections of sea-level extremes in the IPCC reports, expressed as ‘frequency amplification factors’, referring to the amplification in the average frequency of an extreme event (such as ESL) occurring for events which historically have a 100-year return period, i.e., an event occurs once in every 100 years or a 0.01 probability.
        - E.g., a frequency amplification factor of 25 means an event that historically occurred once in every 100 years will, on average, occur every 4 years. An example of frequency amplification factors for ESL is shown in Figure 3.7.

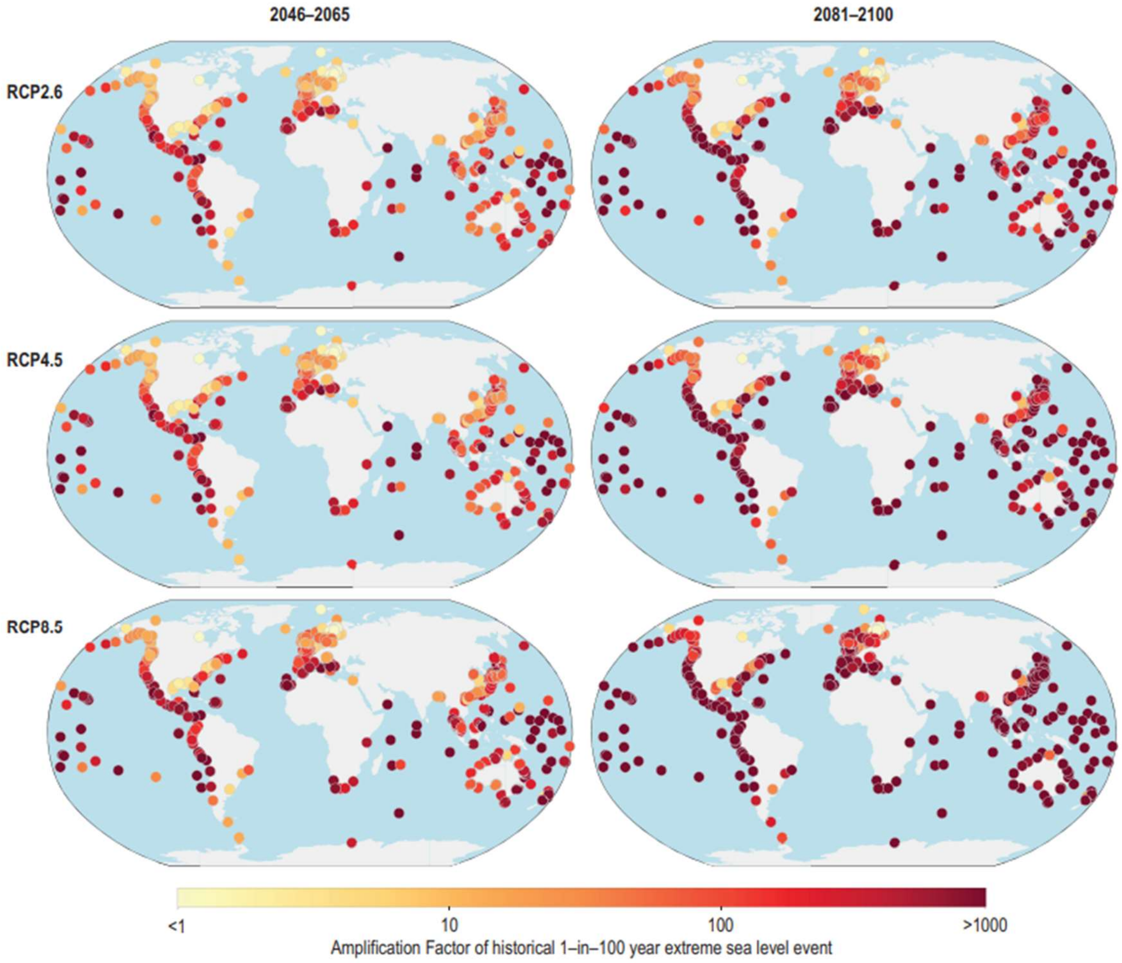

Figure 3-7 - Frequency amplification factor ESL under different scenarios [69].

2. Dynamic approach

This approach uses global climate model derived outputs (atmospheric fields) to force wave or hydrodynamic models and applying relative mean sea level rise projections.

- Melet et al. (2020) [70] projected 21st century changes in extreme coastal water level through 20 year mean wave setup changes. Wave setup refers to the increase in mean water level due to the presence of a breaking wave.
- Vousdoukas et al. (2018) [71] generated global probabilistic projections of extreme sea levels for the 21st century, taking into consideration mean sea level, tides, wind waves and storm surges.
- Kirezci et al. (2020) [72] used global models of tide, storm surge, and wave setup to obtain projections of coastal flooding over the 21st century, identifying in certain hotspot regions.

3.3.3. Storms: Tropical and extra-tropical cyclones

Tropical cyclones (TCs) are tropical storms (of average diameter 200-500km) that form over ocean whereas extra-tropical cyclones (ETCs) (which occur outside the tropics) are much larger (500-2500km in diameter) synoptic low-pressure systems that can cause wintertime storms. The influence of climate change will impact these systems differently.

Successive storms can cause damage to protective nearshore bathymetry, continually weakening defences (through waves and surges, see below) and so increasing potential for inundation flooding events following multiple storms of similar magnitude [73], [74].

Tropical cyclones

- As the tropics expand with warming, the average location where TCs reach their peak wind intensity is projected to migrate poleward, and this is particularly the case in the western north Pacific [69], [75].
    - This means that locations which previously have not experienced TCs may become exposed.
- IPCC report projections indicate increases in intensity and rates of precipitation [76], [77] with confidence that sea-level rise will lead to higher storm surge inundation when TCs occur (see Figure 3.8).
- Though global frequency of TCs is likely to decrease or remain unchanged, the average peak TC wind speeds and proportion of category 4-5 TCs are very likely to increase globally with warming [69].

Extra-tropical cyclones

- ETCs are also projected to shift poleward though changes in frequency and intensity (wind speeds) are less clear and have high local variability.
- As with TCs, projections also indicate that ETC precipitation will increase in line with global increases in water vapour associated with increasing temperatures [69].

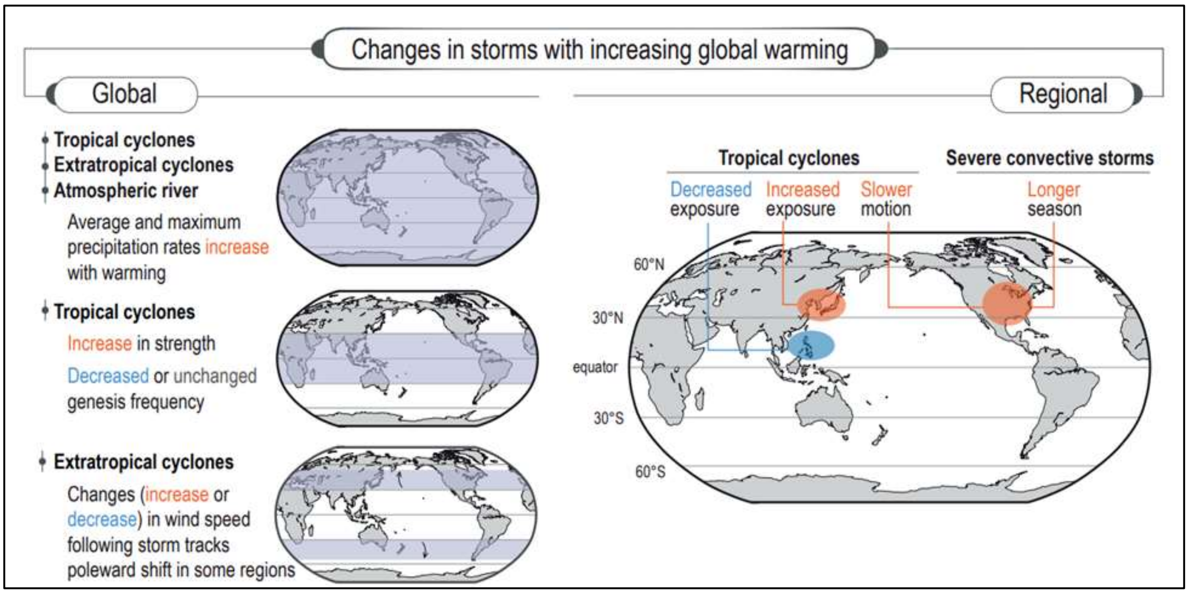

Figure 3-8 - Past and projected changes in tropical and extratropical cyclones with increasing global warming. Areas of decreased and increased exposure (right): observed poleward migration of TCs has also been shown to have large regional variations: Kossin et al. (2016) [75] showed that past observed changes included decreased exposure in regions of the Philippines and increased exposure over Japan [69].

3.3.4. Waves and surges

Understanding the characteristics and variability of storm-driven waves and storm surges in the future is of great importance for understanding extreme sea levels, whether ESWL or ETWL.

- Surges are an abnormal rise of sea level generated by a storm – generally above a normal tide.
- The methods used to estimate the wave contribution to extreme sea level varies but is described in the IPCC AR6 as a combination of wave setup (increase in water level as waves reach shallow zones), infra-gravity waves (lower-frequency waves generated by higher frequency waves) and wave runup (the combination of wave setup and infra-gravity waves – this is the maximum elevation of individual waves and is directly responsible for wave overtopping) – see Figure 3.9.
    - These components are all controlled by nearshore bathymetry [78].
    - Measuring components to understand wave contributions to extreme sea level requires data on wave heights, generally based on wave buoy and satellite observations.
- Waves and surges can combine to cause huge amounts of damage to coastal and offshore infrastructure and ecosystems as well as to important marine industries including fishing and shipping.

- Trends in wave heights are limited by inadequate observations, inhomogeneous records and sensitivity of techniques used to measure and process historic wave component data [64].
- Furthermore, high variability in storms and waves and a lack of understanding of mechanisms means attributing waves to climate change is a difficult task [79]. Observed trends show there is confidence of a poleward shift of storms (and so storm-driven waves and surges) since the 1990s.
- Morim et al. (2019) [80] found projected changes (both increase and decrease dependent on region) of around 5-10% in annual mean wave height along just over half of the global coastline by the end of the century (RCP8.5).

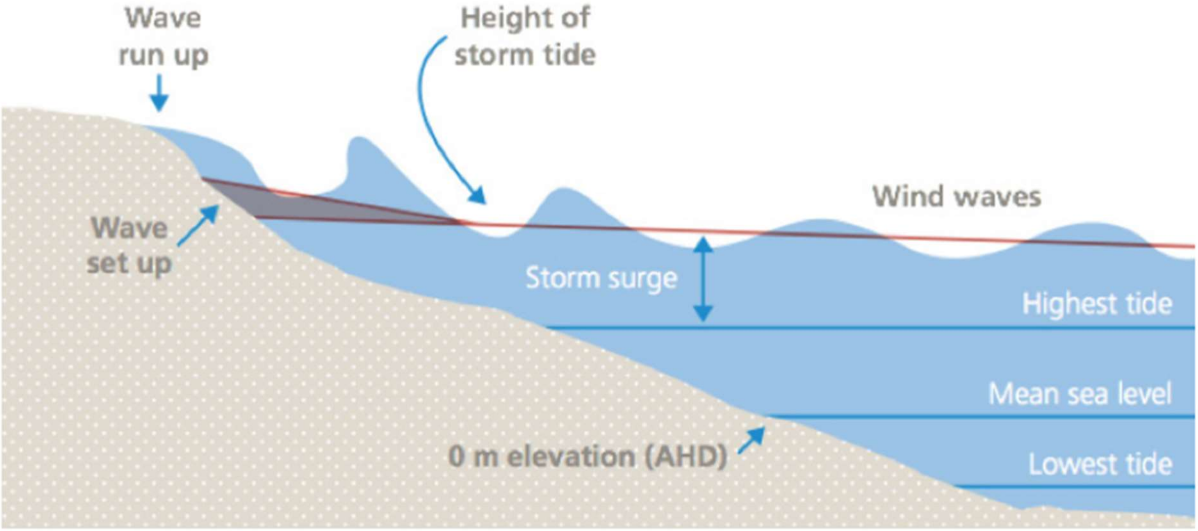

Figure 3-9 - Components of wave setup and runup. Infra-gravity waves not shown in diagram – occur at lower frequencies [81].

3.3.5. Coastal inundation

Coastal inundation occurs when high water levels drive sea water onto land. High water levels can be caused by a number of factors including combinations of storm surges and storm-driven waves (such as those associated with ETCs and TCs) and high tides.

- Risk of coastal inundation is expected to increase due to increasing mean sea levels and changes to factors controlling extreme sea levels which are explored above [82].
- Coastal inundation/ flood modelling is an active area of research with multiple studies at local, regional, and local scales (e.g. [72], [83], [84]).

3.4. Risks to coastal and offshore energy production / resource extraction

To understand the vulnerability of coastal and offshore energy production to current and projected future climate change, it is vital to understand where the key infrastructure for these industries is located and the specific sensitivities to weather and climate variables.

The availability of electricity is crucial to maintain standard of living, industrial production, and transportation. Generation of electricity including wind, nuclear and coal power stations are often found in coastal locations. Wind power, oil and gas extraction and mining also operate offshore. The infrastructure of these industries is vulnerable to natural disasters and weather events, and is likely to be vulnerable to projected future climate change in the following ways:

- Stronger and more frequent storms can reduce fuel supply (oil and gas) as platforms are damaged or destroyed [85].
- Storms can also dislodge pipes from the sea floor, impacting transport of oil from platform to refinery [85].
- High wind speeds (i.e., >55 mph) can reduce the supply of wind energy due to limitations of turbines and impact the ability to get personnel on and off oil rigs.
- Higher wind speeds could also cause a wider dispersion of pollutants in a spillage or contamination event [85].
- Coastal flooding caused by sea level rise, storm surges, and ground subsidence poses a risk to infrastructure used for both energy generation and dispersion.
- Increased wind speeds and wave power could damage wind turbine foundations.
- Increased ocean temperatures have more severe impacts that higher air temperatures, particularly where water is used for cooling (e.g., nuclear and coal).
- Loss of life on offshore platforms from extreme conditions.

When assessing the risk of climate change to coastal and offshore energy production, it is first important to identify the location of key infrastructure for each industry using infrastructure databases then assess impactful weather and climatic factors impacting these infrastructures – these factors are derived mostly from coastal hazards (Section 3.3). Key infrastructure datasets are outlined in Section 3.

4. Guidance for Understanding Maritime Climate Risks: Key Variables and Datasets

The following table notes key climate variables and datasets identified for understanding maritime climate risk. Each priority areas are indicated by colour: green (ecosystems), blue (fisheries), yellow (coastal hazards) and grey (energy). Time Scales refer subjectively to which climate impacts have 'short-term' or immediate effects, versus 'longer-term' shifts in baseline conditions.

Areas of risk	**Current monitoring**	**Time scale**	**Hazards and Impact**	**Regional hotspots for climate hazards**	**Key metrics/ thresholds**	**Gaps and Opportunities**
Mangroves	Global Mangrove Watch: time series data for individual countries Remote sensing: Landsat and Sentinel The Google Earth Engine Mangrove Mapping Methodology [86]		**Sea Level Rise** causing inundation of mangrove forests	Micro-tidal areas in **tropical-subtropical** regions.	**SLR rates exceeding 6.1mm/yr** would exceed rates of ecosystem adaptation [87]. Relative Sea Level Rise accounts for steric effects and is measured using Tidal gauges and Satellite altimetry	Quantifying the spatial extent/redistribution of mangrove growth is limited by the sophistication of remote sensing technologies. Machine learning could be an alternative, efficient solution to computationally costly numerical models to project climate change impacts on mangrove forests
Sea grass	SeagrassNet: Field data collated by monitoring websites: Seagrass-Watch: time series at various sites globally		**Increasing SSTs** which affects distribution and physiological function.	Tropics	**32-38°C** depending on the species	Seagrass mass mortality events caused by e.g., hotspots/ heatwaves are more recent than

Areas of risk	Current monitoring	Time scale	Hazards and Impact	Regional hotspots for climate hazards	Key metrics/ thresholds	Gaps and Opportunities
Brown Macroalgae	Surveys, Species Distribution Models, Remote Sensing techniques. AlgaeBase: global algal database Ocean Biogeographic Information System (OBIS): global marine biodiversity data Kelpwatch: largest dynamic map of canopy-forming kelp species		**Increasing water temperatures** have led to range contractions in lower latitudes and range expansions in higher latitudes such as the Arctic but this could be complicated by **increased turbidity** and **freshwater input** due to sea ice loss and glacial retreat [88], [89].	**Equator-ward range edges** of kelp populations living near to thermal tolerance thresholds	Thermal tolerance varies widely depending on species but for e.g., kelp, tolerance is restricted from **~3-~24°C** [90].	e.g. coral bleaching events so less is known about their triggers More investigations into the thermal tolerance of sea grass and kelp species and how this is moderated by other variables. Requirement for modelling climate impacts in the Indo-Pacific where most seagrass diversity exists Mismatch between point observations of seagrass and macroalgal forests vs. gridded environmental data making projections for these ecosystems challenging
Coral reefs	Coral Reef Watch: temperature thresholds of coral reefs Caribbean reef watch Virgin Islands Reef monitoring	Short-term	**Marine Heatwaves** (MHW) causes coral bleaching [68] **Nutrient enrichment** from increased runoff from land can reduce	MHW affect tropical corals particularly - **Equatorial Pacific, Australia,**	MHWs = **SSTs >90th percentile for 5 consecutive days** [29].	Seasonal outlooks for coral bleaching to aid reef management through early warning systems and response plans to bleaching events [93].

Areas of risk	Current monitoring	Time scale	Hazards and Impact	Regional hotspots for climate hazards	Key metrics/ thresholds	Gaps and Opportunities
	Micronesia reef monitoring Coral restoration database Distribution of global coral reefs NOAA reef information and data products		oxygen and cause algal blooms which can lead to coral bleaching **Destructive fishing practises** cause structural damage to the reef	**South East Asia** [68] Nutrient enrichment and fishing practises affect predominantly **South East Asia, Caribbean, Indian Ocean** [68] Destructive fishing occurs mainly in **South East Asia**, especially Indonesia [91]	SSTs down to 40-60m for MHW [92].	Future risk assessment for corals should account for the effects of multiple stressors in order to quantify cumulative risks (i.e., how short-term stressors such as MHWs impact the resilience of corals to long-term stressors such as Ocean Acidification).
		Long-term	**Increased baseline SSTs** lead to increase likelihood of coral bleaching (exceeding biological temp. thresholds), spread of disease and pathogens, deoxygenation, and increased likelihood of heatwaves,	Tropical water corals such as the **Indo-Pacific, Caribbean and Gulf of Mexico** are most at risk from increased SSTs [43]	**1-2°C increases above the long-term summer SST maxima** (specific to location) can trigger mass coral bleaching and mortality (see main text)	Targeted species conservation and reef management would be improved by a greater understanding of the genetic architecture of reefs and percentage of thermally tolerant coral species.

Areas of risk	Current monitoring	Time scale	Hazards and Impact	Regional hotspots for climate hazards	Key metrics/ thresholds	Gaps and Opportunities
			Ocean acidification (OA) can cause reduction in calcification **Increased cyclone intensity** causing structural damage to corals [49]	**Cold water corals** are at more risk of acidifying waters due to **high latitude waters** acidifying at a faster rate	**Increases in SSTs up to 30°C** can increase abundance of Acanthatser, esp. in Indo-Pacific, but dec. abundance at **SSTs >32°C** [34] Degree Heating Weeks/Months used as a standard metric for coral bleaching developed by NOAA Aragonite Saturation Index to measure extent of OA	Monitoring the extent of adaptation through migration of coral to 'Deef Reef Refugia' would be useful for reef management
Declining fish stocks and changing distributions	**Sea Around Us: fisheries and fisheries-related data including catch data, biodiversity etc.** International Council for Exploration of the Sea EcoSystem Data database: includes data from fish trawl surveys, historical plankton etc.	Short- and long-term	**Ocean warming** The ability of marine species to redistribute in response to changes in temperature depends on their ability to acclimatise and respond to acute	SIDS, particularly **Kiribati, Micronesia, Solomon Islands and the Maldives**.	Thermal safety margins and responses to ocean acidification are species/ population specific and often unknown.	National and sub-national scale CRAs using multiple ecological models with multiple driving climate model ensembles.

Areas of risk	Current monitoring	Time scale	Hazards and Impact	Regional hotspots for climate hazards	Key metrics/ thresholds	Gaps and Opportunities
	Ocean Biogeographic Information System (OBIS): global marine biodiversity data Global Biodiversity Information Facility (GBIF): an international network and data infrastructure for all types of life FishBase: global biodiversity information system on finfishes, providing information on population dynamics for 200 major commercial species		stress (thermal safety margin) as well as their need for particular spawning sites, and the responses of their prey [96]. **Ocean acidification** decreases survival, calcification, growth, development and abundance [46].	**China, Mozambique, Sierra Leone** [58].		Shelf seas modelling of key risk areas. Collation of fish abundance and environmental response datasets for high priority areas. Many datasets e.g., GBIF, FishBase require expert knowledge of marine ecosystems for effective use.
Human aspects such as infrastructure and production processes	Fisheries and Aquaculture - Fishery and Aquaculture Country Profiles (FAO): annual fishery and aquaculture statistics including employment, commodities production, trade, apparent fish consumption and fishing fleets	Short- and Long-term	**Sea level rise** Increased levels causing flood damage **Storms** Increased cyclone intensity causing damage and hazardous fishing conditions	See above	FAO Fisheries statistics such as employment, commodities production and trade, and fishing fleet size/ composition.	FAO Country Profiles for all countries and translations to more languages -Updates to the FAO Country Profiles to include more recent data, wider sources of information

Areas of risk	Current monitoring	Time scale	Hazards and Impact	Regional hotspots for climate hazards	Key metrics/ thresholds	Gaps and Opportunities
Threats to coastal infrastructure, ecosystems, industries, livelihoods (inc. fisheries and farming)	Quality controlled, open-source observational **tide gauge records**: -Permanent Service for Mean Sea Level (PSMSL) -University of Hawaii Sea Level Centre (UHSLC) -Système d'Observation du Niveau des Eaux Littorales (SONEL) (French coastal water level observing system) Observed **satellite altimeter data**: -European Space Agency Sea level Climate Change Initiative -Nasa datasets available through EarthData **Sea level rise projections**: -IPCC AR6: latest, state of the art projections to 2150 (CMIP6). Data via NASA-IPCC sea-level tool. SPF Met Office Sea Level Tool: local relative sea level projections	Long-term	**Sea level rise** Increased flooding, salinisation, ecosystem changes	Flatter coastal regions, including **tropical and sub-tropical river deltas** (e.g. South Coast USA and South and Southeast Asia, SIDS) [72].	Different inundation thresholds exist at each coastal location – these are highly variable and determined by local bathymetry and elevation as well as man-made defences and infrastructure.	Uncertainty in projections due to vertical land movement due to subsidence and tectonics. These are often derived from interpolation and extrapolation of tide gauge records e.g., Southeast Asia, which experience substantial subsidence due to groundwater extraction. Deltaic environments are especially vulnerable such as the Ganges Brahmaputra Meghna delta. Coastal inundation modelling: a developing area but requires up-to-date and high quality elevation data (a big limitation for many SIDS). Gaining accurate elevation data may require working closely with local government organisations (e.g.,

Areas of risk	Current monitoring	Time scale	Hazards and Impact	Regional hotspots for climate hazards	Key metrics/ thresholds	Gaps and Opportunities
						national military may already have these datasets).
	Coastal Dataset for the Evaluation of Climate Impact (CoDEC): dataset of **extreme sea levels**, **tides, storm surges, incl. future projections** using Global Tide and Surge Model [97]. GSTR: Global reanalysis of **storm surges and extreme sea level** based on hydrodynamic modelling [98]. **Wind driven waves**: Coordinated Ocean Wave Climate Project (COWCLIP) wave projections (CMIP5) **ERA5** wave reanalysis **(historical wave data**): wave model data used with observations Various short-term **wave forecasting tools** including WAVEWATCH III – maintained by NCEP (NOAA), with contributions from Met Office	Short term and long-term	**Sea level extremes** Damage from combinations of increased sea level, storms (TCs and ETCs) and associated waves and surges (including inundation events).	As above, but also exacerbated in regions affected by TCs (**south and southeast Asia, Caribbean and Pacific SIDS**) and ETCs, poleward migration means new regions are becoming exposed. Wave modelling tools can be		Both static and dynamic projection processes have limitations due to tide gauge and wave observations; tide gauge records are inconsistent and are not homogenously distributed globally, or GPS enabled, especially in South Asia. To understand impacts of extreme sea levels (including storm-driven waves and storms), information on coastal elevation and bathymetry is essential. Many

Areas of risk	Current monitoring	Time scale	Hazards and Impact	Regional hotspots for climate hazards	Key metrics/ thresholds	Gaps and Opportunities
				used to assess impacts on specific coastal cities and commercially important ports.		model studies do not have up-to-date or high-resolution bathymetric data.

Offshore and coastal energy production: including wind, oil, coal-fired powerplants and nuclear Offshore and coastal mining/ mineral extraction	***Datasets of existing coastal and marine energy/ mining infrastructure:*** **Wind:** 4C Offshore, global database of planned, under construction, and commissioned wind farms, interconnectors and infrastructure **Oil, gas, coal fire powerplants:** Global Energy Monitor, global database of discovered, in development, and operational oil and gas units **Oil:** Oilmap, global map of oil exploration and production blocks **Nuclear:** World Association of Nuclear Operators, map of nuclear power stations in WANO Member locations **Mining/ mineral extraction**: MRData: Global, Global map of mineral resources, mineral deposits and associated geology and geochemistry. ***Climate variables impacting sector:*** **SST:** Past observation and future projections for deep ocean from CMIP6/ IPCC **Wind speeds:** Global Wind Atlas can provide a static snapshot/ seasonal information about wind speeds **Storms, sea level rise and extremes:** *see Coastal Hazards*	Long- and short-term	**Storms (TCs and ETCs)** and **related wind, waves and surges** cause damage to coastal and offshore infrastructure, including seabed pipes used to oil/ gas/ energy supply. **Wind speeds** – needed to generate wind power, high winds can damage oil rigs, and disperse pollutants in a spillage more widely **Increased ocean temperatures** have more severe impacts than higher air temperatures, particularly where water is used for cooling (e.g., nuclear and coal). **Coastal flooding/ inundation, sea level rise, subsidence**	Dependent on regional density of coastal and offshore infrastructure. Areas more vulnerable (and becoming more exposed to) to storms more likely to be affected (**south and southeast Asia, Caribbean and Pacific SIDS**) [85].	Some wind turbines cannot withstand wind speeds >55 mph.	*See Coastal Hazards*

Image location: Kiribati

5. Summary of Research Gaps, Opportunities and Recommendations

The following section summaries the research gaps followed by opportunities within the 4 priority areas. Key recommendations from all areas are presented below.

5.1. Marine ecosystems

Mangroves

- Spatial information is limited i.e., monitoring the changes in spatial extent of mangroves is difficult and limited to the sophistication of remote sensing technologies [82].

Sea grass and macroalgae

- Knowledge on seagrass mortality is lagging behind e.g., corals because seagrass mass mortality events are more recent.
- More coordinated and standardised procedures for monitoring data which are currently very geographic dependent [94].
    - Seagrass monitoring should include indicators that can lead to a loss in resilience such as breaks in connectivity, and range shifts [95].
- Mismatch between point observations of seagrass and macroalgal forests vs. gridded environmental data such as temperature makes projecting changes in these ecosystems very challenging [95].
- Cumulative impacts and ecological feedbacks must be accounted for in all marine ecosystems e.g., there are some variables such as nitrogen which can enhance the thermal tolerance of macroalgae.

Corals

- Marine heatwaves are an important stressor on coral ecosystems that need to be captured in future risk analyses.
    - The Degree Heating Weeks metric which has historically been used to evaluate coral bleaching is inappropriate at capturing these events [30].
    - Future estimations of the frequency and intensity of these events should also account for the changes in depth of the thermocline such as done by Wyatt et al. (2023) [92] which will determine the subsurface profile of these events and hence exposure of corals to higher sea water temperatures.

- It is important to consider the effects of multiple co-occurring environmental variables which will either amplify or regulate the impact of each other at all timescales from seasonal to decadal and longer-term.

[BOX 5.1] OPPORTUNITIES – MARINE ECOSYSTEMS

→ There are evidence gaps on the changing **frequency and intensity of future marine heatwaves** regionally and their impacts on associated marine ecosystems

→ There is a requirement for future risk assessments to account for the **co-occurring (opposing and amplifying) impacts of multiple environmental variables** (e.g., temperature, pH, nutrients, turbidity)

→ There is potential for **machine learning models** to be used to project climate change effects e.g., on mangrove environments.

→ There is a requirement for **modelling in the Indo-Pacific region** where most seagrass diversity exists to explore climate risks to seagrass.

→ A substantial, updated analysis of **regionally-specific risks** to corals such as undertaken in the 'Reefs at Risk' regional summaries[1] published in 2011, would create a baseline from which to understand how differently climate change will affect these coral ecosystems regionally.

→ A better understanding of the proportion and evolution of **thermally tolerant corals** would help to evaluate potential resilience due to rising SSTs

→ Opportunities to create **seasonal outlooks for coral bleaching** which would aid early warning systems and response systems to bleaching events.

5.2. Nationally important fishing territories

- Few studies that attempt to assess the impacts of climate change on marine vertebrate species due to scare and unreliable data for the marine environment. In addition, there exists complex biological interactions and compounding human stressors [53].
- There are large limitations in the ocean environment data available through CMIP and CORDEX as these models are coupled to ocean models that do not contain tides which are essential for resolving important shelf sea processes such as stratification.
- Comprehensive CRAs include multiple aspects of the marine industry and should be carried out by interdisciplinary teams who can provide expert insight on modelling/dataset limitations and interpretation.

- FAO Country Profiles[8] are not available and/or do not contain recent data for all countries.

[BOX 5.2] OPPORTUNITIES – FISHING TERRITORIES

→ National and sub-national scale **CRAs** for fisheries **using multiple ecological models with multiple driving climate model ensembles** would help to account for limitations and uncertainties in models and underlying datasets.

→ **Shelf sea modelling** of key risk areas e.g., SIDS in shelf regions, Southeast Asia to better represent processes such as stratification that determine environmental conditions such as ocean temperature which strongly influences fish distribution, phenology and physiology.

→ Collation of **fish abundance and environmental response datasets** for high priority areas and high priority species from across existing databases and supplemented with local sources.

→ **FAO Country Profiles** could be updated to include more recent data and wider sources of information. Translation to additional languages could also be useful.

5.3. Coastal hazards

Sea level rise

- Sea level estimates and projections are derived from interpolation and extrapolation of tide gauge records.
  - Tide gauge records are inconsistent, not homogenously distributed worldwide, nor regularly GPS enabled, especially in South Asia. Rates of sea level rise are also likely to be underestimated due to subsidence.
  - Satellite altimetry data are not continuous and have limitations close to the coastline – mountains, bays and offshore islands can distort radar signals.
- Up-to-date and high-quality elevation data is a big limitation for many SIDS as it prevents definition of sea level overtopping thresholds.

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[8] Fisheries and Aquaculture - Fishery and Aquaculture Country Profiles (fao.org)

Extreme sea level

- Dynamic datasets assessing extreme sea level have biases due to features such as limited timespan and limits to the understanding of how atmospheric processes lead to sea level change.
- Both static and dynamic projection processes have limitations due to tide gauge and wave observations – gauge data needs to be relatively long-term and continuous (e.g., >20 years) in order to look at long term change.
    - Wave and surge measurements are especially uncertain near coasts as trends are typically observed offshore due to tide gauges being typically located in sheltered locations.

Coastal inundation modelling

- Coastal inundation modelling relies on knowing elevation at a useful resolution.
    - Global datasets such as the Shuttle Radar Topographic Mission have uncertainties (e.g. due to large data voids) along the same order as sea-level rise estimates.
    - This can affect impact assessments (e.g., Mekong delta [96]), especially in data-sparse delta regions.
- Inundation datasets by ClimateCentral[9] do not include features such as coastal defences.

[BOX 5.3] OPPORTUNITIES – COASTAL HAZARDS

→ Accurate elevation data is the first step to understanding exposure to coastal inundation - more accurate elevation (and bathymetry data) is required and can be improved through collaboration with local authorities and organisations.

→ Targeted modelling is required to understand how inundation modelling interacts with coastal defences.

5.4. Coastal and offshore energy production/ wealth extraction

- There is a lot of uncertainty about historical and projections of wind speed trends (and so wind-driven waves) due to uncertainties in GCMs and differing approaches to projecting winds. This affects understanding of impacts to infrastructure.
- The contribution of wind-driven waves is also uncertain due to differing methods for deriving waves – i.e., through different approaches to wind-wave modelling.

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[9] https://coastal.climatecentral.org/

- Storms are complex systems, and their behaviour is influenced by a range of other systems including sea surface temperature, extent of sea ice, position of jet streams and climate patterns.

[BOX 5.4] OPPORTUNITIES – COASTAL AND OFFSHORE ENERGY PRODUCTION / RESOURCE EXTRACTION

→ Localised studies to better understand the effects of increased high wind speeds under climate change scenarios on pollution dispersion and damage potential to coastal and offshore energy infrastructure such as thermal and nuclear power generators. Areas which are likely to become more vulnerable to storms and could be targeted include south and southeast Asia, the Caribbean and Pacific SIDS.

5.5. Recommendations across all priority areas

We have identified 3 recommendations for additional research based on the above gaps and opportunities across the 4 priority areas.

1. Accurate SST projections

A first order metric for understanding future change to maritime environments is accurate SST projections. However, GCMs and RCMS (such as CMIP and CORDEX models) cannot resolve important processes in coastal (shelf sea) regions due to lack of tides in the ocean models with which they are coupled.

In order to understand impacts to marine ecosystems (e.g., marine heatwaves), fisheries (e.g., for understanding impacts to ocean productivity and fish species distributions), coastal hazards (e.g., tropical cyclones) and offshore and coastal energy (e.g., impacts to coastal powerplant cooling systems) **it is crucial to have robust projections of SSTs***.

Shelf sea models contain tides and can provide more realistic SST information (and so more trustworthy projections). While shelf sea modelling is an active area of research, most models are limited by location, available in small regions outside of ODA-eligible areas (such as the Northwest European Shelf that surrounds the UK) – modelling is required in vulnerable regions including *South East Asia, and SIDS located in shelf seas.*

**Note that some SIDS (such as a number of Pacific islands) are not located in shelf sea regions* *but in areas of open ocean*[10]*. In these instances, use of GCMs and RCMs is appropriate – due to the less complex nature of the open ocean, SST projections are more realistic in these regions (see Section and Box 2.1).*

RECOMMENDATION 1

Conducting shelf sea modelling in vulnerable regions

A number of shelf sea models exist but are computationally expensive to run due to the complexities required to accurately resolve the shelf sea environment. Simplified shelf sea models run with GCMs or RCMs may be used instead to look at marine climate impacts (and SSTs) at larger scales **but research is required to understand if using simplified shelf sea models can improve SST projections**.

S2P2v2 is a computationally efficient (simplified) shelf sea model that has been run globally using CMIP models and has been used in regional studies assessing coral bleaching, e.g., on the Great Barrier Reef. Models like this have great potential for use in regional risk reports but require additional resource to use effectively.

2. High resolution coastal elevation and bathymetry data

To fully understand the impact of sea level rise and extreme sea level (including inundation/ coastal flooding), up-to-date, high-quality, high-resolution bathymetry and coastal elevation data is required.

Though global bathymetry and elevation data is available (e.g., through GEBCO), many regions do not have up-to-date and/ or high-resolution data. Coastal morphology is constantly changing (often due to impacts of coastal hazards or natural weathering processes) so regular updates to elevation and bathymetry data is needed. Without such data, the ability to predict overtopping and inundation thresholds for sea level rise and extreme sea levels is highly limited. This is especially the case in extremely vulnerable SIDS and deltaic environments (e.g., South Asia).

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[10] Open ocean SIDS only (non-definitive list compiled by the Met Office): **Pacific Ocean**: Kiribati, Cook Islands, French Polynesia, Palau, Fiji, Tuvalu, Tonga, Niue, American Samoa, Samoa, Nauru, Marshall Islands, Fed. States of Micronesia, Guam, Northern Marianas Islands; **Atlantic Ocean:** Cape Verde, São Tomé and Príncipe; **Indian Ocean:** Comoros, Mauritius, Seychelles, Maldives

RECOMMENDATION 2

Updating and improving elevation and bathymetry data for vulnerable regions

More investigation is needed to identify local datasets of coastal elevation data - local government organisations (e.g., national military) may already have these datasets.

Satellite altimetry data on coasts is poor but several projects are working on improving satellite measurements of coastal elevation e.g., initiatives such as European Space Agency Sea Level Climate Change Initiative. Future work should link with similar organisations.

The UK Hydrographic Office can provide new and high-resolution bathymetry data. Additional resource would allow for mapping of sea floor (and coastal morphology) in vulnerable regions for better estimates of sea level rise and extreme sea levels.

3. Specialised assessment of marine ecosystems and national fisheries

While a large amount of information on responses of marine ecosystems and fisheries to climate change can be gained from literature, for **more robust and in-depth assessment** of these priority areas (in key vulnerable regions) is required from **marine ecosystem experts**.

For example, the production of **national and sub-national scale CRAs using multiple ecological models with multiple driving climate model ensembles** would help to account for limitations and uncertainties in available datasets and existing research.

RECOMMENDATION 3

Collaboration with marine ecosystem experts for specialised assessment

While the Met Office contributes to programmes such as the Marine Climate impacts Partnership (MCCIP), other UK-based organisations in MCCIP may be better placed to conduct specialised assessment of marine ecosystems in vulnerable locations.

For example, building on the MCCIP Marine Report Cards for UK Overseas territories which were a collaboration between the Centre for Environment Fisheries and Aquaculture Science (CEFAS), UKHO and National Oceanography Centre (NOC) in addition to regional specialists.

Image location: Bangladesh

6. Acronyms

CEFAS- Centre for Environment Fisheries and Aquaculture Science

CiC- Climate in Context

CoDEC- Coastal Dataset for the Evaluation of Climate Impact

CORDEX- Coordinated Regional Climate Downscaling Experiement

COWCLIP- Coordinated Ocean Wave Climate Project

CMIP(5,6)- Coupled Model Intercomparison Project (Project Phase 5, or 6)

CRA- Climate Risk Assessment climate risk assessments (CRAs)

ECMWF- European Centre for Medium-Range Weather Forecasts

EEZ- Exclusive Economic Zone

ENSO- El Niño Southern Oscillation

ETC- Extra-tropical Cyclones

ETP- Eastern Tropical Pacific

ETWL- Extreme Total Water Level

ERA5- ECMWF Reanalysis v5

ESL- Extreme Sea Level

ESWL- Extreme Still Water Levels

FAO- Food and Agriculture Organization

FCDO- Foreign, Commonwealth and Development Office

GBIF- Global Biodiversity Information Facility

GCM- Global Climate Model

GEBCO- The General Bathymetric Chart of the Ocean

GMSL- Global Mean Sea Level

GPS- Global Positioning System

GTSR- Global Tide and Surge Reanalysis

IPCC (AR6)- Intergovernmental Panel on Climate Change, Sixth Assessment Report (2021)

MCCIP- Marine Climate Impacts Partnership

MHW- Marine Heat Wave

NASA- National Aeronautics and Space Administration

NCEP- National Centers for Environmental Prediction

NOAA- National Oceanic and Atmospheric Administration

NOC- National Oceanography Centre

OA- Ocean Acidification

OBIS- Ocean Biogeographic Information System

PERSGA- Red Sea and Gulf of Aden

PSMSL- Permanent Service for Mean Sea Level

RCM- Regional Climate Model

RCP(2.6, 4.5, 8.5)- Representative Concentration Pathway (2.6, 4.5, 8.5) W/m^2

ROPME- Regional Organization for the Protection of the Marine Environment

SDM- Species Distribution Model

SIDS- Small Island Developing States

SLAMM- Sea Level Affecting Marshes Model

SLR- Sea Level Rise

SONEL- Système d'Observation du Niveau des Eaux Littorales

SPF- Strategic Priorities Fund

SSP- Shared Socioeconomic Pathway

SST- Sea Surface Temperatures

TC- Tropical Cyclone

UKHO- UK Hydrographic Office

7. References

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8. Appendix: Information on key marine datasets

This table contains key datasets (non-exhaustive) which could be made use of in marine climate risk assessments. For full details see the links provided.

Hazard/ Risk	Key Impacts	Variables	Dataset name/ Institute	Domain	Time Period	Temporal Resolution	Spatial Resolution	Reference/ DOI	Advantages and Caveats
Sea Level Rise	Coastal infrastructure including fisheries and mangrove inundation. Can also cause salinisation and ecosystem changes. Exacerbation of storms and tropical cyclones	Dynamic sea level	CMIP6	Global	Historical to 2100	Monthly, daily, fixed	Varies between 100-300km – see More information on resolutions can be found here: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_AnnexII.pdf	CMIP Phase 6 (CMIP6) - Coupled Model Intercomparison Project (wcrp-cmip.org)	CMIP6 has limited capacity at representing observations over the subtropical (particularly North Atlantic) regions due to association with western boundary currents. It also has poor representation over shelf sea environments. Nearshore bias can be reduced by using

	including surges and inundation events								HighResMIP: https://hrcm.ceda.ac.uk/research/cmip6-highresmip/
		Mean Sea level	Copernicus Data Store incorporating reanalysis and high res CMIP6 projections	Global	ERA5 reanalysis: 1979 to 2018 Climate model historical simulations: 1950 to 2014 Future Climate projection: 2015 to 2050	Reanalysis: 10-minute, hourly and daily maximum Climate projections historical and future: 10-minute, annual	Coastal grid points: 0.1° Ocean grid points: 0.25°, 0.5°, and 1° within 100 km, 500 km, and >500 km of the coastline, respectively	https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-level-change-timeseries-cmip6?tab=overview	Resolves tides with the Deltares Global Tide and Surge Model: Global modelling of tides and storm surges | Deltares
			UKCRP sea level rise tool – using the UKCP18	Globally relocatable tool (based on latitude and	2007-2300	Annual	12km around UK coastline	Marine Projections - Met Office	Very long projection. Can be used seamlessly with the UKCP18 Climate

			global projections	longitude) following methodologies in UKCP18					Projections. Results beyond 2100 are exploratory and have a far greater degree of uncertainty post-2100 and should be treated as illustrative.
Ocean warming	Various impacts on marine ecosystems e.g. species redistribution, range contractions, adjusted physiological functioning of e.g. spawning, increased spread of disease and pathogens,	SSTs	CMIP6	Global	Historical to 2100	Monthly, daily, fixed	From 0.125° x 0.125° to 5° x 5° depending on the model 1850 – 2100 (can extend to 2300 for some experiments) (Eyring et al., 2016).	[CMIP Phase 6 (CMIP6) - Coupled Model Intercomparison Project (wcrp-cmip.org)](wcrp-cmip.org)	Not well resolved over shelf sea environments. More detailed modelling needed to apply to localised reefs and fish habitats.
		Reanalysis products recording various	e.g. OCEAN5 (ECMWF)	Global	1979-present	Monthly and daily	ORCA 0.25°	https://www.ecmwf.int/en/research/climate-reanalysis/ocean-	

	deoxygenation of sea water and increased likelihood of marine heatwaves, increased number of coral bleaching events Reduced cooling potential for power plants	variables						reanalysis	
			Copernicus marine data service for GLORYS12V1 product (CMEMs)	Global	1993-present	Monthly and daily	1/12° (approx 8 km) and on 50 standard levels	https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description	
		NOAA reanalysis products	See link	Global	Various	Various	Various	https://psl.noaa.gov/data/gridded/tables/sst.html	
		Ocean heat content (OHC)	Copernicus marine data service	Global Ocean Lat -60° to 60°, Lon -180° to 180°	2005-2019	Annual	Timeseries averaged over several different depths	Global Ocean Heat Content (0-300m) from Reanalysis & Multi-Observations Reprocessing | Copernicus Marine MyOcean Viewer	Useful to obtain the mean OHC to monitor the large-scale variability and change and to monitor the amount heat stored in the ocean.
		Observati	Copernicus marine	Global	2007-	Daily	0.05 x 0.05°	https://data.marine.copernicus.eu/p	Very high resolution

		ons of SST	data service for OSTIA product		present			roduct/SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001/description	
Ocean Acidification	Reduction in the calcification of aragonite and calcite forming organisms, making them more vulnerable to other climate stessors.	Concentration of aragonite, Aragonite saturation, Calcite concentration and saturation, ocean pH	CMIP6	Global	Historical to 2100	Monthly, daily, fixed	Varies between 100-300km – see More information on resolutions can be found here: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_AnnexII.pdf	CMIP Phase 6 (CMIP6) - Coupled Model Intercomparison Project (wcrp-cmip.org)	Some models may underestimate the alkalinity in the sea surface (Hinrichs et al. 2023)
			NCEI fused data product	Global	Historical (1850-2010),	Decadal	1° × 1° grid	https://www.ncei.noaa.gov/data/oceans/ncei/ocads/m	Model-data fusion product provides more

					Future (2020-2100)			etadata/0259391.html	accurate carbonate chemistry projections
			Observation data e.g. GLODAP, SOCAT	Global	GLODAP: Data from multiple water samples from cruises, SOCAT: Surface Ocean CO_2 measurements	Various, irregular resolution	Gridded observation data (irregular resolution)	https://www.glodap.info/ https://www.socat.info/	Interactive digital earth viewer is available through: https://www.glodap.info/index.php/merged-and-adjusted-data-product-v2-2022/
			Copernicus marine data service	Global	1993-2020	Daily and monthly	0.25° × 0.25°	https://doi.org/10.48670/moi-00019	
Cyclones	Damage to coastal infrastructure through increased	Maximum Sustained Wind Speed (knots),	IBTrACS	70° N to 70° S and 180° W to 180° E	1841 - present	Interpolated to 3 hourly	0.1°	https://www.ncei.noaa.gov/products/international-best-track-archive	IBTrACS is a collection of other cyclone track data.

	cyclone intensity and associated waves and storm surges, hazardous fishing conditions	Minimum Central Pressure (mb), Storm Center of Circulation (degrees lat/lon)							The time between a storm's end and when its reanalysis is complete can be more than one year.

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Image location: East Java