Climate Change Vulnerability Assessment (CCVA) toolkit for near-shore marine socio-ecological system in the Western Indian Ocean

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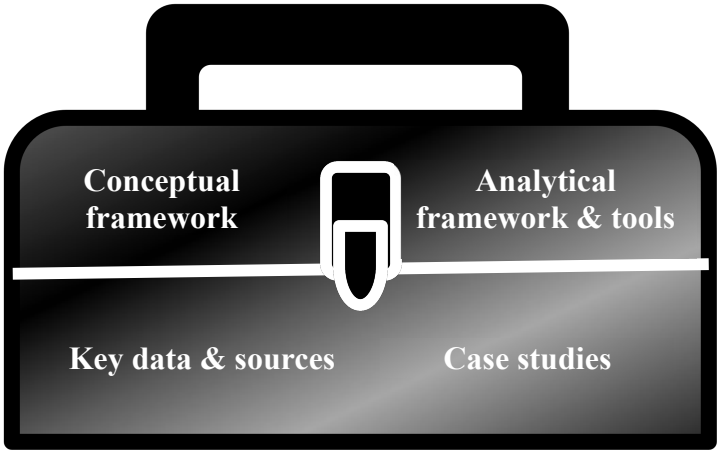

Document Length:

Main text (excluding title page, table of contents and references): 40 pages

127 References

12 Figures

6 Tables

4 Table Annexes

2 Case Study Annexes (including one draft manuscript for peer reviewed publication)

Draft report submitted to UNEP – Nairobi Convention

April 3, 2019

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1 Climate Change Vulnerability

1.1 What is climate change vulnerability?

Climate change is expected to drastically alter ecosystems and their capacity to provide benefits to human society, as has been the case for centuries. The intensity and magnitude of change will vary over spatial and temporal scales leading to differential impacts on ecosystems and community livelihoods. Furthermore, the heterogenous nature of climate change impacts and the differential responses of the socioecological systems complicates the management intervention to address the impacts of climate change. Therefore, informing the management on strategies that can help the social and ecological systems to adapt, resist, recover or minimize the impacts is key to effectively addressing climate change impacts on social and ecological systems. One way of generating information that can inform spatially and temporally adaptive climate change adaptation strategies is through Climate Change Vulnerability Assessment (CCVA).

Climate change vulnerability is the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change including climate variability and extremes (Füssel and Klein, 2006). Vulnerability is an integrated measure of the expected magnitude of adverse effects to a system caused by a given level of certain external stressors to generate risk (Figure 1) (Oppenheimer et al. 2014). It reflects the potential for a system to experience harm in response to some external influence, pressure or hazard. The relevant system or process may be an individual or population; a single species or an entire ecosystem; a business enterprise or an entire regional economy. Moreover, vulnerability index refers to "*a metric characterising the vulnerability of a system, which is typically derived by combining, with or without weighting, several indicators assumed to represent vulnerability*" (IPCC, 2014). CCVA is typically conducted to inform the identification of measures to adapt to climate change impacts, and to enable practitioners and decision-makers to identify the most vulnerable areas, sectors and social groups. Therefore, climate change adaptation options targeted at specific contexts can be developed and implemented.

The CCVA toolkit has been created to address the urgent regional challenge of enabling countries in the Western Indian Ocean to adapt more effectively to the impacts of climate change and variability. This report aims to provide a guideline and tools that can be useful for the development of CCVA to support climate change adaptation strategies. The toolkit consists of climate data (future and retrospective) and essential information and on climate change data, conceptual and analytical frameworks and regional case-studies.

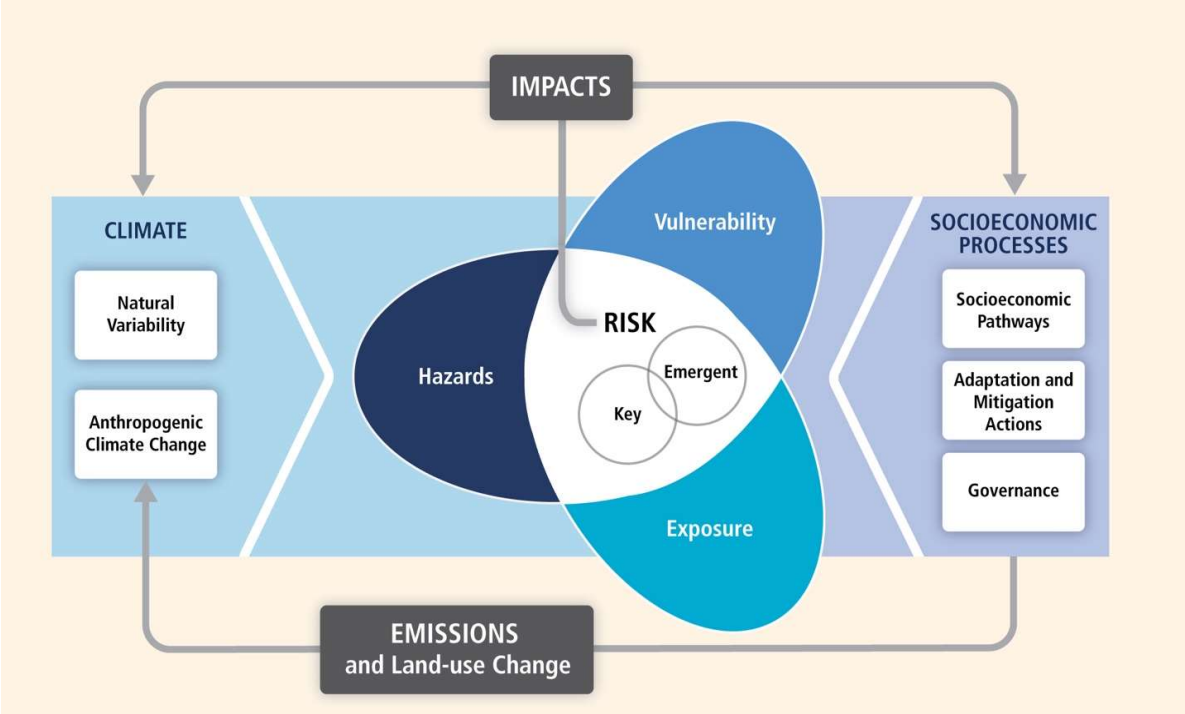

Figure 1: Schematic diagram illustrating the interactions among the physical climate, exposure, vulnerability and risk. The key words (*exposure, vulnerability, risk* and *hazard*) are defined in Box 1 (adopted from Oppenheimer et al. 2014).

The risk of climate-related impacts (Figure 1) stems from the interaction of climate-related hazards with the vulnerability and exposure of human and natural systems. The severity of the impacts of extreme and non-extreme climate depends strongly on the degree of vulnerability and exposure to these events (Cardona et al. 2012). For example, coral reefs across the world's Oceans were *highly exposed* to a prolonged period (2014-2016) of elevated sea surface temperature, which led to the 3rd global bleaching event of 2016. Following this event, 30% of the exposed reefs in WIO bleached severely while 10% experienced severe mortality (Obura et al. 2017). The differential response of a system is primarily driven by the capacity inherent within the system to 'resist' the external pressure it is exposed or subjected to. Consequently, climate change impacts can be avoided if a population or ecosystem is exposed but has inherent capacity (i.e. adaptive capacity to avoid/resist harmful effects and to recover from the impacts. In social-ecological system context, vulnerability and exposure of ecological and social environments are interlinked.

Changes in both the climate system and socioeconomic processes (Figure 1) are central drivers of the three core components that constitute risk (i.e. *vulnerability, exposure*, and *hazards*). As illustrated on the conceptual framework (**Error! Reference source not found.**), a *risk* is influenced by *hazard, exposure and vulnerability*. Risk can therefore be expressed as:

$$Risk = Hazard\ x\ Exposure\ x\ Vulnerability \quad (1)$$

Given that vulnerability can be split into its constituting dimensions (*exposure, sensitivity* and *adaptive capacity*), risk can also be expressed as:

$$Risk = Hazard\ x\ Exposure\ x\ Sensitivity\ /\ Capacity\ to\ cope\ and\ adapt \quad (2)$$

Using this expression, it can be deduced that a system is at high risk when:

- *Hazard is high* – intensive and frequent in both spatial and temporal dimensions;
- *Exposure is high* –presence of ecosystem exposed to hazard during a specific period / time/ season and in a geographical area (space). For example, during the strong El-Nino in 2016, coral reefs and mangroves around the world were exposed to heat waves.
- *Sensitivity is high* – the sensitivity or susceptibility of an exposed unit to be harmed or adversely affected is high. For example, sensitivity of coral reefs to thermal stress can coral bleaching or the whitening of the coral skeleton.
- *Capacity to cope and adapt is low* – the knowledge, skill, social, physical, financial and natural resources that enhance the capacity of the exposed unit are low.

Therefore, risk reduction can be conceptualized as follows:

- Reducing hazard – the hazard mitigation parts
- Reducing the exposure – keeping the elements / units / system away from the hazard areas and time or period of hazard
- Reduce the sensitivity or susceptibility – minimise the weaknesses of the exposed elements, units, or systems through proper management strategies and policies
- Strengthen the capacity to cope and adapt – enhance the strength parts of the exposed elements, units, or systems, if they cannot be removed from the hazard areas or period, or even in the period and locations where and when they have been relocated.

Box 1: key definitions

Adaptive Capacity is the ability of a system to accommodate or cope with climate change impacts with minimal disruption on its functioning. This can be through ecosystem or species response, and through human actions that reduce vulnerability to actual or expected changes in climate.

Exposure is the nature and degree of a system's exposure to significant climatic variations. In the climate change context, exposure captures important weather events and patterns that affect the system, but can also represent broader influences such as changes in related systems brought about by climate effects.

Hazard is the potential for the occurrence of a natural or human-induced physical event that may cause loss or damage to ecosystems, environmental resources and livelihoods**.**

Risk is the potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. For example, a projected increase in the intensity of tropical cyclones will significantly increase the risk of coral reefs from physical damage due to strong winds and waves. Tropical cyclones also cause heavy rainfall, which can cause flooding leading to socioeconomic distress and sediment plumes that can cause stress on coral reefs.

Sensitivity reflects the responsiveness of a system to climatic influences, and the degree to which changes in climate might affect it in its current form. Sensitive systems are highly responsive to climate and can be significantly affected by small changes in climate.

As an example of applied vulnerability framework for mangrove systems in Gazi, Kenya, one would consider the exposure elements such as high temperature and sedimentation from adjacent mining locations, and other pressures. Sensitivity elements would consider the types/species composition and their ecological response to pressures, while adaptive capacity would consider how well the mangroves can resist and recover from perturbations.

1.2 Intergovernmental Panel on Climate Change (IPCC) vulnerability framework

The broader vulnerability literature, including IPCC reports describe climate change vulnerability framework comprised of three dimensions, suggesting that the extent to which people's livelihoods are vulnerable to the impacts of climate change is dependent on: 1) their exposure to climate impacts (i.e. if impacts are felt in their location); 2) their sensitivity (i.e. the extent to which their livelihood is affected by an impact); and 3) their capacity to adapt to the likely impacts (Cinner et al. 2013; Oppenheimer et al. 2014). Quantifying each dimension for a system over varying spatial and temporal scales is key to estimating the systems spatially and/or temporally explicit vulnerability. This framework of vulnerability highlights the key dimensions that combine to amplify (or alleviate) the costs and risks that climate change can impose on a system. Understanding these dimensions and their constituent variables and indicators can help in

identifying climate change threat to allow for the formulation of strategic actions that can facilitate threat reduction (Marshall et al. 2010) (see Box 1).

1.2.1 Climate Change Emission scenarios

Projections of climate are based on future scenarios of Greenhouse gas (GHG) emissions (IPCC, 2013). Therefore, it is essential that CCVA explicitly states and describes the assumptions pertaining GHG emission (i.e. climate change scenarios) considered in the assessment. For example, the IPCC climate change assessment reports explicitly describe the scenarios considered (i.e. AR4 scenario in the 4th generation models (Commonly referred to as SRES); AR5 scenario in the 5th (current) generation models; and AR6 in the 6th generation (expected in 2021) models). Climate projections from the fourth IPCC assessment report (AR4) are based on a previous set of socio-economics based scenarios termed the *Special Report on Emissions Scenarios* (SRES; Nakicenovic et al. 2000). These SRES scenarios were the basis for the Coupled Model Inter-comparison Project (CMIP4) suit of Ocean and Atmosphere General Circulation Models (i.e. future climate data). Projections for the IPCC fifth assessment report (AR5) are based on the radiation-based scenarios of *Representative Concentration Pathways* (RCP; Moss et al. 2010; van Vuuren et al. 2011) and simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Understanding the assumptions underpinning each of the emission scenarios is necessary for comparing and matching future climate predictions across different generations of IPCC climate change scenarios (i.e. SERS, AR5, AR6) to allow the use of data from the diverse set of models and scenarios (e.g. Table 1).

Table 1: Comparison and matching of two generations of IPCC climate change scenarios (i.e. SRES and RCP; Rogelj et al. 2012). SRES and RCP Scenarios are described in greater detail by Moss et al. (2010) and van Vuuren et al. (2011).

GHG Scenarios		**Descriptions**
RCP	**SRES**	**Particular difference**
RCP 2.6	None	
RCP 4.5	SRES B1	Median temperatures in RCP4.5 rise faster than in SRES B1 until mid-century, and slower afterwards.
RCP 6	SRES B2	Median temperatures in RCP6 rise faster than in SRES B2 during the three decades between 2060 and 2090, and slower during other periods of the twenty-first century.
RCP 8.5	SRES A1FI	Median temperatures in RCP 8.5 rise slower than in SRES A1FI during the period between 2035 and 2080, and faster during other periods of the twenty-first century.

1.3 Social-ecological vulnerability

An increasingly critical aspect of sustaining ecosystems (e.g. coral reefs) and the livelihoods of dependent people is the understanding of vulnerability of the socio-ecological system (Folke, 2006). Approximately 60 million people live within 100 km of the coast across the Western Indian

Ocean (Obura et al. 2017). Over time, coastal residents have developed many connections with the Ocean, including cultural, livelihoods from fishing and aquaculture/mariculture, transport, tourism, and recreation. These connections, some of which are key for the survival and wellbeing of coastal communities, are under threat from climate change. CCVA of coastal social-ecological system as a management tool can be used to inform management decisions on mitigating climate change impacts (Beroya-Eitner 2016), and for developing climate change adaptation strategies for coastal communities.

In estimating climate change vulnerability of socio-ecological system, some of key questions the assessment addresses include:

- What threats or pressures are faced by ecological and/or a social system?
- Are threats different across the different systems being considered or are they similar?
- What is the degree of exposure, how sensitive is the system to perturbations, and what is the capacity for system to adapt?
- What consequences does the response of one system have on another system's integrity?

Solutions to these questions may involve ecological research, analyses of climate change data and socioeconomic assessments among other activities. The conceptual framework of climate change vulnerability provides a basis for operationalizing and assessing the vulnerability of linked social and ecological systems (Cinner et al. 2013).

An alternative framework modified from the IPCC framework (Cinner et al. 2013; Marshal et al. 2009) idealizes two linked sub-sets of vulnerability: one subset represents the components of ecological vulnerability to the exposure to climate change, while the other represents social vulnerability to changes in the ecological system (Cinner et al. 2013). The ecological exposure, ecological sensitivity, and ecological capacity for adaptation are synthesized to represent the degree to which climate change will impact on the continued supply of ecosystem goods and services (i.e. the ecological vulnerability). Therefore, in this framework, ecological vulnerability represents the exposure of the socioeconomic domain to climate threats. The overall social-ecological vulnerability is conceived as a result of the sensitivity of socioeconomic systems to ecological vulnerability, and the capacity of the society to adapt to such impacts (Cinner et al. 2013). An example of the interpretation or deductions of socio-ecological vulnerability from assessments based on the modified framework can be found in the work done in WIO (Cinner et al. 2013) on assessment of social-ecological vulnerability of coral-reef fisheries for resource-dependent communities in Kenya. They found that communities living in close proximity to fished sites were marginally more vulnerable than those practicing community-based closures and those adjacent marine reserves. Communities were found to differ in relative strengths and weaknesses in terms of social-ecological vulnerability to climate change. A fisher community village in Kenya (*Takaungu*) was found to be highly vulnerable to climate change owing to high ecological exposure, low social adaptive capacity and low social sensitivity.

More recently, Aswan et al. (2018) developed an integrated vulnerability framework, which synthesises ecological exposure, sensitivity and adaptive capacity (i.e. ecological vulnerability) with social livelihoods and food security approaches (**Error! Reference source not found.**). In this framework, vulnerability comprised of two high-level components representing biological and

human subsystems. In this approach, environmental exposure is combined with the biological/ecological sensitivity to estimate ecological vulnerability within the ecological subsystem (Pecl, et al., 2014). The ecological vulnerability is then integrated with socio-economic subsystem to influence socio-ecological vulnerability (Figure 2).

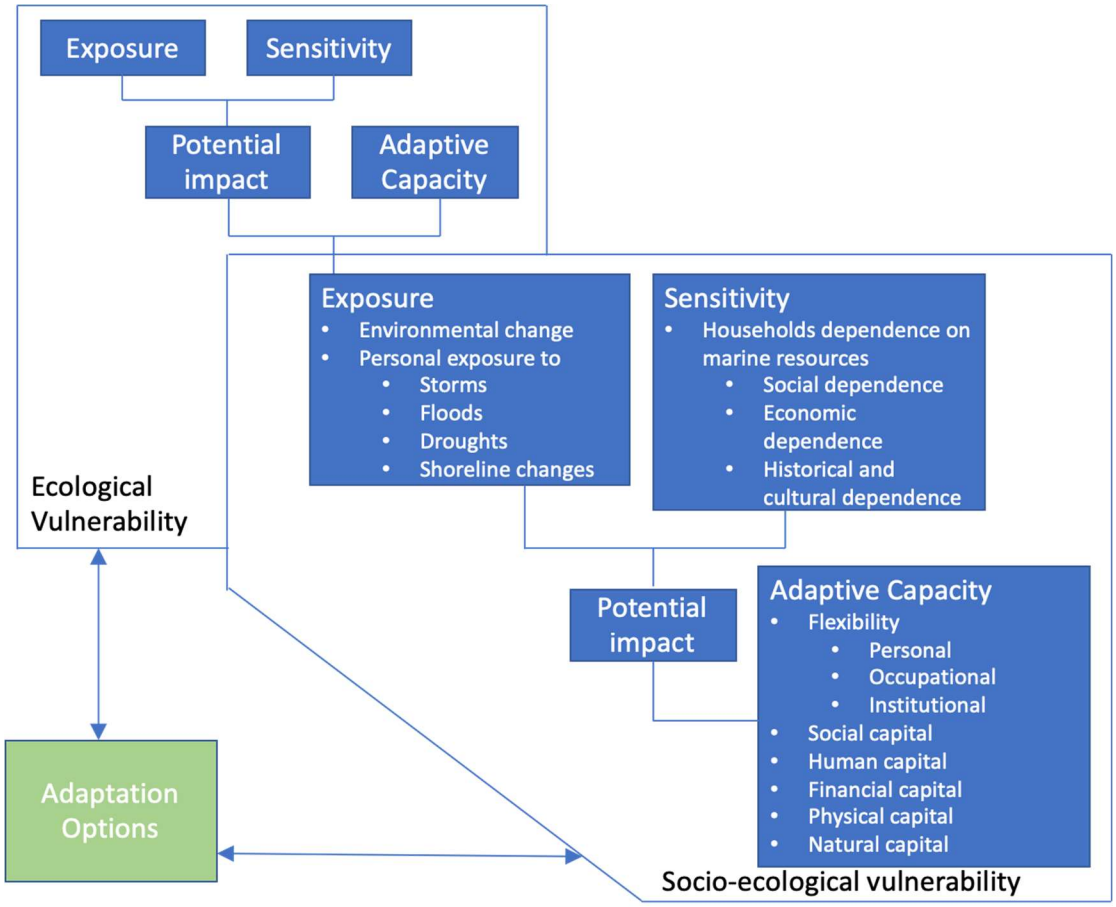

Figure 2: A conceptual CCVA framework for climate-sensitive socio-ecological systems, which builds on the IPCC vulnerability framework (adopted from Aswani et al. (2018). Examples of indicators for each of the vulnerability dimensions are also listed.

1.4 Approach to conducting CCVA and concepts

Approaches to vulnerability assessments are based on two main interpretations of vulnerability, which have been conceptualized as *outcome vulnerability* and *contextual vulnerability* (Kelly and Adger, 2000; Dessai & Hulme, 2004; O'Brien et al. 2007; van Aalst, et al. 2008). These are linked respectively to a *scientific pitch/relevance* and a *human-security pitch/relevance*. Each of the pitching prioritizes the production of different types of knowledge and emphasizes different types of policy responses to climate change (O'Brien et al. 2007; van Aalst, et al. 2008). Ultimately, the framework, interpretation and the approach adopted in CCVA is dependent on management goals or on the goals of the exercise and on the data available.

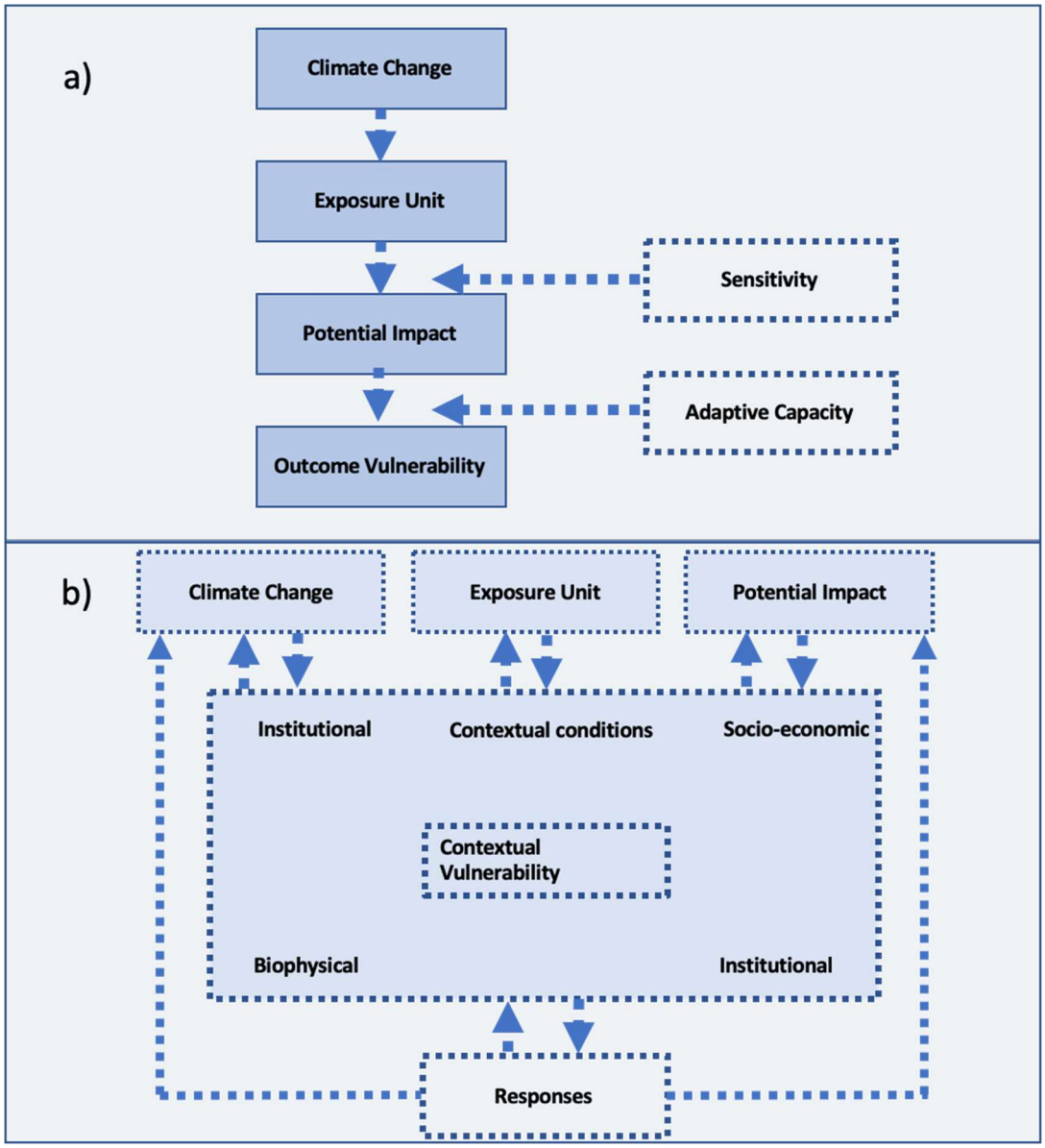

Figure 3: An illustration of the two climate change vulnerability interpretations, which can lead to different approaches to the assessments: (a) outcome vulnerability and (b) contextual vulnerability (Adapted from Füssel (2009) and O'Brien, K. L. et al. 2007).

Outcome vulnerability (Figure 3a) begins with a scenario-based analysis of climate models primarily global or regional to project future impacts and only considers socio-economic impacts if quantitative models are available to link to the biophysical effects (Kelly and Adger, 2000). Therefore, the main output from such studies is an assessment of physical vulnerability for a time period in the future as it assumes a direct cause-effect relationship between climatic stresses and their impacts on biophysical systems, e.g. the effect of a decrease in total rainfall on mangrove growth. Assessment of outcome vulnerability often leads to a technical recommendation to reduce vulnerability or the susceptibility to damage (Eriksen and Kelly, 2007).

Contextual vulnerability (Figure 3b) approach (Figure 3b) consider vulnerability as an overarching concept within social, economic, and ecological contexts at multiple scales from local to global

(O'Brien et al. 2007). In this approach, rather than focusing on the climate hazard itself, it addresses the underlying development context, for example, why people or ecosystem of interest are sensitive and exposed in the first place. This approach entails a multidimensional view of climate and society or ecosystem interactions which may draw upon climatic, biophysical, socio-economic, political and institutional structures and dynamics (Okpara et al. 2016).

Table 2: Diagnostic tool for identifying different vulnerability approaches (based on Füssel, 2007 and O'Brien et al., 2007).

	Outcome	**Contextual**
Illustrative research questions	What are the expected net impacts of climate change for different ecosystems?	Why are some ecosystems more affected by climate-induced stress than others?
Focal points/starting point of analysis	Future implications of climate change on ecosystems	Past and current climate variability and change interactions with ecosystems
Methods	Simulations/scenario-based approaches; integrated assessment models	Cross-sectional surveys, household surveys, quantitative/qualitative case studies, context-specific indicator approaches
Policy recommendations	Reduce GHG emissions, technical and sectoral adaptations	Address local constraints in vulnerable areas through conflict preventive actions, building socio-economic adaptation capacities, promoting internal conflict resolution, and supporting livelihood security.

Outcome and contextual vulnerability differ in their descriptions of vulnerability (Table 2). Therefore, the choice of one approach or concept over the other has implications on the resources required to execute a CCVA. Outcome approaches are usually applicable at global, national and regional levels, while the contextual approaches begin their analyses on the local level (e.g., households, villages, communities). Therefore, vulnerability cannot generally be assessed by taking a single method, as it requires an integration of both approaches i.e. outcome and contextual (Figure 4) (Hinkel et al., 2011; Mastrandrea, et al., 2010).

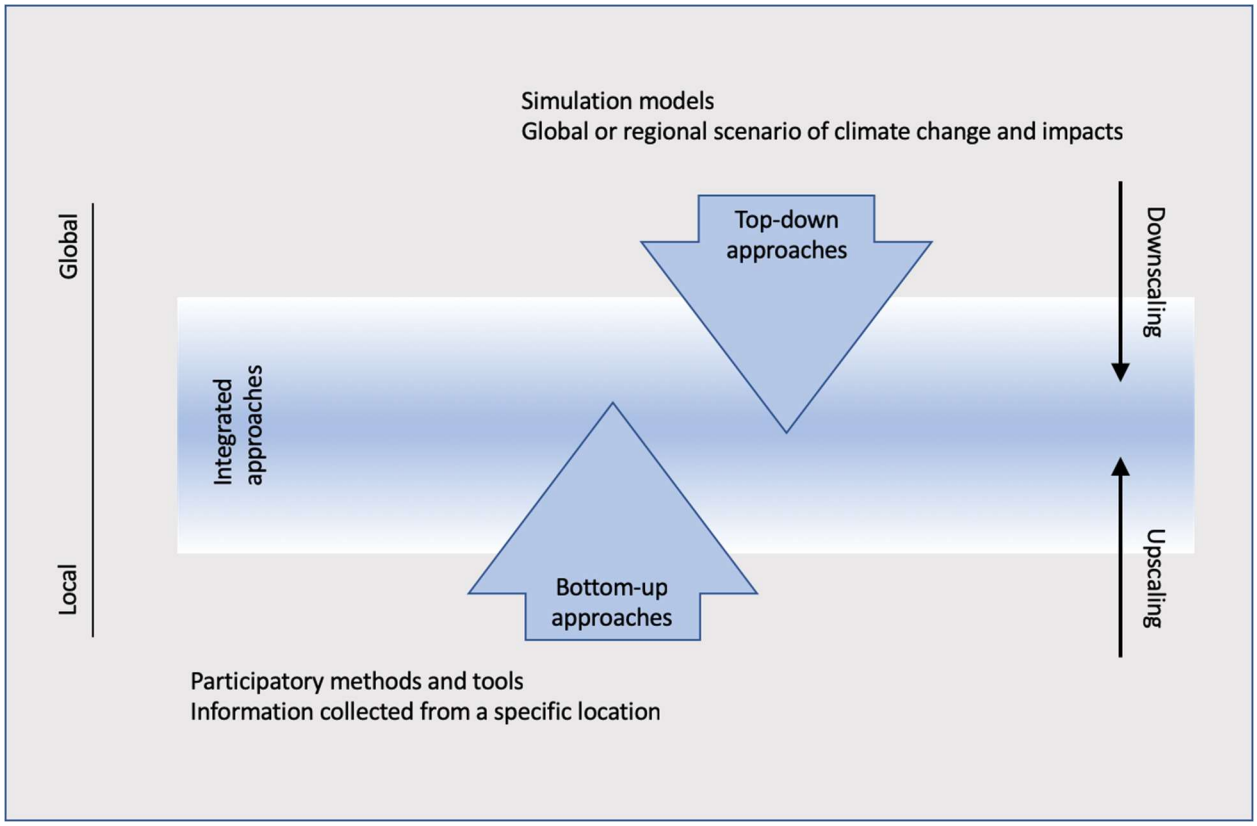

Figure 4: Schematic representation of how simultaneous upscaling and downscaling of the respective assessment types can lead to a realm in which integrated approaches can be developed (Adapted from Dessai & Hulme, 2004).

2 Indicators of vulnerability dimensions

An indicator is a measurable variable used as a representation of an associated measurable or non-measurable variable (e.g. temperature, rainfall). An indicator represents the state or level of a system (Gallopin, 1997). For example, in socio-ecological vulnerability assessments, multiplicity of livelihoods, or the availability of livelihood options to communities, is considered as an indicator for social adaptive capacity of the local communities (Cinner et al. 2013; Maina et al. 2016). Vulnerability indicators can also be linked to specific actions that may be prescribed as part of a climate change adaptation strategy, to manipulate the different dimensions of vulnerability and ultimately the overall vulnerability. By their very nature, indicators are less complex to understand and are typically combined with other indicators to represent a vulnerability dimension (Hinkel, 2011). Choosing indicators requires a clear understanding of how they influence or contribute to a vulnerability dimension. In considering the multiplicity of livelihood as one of the indicators of social adaptive capacity, for instance, there would be other indicators of social adaptive capacity that when synthesized result in overall adaptive capacity dimension of vulnerability.

2.1 Climate Change Indicators

Climate change indicators are a set of geophysical parameters that represent aspects of climate change and provide information on the most relevant domains of climate change. In vulnerability

context, climate change indicators are primarily used to estimate the exposure of a system to climate change.

2.1.1 Air temperature

Temperature is a key metric for assessing the state of the climate. The last three decades were the warmest period since the 1950s (IPCC, 2014). The warming is unequivocal and unprecedented (Pauchari et al., 2014). Estimates of air temperature are based on independently maintained global temperature data[1].

The earths average air temperature has increased by about 0.6°C since 1980 relative to the period 1961 to 1990 (at 0.25°C/decade). The 10 warmest years on record have all occurred since 1998, and the three-year streak of new record temperatures was set each year from 2014 to 2016 (1.01, 1.34 and 1.45°C) followed by 2017 (1.33°C). 2018 started with a weak La Niña event, which continued until March. By October, sea- surface temperatures in the eastern Tropical Pacific were showing signs of a return to El Niño conditions, although the atmosphere as yet has shown little response. If El Niño develops, 2019 is likely to be warmer than in 2018.

Relative to 1985 to 2005, global mean surface temperatures are projected to increase by 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5 (IPCC, 2013). This temperature increase is likely to influence mangrove species composition, phenology, productivity, and ultimately the latitudinal range of their distribution. For example, where temperatures exceed that of peak photosynthesis, productivity decreases. Furthermore, high temperatures increase evaporation rates, which can result in salinity increases; the synergistic impacts of salinity and aridity can influence species diversity, size, and productivity of mangrove forests (Ball and Sobrado 2002).

2.1.2 Rainfall

Changes in rainfall patterns can have profound ecological and societal consequences, particularly across the WIO countries where rainfall plays a crucial role in sustaining livelihoods and economic development. East African countries (Somalia, Kenya, and Tanzania) experiences a semi-annual rainfall cycle, driven by the Inter-Tropical Convergence Zone (ITCZ) movement across the equator. Teleconnection relationships between Eastern Africa rainfall patterns and large-scale climate modes have been demonstrated (Ropelewski and Halpert 1987; Ogallo et al. 1988; Indeje et al. 2000; Kijazi et al., 2005; Gamoyo et al. 2012), but variations in Indian Ocean SST (phases of the Indian Ocean Dipole - IOD) are recognized as the dominant driver of east African short rain (Mutai et al. 1998; Nicholson and Kim 1997; Clark et al. 2003; Marchant et al., 2007).

The long rains over the region are weakly correlated to global sea surface temperatures (SSTs) (Camberlin and Philippon 2002a; Camberlin et al. 2009). On the other hand, southern African countries receive most of its annual precipitation during austral summer (December–February) and are strongly influenced by sea surface temperature (SST) anomalies across the global oceans (Rouault et al., 2003; Hansingo and Reason, 2008, 2009; Hermes and Reason, 2009) as well as by ENSO (Vigaud et al., 2009; Pohl et al., 2010). Although it is generally observed that El Niño events correspond to conditions of below-average rainfall over much of southern Africa (Mason, 2001; Giannini et al., 2008; Manatsa et al., 2008) the ENSO teleconnection is not linear,

[1]The data sets are: the UK Met Office Hadley Centre and the University of East Anglia Climatic Research Unit (CRUTEM4), the National Oceanic and Atmospheric Association's (NOAA's) National Center for Environmental Information (NCEI), the NASA Goddard Institute for Space Studies (GISS), and the Berkeley Earth Surface Temperature Project (Berkeley)

but rather has complex influence in which a number of regimes of local rainfall response can be identified (Fauchereau et al., 2009). Additionally, there is a growing body of work that suggests southern Africa summer precipitation is also related to the Subtropical Indian Ocean Dipole (SIOD) (Behera and Yamagata 2001, Reason 2001, Washington and Preston 2006).

The development of several long-term satellite-based data sets tailored for African research and climate monitoring has provided an opportunity to assess recent changes in African precipitation. Over east Africa, the decline in the long rains (March to May) led to widespread famine affecting over 10 million people during 2010 through 2011 (OCHA, 2011).

There has been no such downward trend in the "short rains" (October to December), but this season has continued to exhibit large year-to-year variability, which at times has exacerbated the impact of the long rains decline.

Overall, rainfall in the WIO has decreased over the decades by around -1.5 mm/ per decade between 1960-2017 (Figure 5), which implies that the climate is getting drier. Changing rainfall patterns are likely to influence the distribution, extent, and growth rates of mangrove forests (Gilman et al. 2008) particularly in mangroves at the edge of their tolerances. For example, decrease in rainfall and increase in evaporation may lead to increase in soil salinity, resulting to decrease in seedling survival, productivity and growth rate (Duke et al. 1998). Furthermore, coral reefs and seagrass may be impacted by changes in salinity and changes in sediment and nutrient regimes that are partially driven by precipitation.

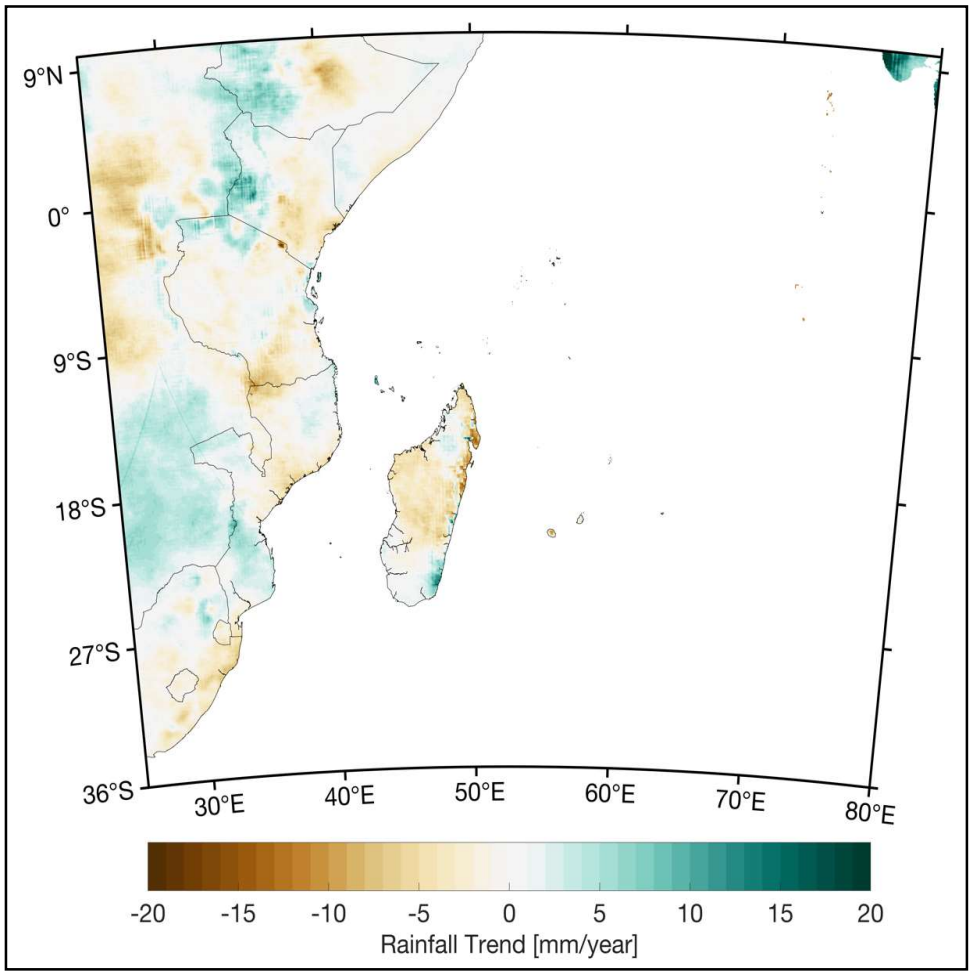

Figure 5: Spatial trends in annual rainfall from 1981-2017 based on CHIRPS dataset (Climate Hazards Group InfraRed Precipitation with Station data), (Funk et al. 2014).

2.1.3 Sea Surface Temperature

The tropical Indian Ocean experiences strong, seasonally reversing winds. Generally, strong southwesterly and northeasterly winds blow in the austral winter (June to September) and summer (December to March) from and to the tropical western Indian Ocean respectively. The seasonally reversing winds in the tropical Indian Ocean influence the sea surface temperature (SST) and the upper ocean circulation (Manyilizu et al. 2016). The strong winds during the Southwest Monsoon lead to significant cooling over the tropical western Indian Ocean. Analysis of SST shows that strong East African rainfall is associated with warming in the Western Indian Oceans and cooling in the Eastern Indian Ocean (Hastenrath et al., 1993; Mutai et al. 1998; Saji et al.1999; Black 2003, 2005; Gamoyo et al., 2012).

The Indian Ocean has been warming over the past three decades (Figure 6). This has elicited interest among the research community due the significance of the Indian Ocean in driving global climate variability. Over the past 60 years, it has warmed two to three times faster than the tropical Pacific (Williams and Funk 2011), eliciting more questions than answers on how this might impact on socio-ecological systems and global climate in general.

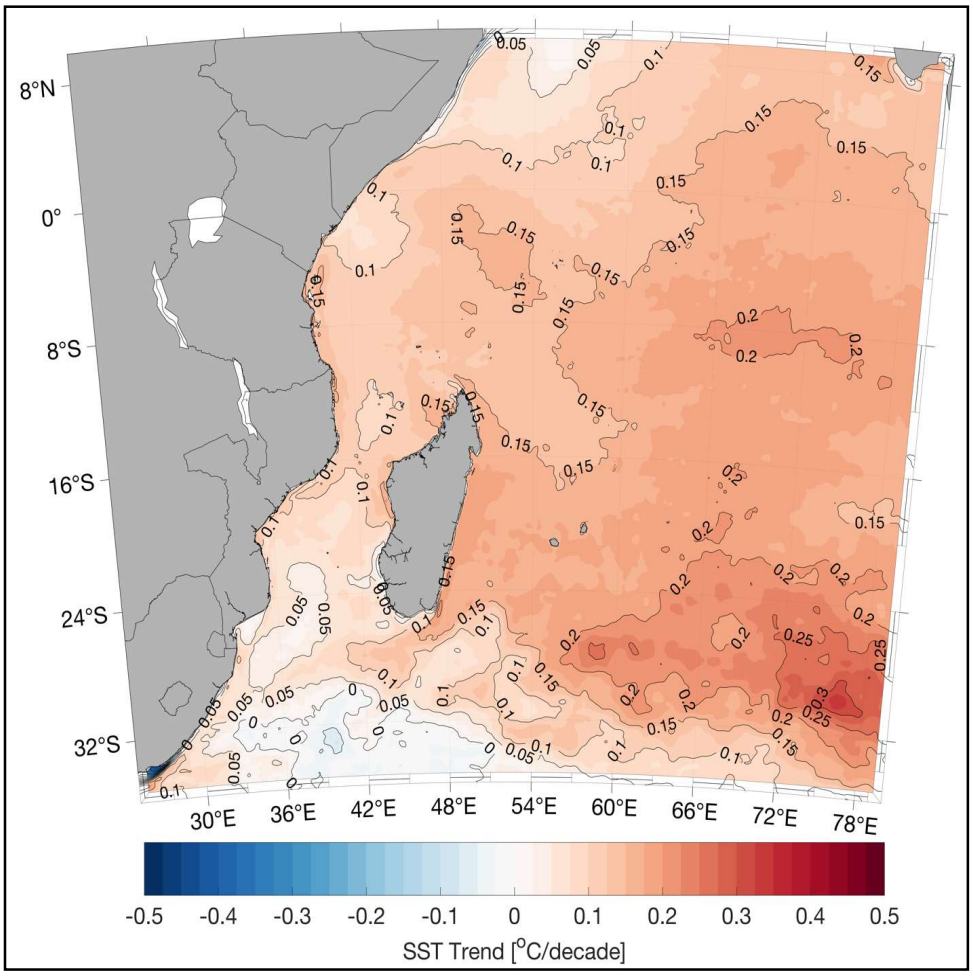

Figure 6: SST rate of rise (°C/decade) calculated from high resolution coral reef watch SST data from 1982 to 2017. See Table Annex 2 for data sources.

The increasing frequency of positive thermal anomalies has triggered mass coral bleaching and mortality events across the region over the past two decades (McClanahan et al., 2007, Baker et al., 2008; Obura, 2005; Ateweberhan and McClanahan, 2010). Differences in the susceptibility of reef-building corals to stress from rising sea temperatures have also resulted in changes to the composition of coral (McClanahan et al., 2007) and benthic fish communities (Graham et al., 2008; Pratchett et al., 2011).

The warming has the potential to also change the Asian monsoon circulation and rainfall, as well as to alter the marine food webs (Roxy et al., 2015). It is estimated that up to 20% in phytoplankton over the tropical Indian Ocean has decreased over the past six decades (Roxy et al., 2015). Changes in the surface temperatures of the ocean basin are consistent with temperature trends simulated by ocean-atmosphere models with anthropogenic greenhouse gas (GHG) forcing over the past century (Hoegh-Guldberg et al., 2014). Annex Table A lists trend in SST from 1982 to 2017 for 15 exclusive economic zones (EEZ). These changes were estimated from linear regressions of annual mean SST.

2.1.4 Ocean acidification

Since the industrial revolution began, the concentration of carbon dioxide (CO_2) in the atmosphere has increased due to the burning of fossil fuels and land use change (Doney & Schimel 2007; Doney at al. 2009). During this time, the pH of surface ocean waters has fallen by 0.1 pH units from approximately 8.21 to 8.10 (Royal Society, 2005), and is expected to decrease a further 0.3–0.4 pH units in coming decades (Orr et al. 2005). The pH scale, like the Richter scale, is logarithmic, so this change represents approximately a 30 percent increase in acidity. This process is known as ocean acidification.

Changes in pH is linked to shifts in ocean carbonate chemistry that can affect the ability of marine organisms such as mollusks and reef-building corals, to build and maintain shells and skeletal material (Figure 7). This makes it particularly important to fully characterize changes in ocean carbonate chemistry. While ocean acidification is a global phenomenon, its impacts are felt locally and those impacts vary across populations and ecosystems. Unfortunately, the region lacks a long-term observation data on ocean acidification.

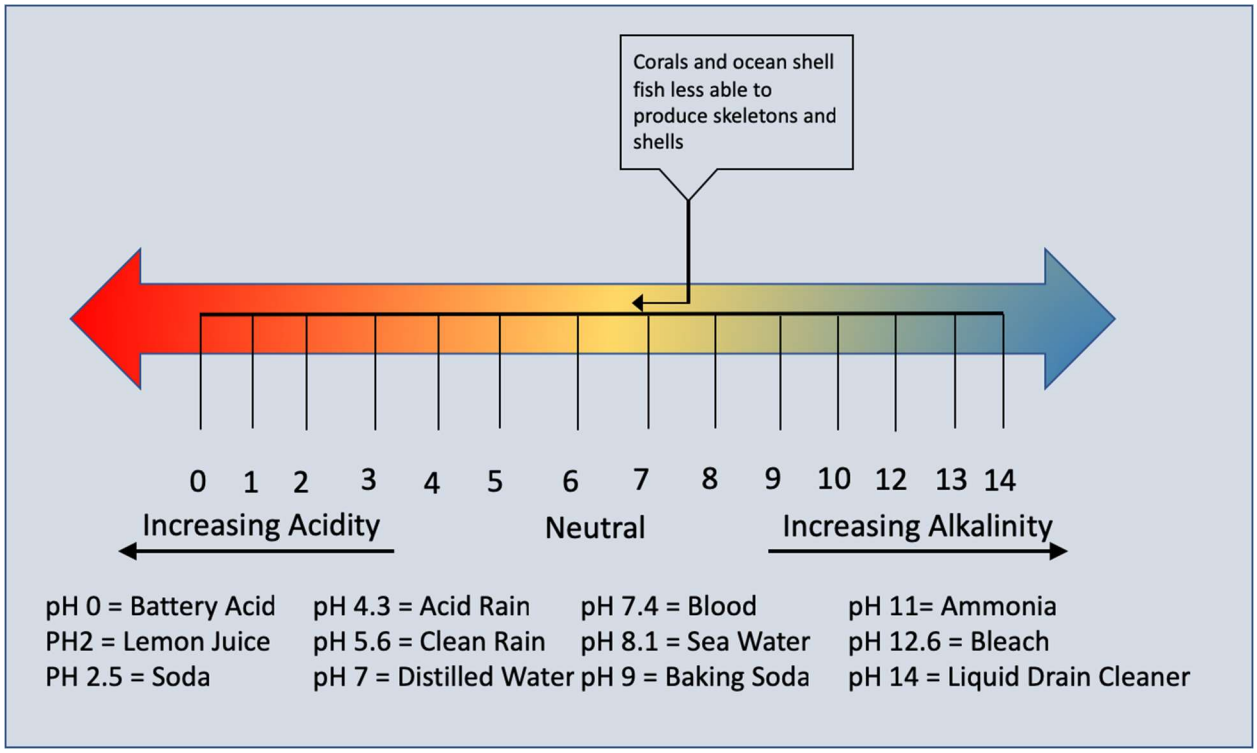

Figure 7: Acidity and alkalinity measured using a pH scale for where 7.0 is neutral. pH lower than 7 is acidic, while greater than 7 is alkaline (Kleypass et al. 2008). Adapted from https://www.epa.gov/climate-indicators/climate-change-indicators-ocean-acidity.

2.2 Coastal geomorphology

2.2.1 Sea level rise

Changes in sea level occur over a broad range of temporal and spatial scales, with the many contributing factors making it an integral measure of climate change (Milne et al., 2009; Church et al. 2011). The primary contributors to contemporary sea level change are the expansion of the ocean as it warms and the transfer of water currently stored on land to the ocean, particularly from land ice (glaciers and ice sheets) (Church et al. 2013). The instrumental record of sea level change is mainly comprised of tide gauge measurements[2] and since the 1990s, satellite-based altimetry measurements[3].

The backbone of the global tide gauge network is the Global Sea Level Observing System (GLOSS) established by the UNESCO Intergovernmental Oceanographic Commission (IOC) in 1985 to establish a well-designed, high-quality in situ sea level observing network to support broad research and operational user base. Globally, there are about 300 tide gauge stations that provide optimal sampling of the global ocean (Figure 8). Tide gauge data can be obtained from http://www.psmsl.org/data/obtaining/

[2] The Global Sea Level Observing System
[3] AVISO (https://www.aviso.altimetry.fr)

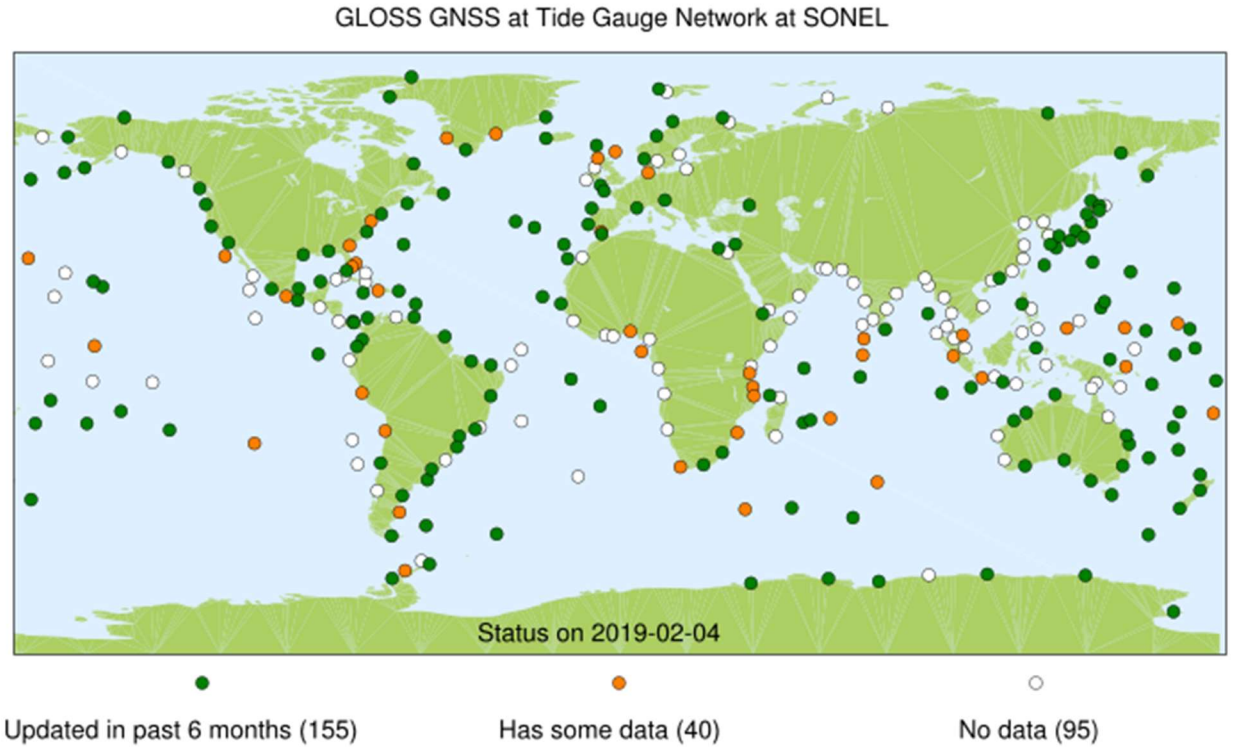

Figure 8: Map of the Global Sea Level Observing System (GLOSS) showing stations that are active and those with no data stream.

With the satellite altimetry missions, mean sea level trends can be calculated (Figure 9). Although the trend indicates a rise in the mean level of the oceans, there is marked spatial variability. These spatial patterns are not stationary. As a result, sea level trends patterns observed by satellite altimetry are transient features. These data are freely available for download and can be applied for vulnerability assessments, for example (Annex Case Study 2; Annex Table B).

Sea-level rise is a potential climate change threat to long-term sustainability of valuable ecosystems such as corals reefs and mangroves (Nicholls & Cazenave, 2010). Mangroves for example, are sensitive to changes in inundation duration and frequency. Low sea level can lead to mangrove dieback associated with increased soil salinization (Lovecock et al. 2017) while increase in coastal flooding duration can lead to plant death at the seaward mangrove margins (He et al. 2007). Global sea levels have risen by 3.2 mm/yr over 1993 to 2012 and are likely to rise by between 0.28 and 0.98 m by 2100 (Church et al. 2013). The rise, however, is not globally uniform as sea-level rise in some regions accompanies a fall in others. For example, it has been shown that sea level in other WIO region countries has increased since the 1960s, except for Zanzibar showing a decreasing trend (Han et al. 2010). Tidal range is likely to significantly influence the level of impact of sea-level rise on mangroves. In Mozambique for example, mangrove forests are among the most affected by sea-level rise due to the low-lying coastline (Alongi 2012).

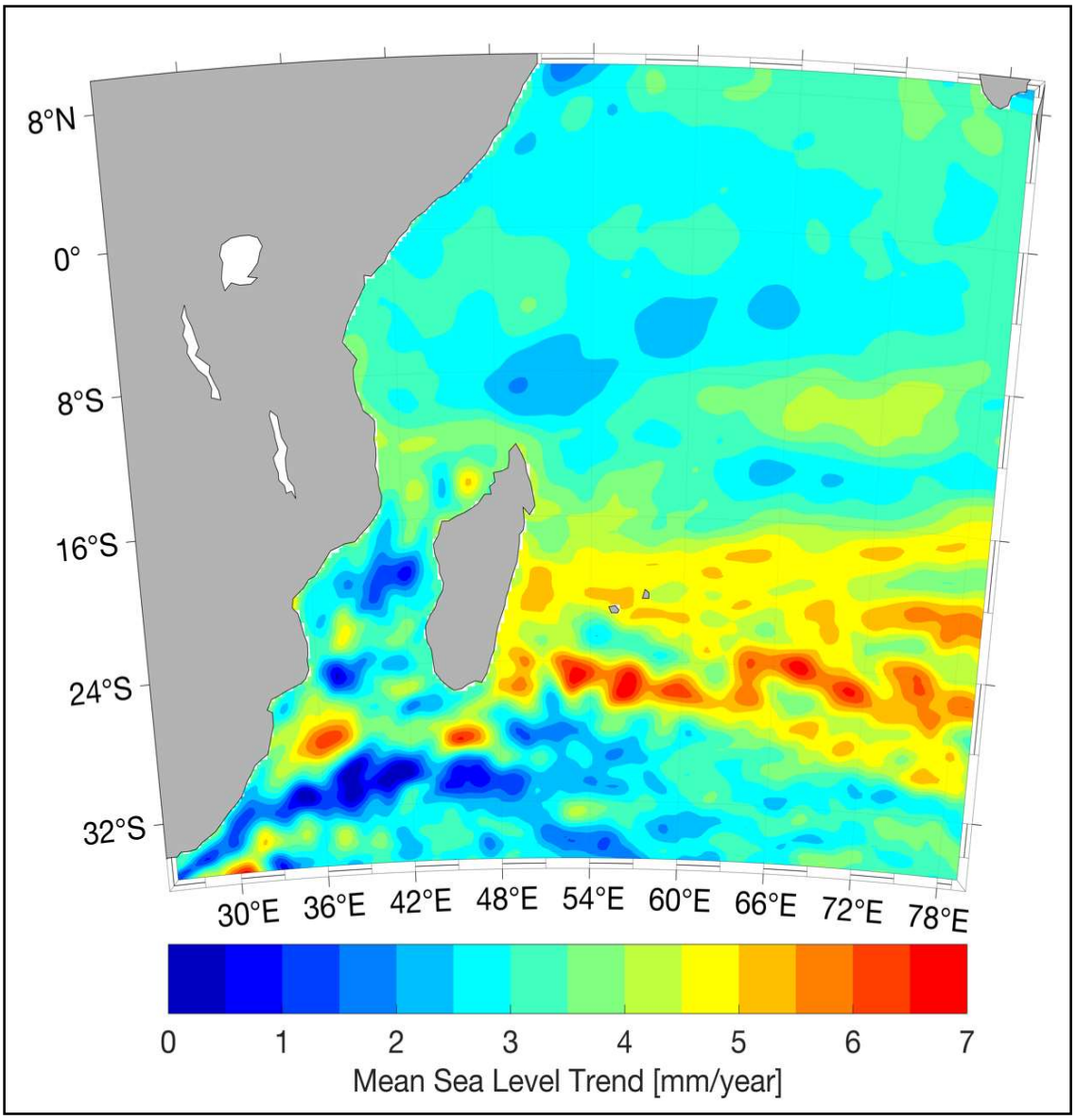

Figure 9: Map of regional patterns of observed sea level trend (in mm/year). This map was created using gridded, multi-mission Ssalto/Duacs data since 1993. Data source: http://www.aviso.oceanobs.com/duacs/.

2.3 Coastal ecological systems

Coastal ecosystems occur at the nexus of land and sea to create an environment with a distinct structure, diversity, and flow of energy. Key components in coastal ecosystems include:

- Physical habitat: e.g. water, sediment, rocks
- Biological habitat: e.g. mangroves, seagrass, coral reef
- Primary producers (plants): e.g. phytoplankton, macroalgae, aquatic plants (e.g. seagrasses), mangroves, terrestrial plants

Mangroves, corals, and seagrass provide a wide variety of ecosystem services such as subsistence, preventing coastal flooding and sustaining fishing and tourism industries. Across the WIO, peoples' livelihoods and income are often inextricably linked to healthy functioning ecosystems. However, once the declining health of these ecosystems (as measured by coral and seagrass cover, mangrove biomass etc.) from the combined impacts of local use and global threats such as climate change surpasses the tipping point, the natural capital of the Western Indian Ocean region will be eroded, undermining the ocean's value for present and future generations.

2.3.1 Coral reefs

The fate of coral reefs on a warming planet has been of great interest from scientists, governments, and the general public over the past few decades. Prolonged ocean temperatures of 1–2°C above the range of usual coral experience can lead to the paling of reef-building animals due to a breakdown of the symbiosis with the colorful dinoflagellate Symbiodinium (Rowan et al. 1998) that reside in coral tissue (Brown, 1997).

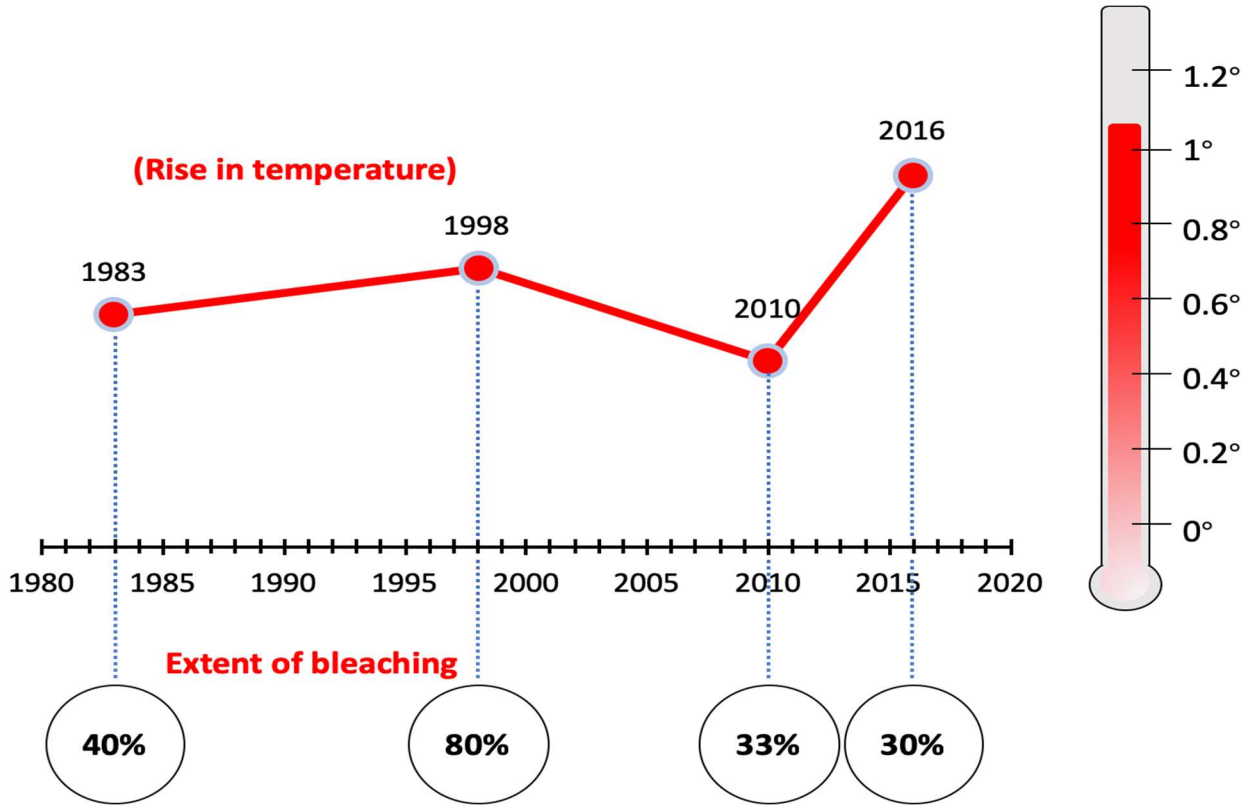

Figure 10: Rise in sea surface temperature with corresponding mass coral bleaching years (Adapted from Obura et al. (2017).

Episodes of mass coral "bleaching" in the WIO since the early 1980s (Figure 10) have led to widespread coral mortality and has raised questions about the viability of coral reef ecosystems during this period of rapid climate change. Climate attribution research has found that anthropogenic forcing is likely to drive mass bleaching episodes (Donner et al., 2005). Modeling studies suggest that projected ocean warming over the next three to four decades may render mass coral bleaching events a frequent and more intense occurrence on most reefs worldwide, unless corals can adapt or acclimate (Donner et al. 2009; van Hooidonk et al. 2013,2016; Logan et al. 2014; Kwiatkoski et al. 2015; Gamoyo et al. 2018).

The latest IPCC report indicates that global warming of 1.5°C by 2100 would significantly damage coral reef systems. For example, tropical coral reefs are projected to decline by 70-90 percent with 1.5°C warming, whereas virtually all (> 99 percent) would be lost under 2°C by 2100 scenario (IPCC, 2018).

2.3.2 Mangroves

Mangroves are important coastal resources, which support the livelihoods of millions of people in the tropics and sub-tropics (Siddiqi and Khan 1996, Kairo et al. 2002, Bosire et al. 2003, Mumby et al. 2004, Dahdouh-Guebas et al. 2005, Bosire et al. 2008). According to the most recent estimates, mangroves globally cover about 15.2 million ha straddling coastlines in 123 tropical and subtropical countries (Spalding et al. 2010). Of these, it is estimated that ~1.0 million ha (or 5%) are located in the western Indian Ocean region (FAO 2007). Majority of these are found in Mozambique (Zambezi delta), Madagascar (Mahajamba Bay), Tanzania (Rufiji delta) and Kenya (Lamu) (UNEP-WCMC 2006; Spalding et al., 2010). However, mangroves coverage has continued to the decline due to multiple global and local pressures (Aksornkoae et al., 1993; MacKinnon 1997; Valiela et al. 2001; FAO 2007, Gilman et al. 2008), thus rapidly altering structure and function of these ecosystems and their capacity to provide essential goods and services to millions of people in the tropics (Kairo 2002, Bosire et al. 2004, Mumby et al. 2004, Dahdouh-Guebas et al. 2005; Duke et al. 2007).

2.3.3 Seagrass

Seagrasses are one of the most productive and diverse coastal marine ecosystems. They provide nursery grounds and food for fish and invertebrates, coastline protection from erosion, carbon sequestration, and nutrient fixation (Spalding et al., 2007; Harley et al., 2012). Despite their vital social and ecological value, seagrass communities are declining yearly worldwide by over 7% (Cullen-Unsworth & Unsworth 2013), with about 29% of the world seagrass stock having already been destroyed (Waycott et al., 2009; Coles et al. 2011) mostly due to human activities, with further anticipated losses due to global warming and climate change (Short et al., 2016). Although widely distributed throughout the region, the exact extent and coverage for the region is unknown.

2.4 Socio-economics

From a social perspective, vulnerability varies as a consequence of the capacity of groups and individuals to reduce and manage the impacts of climate change. Among the key factors determining vulnerability are gender, age, health, social status, ethnicity, and class (Adger et al., 2009). For example, a review of global trends in tropical cyclones found that mortality risk at country-level depended most strongly on three factors: storm intensity, quality of governance, and levels of poverty (Peduzzi et al., 2012). Individuals and households most vulnerable to climate hazards tend to be those with relatively low socioeconomic status. Therefore, to identify critical needs of populations, and the underlying conditions giving rise to these needs, social assessments (i.e. livelihoods, education level, and many others) can benefit by looking across institutional domains and across local and national scales. Local assessments provide a means to identify existing vulnerabilities; the policies, plans, and natural hazards contributing to these vulnerabilities; as well as in identifying adaptation actions.

2.4.1 Coastal fisheries

Coastal fisheries encompass all fisheries within the exclusive economic zones (EEZ) that provide food, nutrition, and livelihoods, particularly to coastal communities. Small-scale fisheries supply 93 – 98 % of the marine catch and are the principal income generating activity for a large number of coastal households (Samoilys et al., 2015). In Kenya, for example, artisanal fisheries tend to be restricted closer to land at inshore shallow reefs and lagoons. The fishing is normally for local consumption and sale (Obura & Wanyonyi, 2001). Industrial offshore fisheries, on the other hand, contribute to export revenues accounting <15% of the Kenyan national economy (Walmsley et al., 2006).

Current fishing practices in the WIO are largely unsustainable and in many areas, finfish stocks are, on the decline (Kaunda-Arara et al., 2003; McClanahan et al., 2008) while invertebrate fisheries such as for sea cucumbers are on the point of collapse in most countries (Muthiga and Conand, 2014). This threatens the livelihoods, food security, and nutrition of many poorer population groups.

2.4.2 Migrant fishers

Migrant fishing is a major feature of fisheries in East African and an essential livelihood strategy for many fisherfolks due to decline in near-shore fisheries (Wanyonyi et al., 2016). Migrant fishers are known to move to distant fishing grounds for periods ranging from weeks to months (FAO, 2008; Curran, 2002; Njock and Westlund, 2010; Wanyonyi et al., 2016) and often operate in remote locations less accessible to fisheries management authorities (Islam & Herbeck, 2013), therefore are difficult to monitor. Migrant fishers operate within the socio-economic and ecological setting, and are influenced by external factors and processes that result in changes at both the individual and community level (Wanyonyi et al. 2016). For example, migration results to changes in socio-economic, cultural and ecological (changes in natural resource base, such as fish stocks due to pressure on target fisheries). In as much as migration offers opportunities (i.e. social adaptive capacity), it can also lead to a considerable social disruption to reinforce vulnerability for both those migrants and those left behind. For example, Wanyonyi et al. (2016) demonstrated that migration leads to increased income and increased savings thus improving the standard of living for the family and the overall adaptive capacity. On the other hand, migrant fishers have to leave the rest of their family members at home, thereby forcing spouses to take on men's responsibilities such as farming. If there's drought, the family experience hard times due to low food production from farming. This increases the level of socio-economic vulnerability.

2.5 Governance

Significant efforts have been made to understand the impacts of climate change and how communities or ecosystems adapt to these impacts. Yet, there is an urgent need to interrogate the role of governance and institutional arrangements in the adaptation processes. The processes of governance (how societal problems are addressed by governments and other organizations) both shape and respond to climate change vulnerability. In the Fifth IPCC Assessment Report (IPCC, 2014), institutions provide the enabling environment for implementing adaptation actions. In other words, institutional weaknesses, lack of coordinated governance, and conflicting objectives among different actors can constrain adaptation. However, enhancing the awareness of individuals, organizations, and institutions on climate change vulnerability, impacts and adaptation can be a starting point to build individual and institutional capacity for planning and implementing adaptation. Under the UNFCCC, information on institutional arrangements for adaptation can be

sourced through National Communication and National Adaptation Programmes of Action (NAPAs). National adaptation frameworks are usually led by a designated national institution or agency or jointly by several governmental institutions. Some of the WIO countries that have developed national climate change adaptation action plans/response strategy include: Comoros, Madagascar, Mozambique, Tanzania, Kenya, Mauritius, Seychelles.

3 Linking vulnerability framework to Sustainable Development Goals

The 2030 Agenda for Sustainable Development is the central UN platform for achieving 'integrated and indivisible' Sustainable Development Goals (SDGs) across three dimensions: social, environmental and economic[4]. Within the SDGs, goal 13 on climate change aims to promote actions against combating climate change impacts with the following specific targets:

- Strengthen resilience and adaptive capacity to climate-related hazards, and natural disasters in all countries.
- Integrate climate change measures into national policies, strategies, and planning.
- Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning.
- Implement the commitment undertaken by developed-country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible.
- Promote mechanisms for raising capacity for effective climate change-related planning and management in the least developed countries and small island developing States, including focusing on women, youth and local and marginalized communities.

A complementary agreement to the SDG 13 on climate change is the Sendai framework for disaster risk reduction (Aitsi-Selmi et al. 2015), which aims to achieve a substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries over the next 15 years (2015 to 2030)[5]. The Sendai framework focuses on four priority of actions:

- Understanding disaster risk: which should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment.
- Strengthening disaster risk governance to manage disaster risk at the national, regional and global levels for prevention, mitigation, preparedness, response, recovery, and rehabilitation.
- Investing in resilience through structural and non-structural.
- Enhance disaster preparedness by ensuring capacities are in place for effective response and recovery.

[4] https://www.undp.org/content/undp/en/home/sustainable-development-goals.html

[5] https://www.unisdr.org/we/coordinate/sendai-framework

Achieving both SDG 13 and Sendai framework targets or goals may require CCVA to inform actions geared at enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development. For example, impacts of better health and well-being on poverty reduction and increased equality on coastal communities in the WIO, can be realized using socioecological vulnerability to inform on specific actions that build resilience, leading to overall sustainable development.

As a first step towards integrating CCVA with SGDs and disaster risk reduction (Figure 11), one would need to compile and compare lists of related targets (from SDG and disaster risk reduction) with the indicators of vulnerability (or indicators of dimensions of vulnerability). For example, under Goal 13 of SDGs, there are five targets aimed at combating climate change and its impacts while Sendai framework has four priorities aimed at building resilience. As a next step, identifying linkages between SDGs, disaster risk reduction and climate change vulnerability indicators can reveal actions that reduce vulnerability and at the same time address SDG and Sendai framework targets.

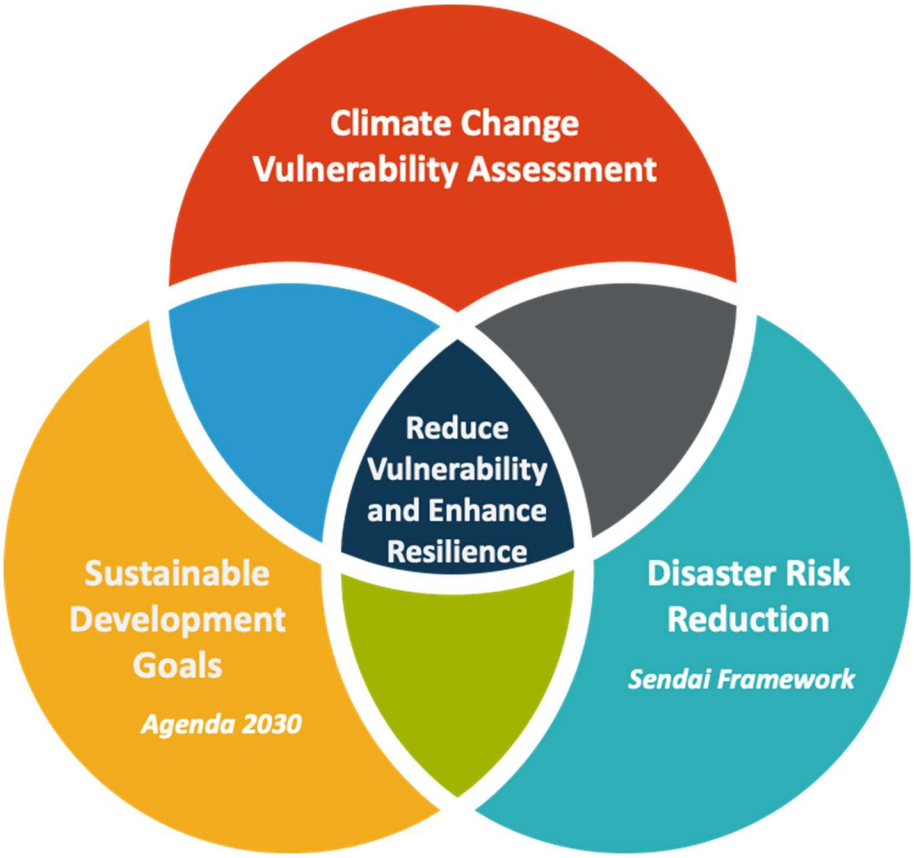

Figure 11: Vulnerability Assessments with the Sustainable Development Goals and the Sendai Framework. Adapted from UNFCC 2017.

4 Getting started with a CCVA

As a prerequisite to conducting CCVA, several activities and key decisions about the CCVA process and data acquisition and analyses are carried out. This section provides a guideline on

the key steps in conducting a CCVA. In designing a CCVA, the following questions can be used to define the scope of the assessment (adapted from Foden and Young 2016):

- What climate stressors (e.g., rainfall changes, temperature change) contribute to ecological vulnerability?
- Who or what is vulnerable to climate variability and/or change (e.g., fishing communities, mangrove forests, seagrass or coral reefs)?
- Where are the vulnerable people, ecosystems, infrastructure and resources are located (e.g., near the coast or in a floodplain)?
- When are people or resources are likely to be vulnerable (e.g., during monsoon or cyclone season)?
- What internal and external factors make specific groups of people (e.g., children, elderly individuals) and resources vulnerable (e.g., poor community cohesion)?
- How well people and communities' actions are working to reduce their own vulnerabilities.
- To what extent have climate stressors (e.g., sea level rise) have become barriers to development relative to non-climate stressors (e.g., population growth).
- What options are available to help people and communities adapt to the effects of climate variability and change (see text box on estimating the cost of these options).

Considering the multitude of factors to consider, an integrated approach to CCVA framework which integrate climatic, ecological, and social-economic information, and consider non-climate determinants of vulnerability through adaptive capacity should be adopted. CCVA outputs provide knowledge to help identify actions that can address any of the vulnerability dimensions and in effect, overall vulnerability; prioritize adaptation efforts; and assess the relative costs and benefits (including risks) of potential management interventions. Figure 12 is an illustration of the sequence of overall CCVA framework.

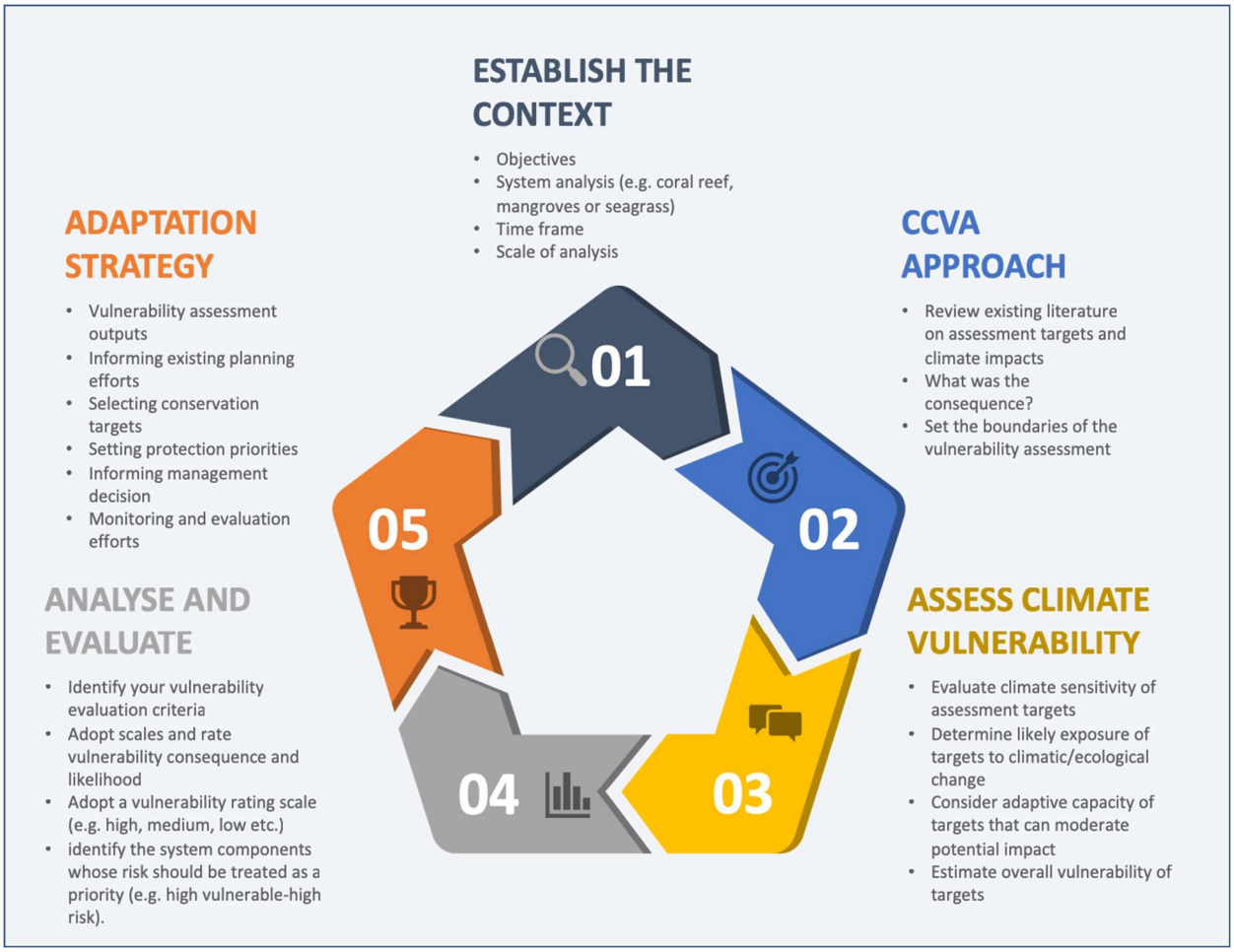

Figure 12: Climate Change Vulnerability Assessment cycle for adaptation planning and implementation of relevant strategies

The steps on figure 12 are described below in detail.

4.1 Step 1: Setting CCVA goals and objectives

Clearly defining the purpose and scope of the CCVA exercise is essential for designing an efficient and effective CCVA. Explicitly stating the goals will help tailor the assessment process to information on explicit actions that will address aspects that undermine the adaptive capacity or coping mechanisms and increase vulnerability. Furthermore, defining clear goals facilitates the establishment of well-structured objectives and facilitate development of CCVA outputs effectively impact on decisions on climate change adaptation.

A well-defined goal answers the following questions:

- What is the purpose of the CCVA?
- Who is the audience/who are the end users?
- Which decisions can CCVA influence?

623 Objectives describe one or more specific action steps needed to achieve the goal of the CCVA. Six
624 broad CCVA objective categories are described in Table 3 below.

625 **Table 3: Examples of CCVA objectives and their scope of focus (**adapted from Foden and
626 Young 2016)

Which?	Which ecosystem (e.g., corals, mangroves or seagrass) are most and least vulnerable to climate change across their regional distribution ranges
How much?	How vulnerable are the ecosystems or species?
Why?	Why components of changing climate pose the greatest risk to the focal ecosystem (e.g., maximum temperatures)
Where?	Which regions or countries contain ecosystems most vulnerable to climate change?
When?	Is climate change likely to affect the ecosystem within x timeframe (for example 10 years)?
What's missing?	Which are the key uncertainties that require additional data collection and/or research for better assessing vulnerability to climate change of the ecosystem?

627

628 ## 4.2 Step 2: Choosing the most appropriate CCVA approach

629 Having set the goals and objectives, it is important to determine which CCVA approach will
630 deliver the results needed to support decisions on adaptation strategies. This subsection provides
631 steps to systematically guide users through the necessary decisions.

632 ### 4.2.1 Assess the profile/condition of the system of interest

633 The profile or condition assessment evaluates the general status of the system of interest. The
634 following list provides key questions to understand the profile of the system of interest.

635 - What are the environmental issues affecting the system of interest?
636 – Identification of key environmental issues (e.g. deforestation, pollution,
637 overfishing, coral bleaching)
638 – Sectorial implications due to identified environmental issues (e.g. impacts on
639 fisheries dependent livelihoods)
640 – Temporal trends (e.g. percentage decline in mangrove forest cover)
641 - What are the developmental issues in the system of interest?
642 – Governance and institutional context (e.g. existing governance structure, rules,
643 regulations, village institutions)
644 – Key developmental issues (e.g. migration)

- What kind of socio-economic dynamics exists in the system of interest?
    - Demographic profile (e.g. number and density of the population, population below poverty line, literacy rate)
    - Livelihood profiles (e.g. main sources of livelihood, diversity of livelihood strategies, gender-specific livelihood strategies)
    - Human health status (e.g. incidences of vector-borne diseases)

Explicit questions required for profiling a system of interest depend on the purpose of the vulnerability assessment. Profiling provides the basic information about the biophysical and socio-economic status of the system of interest.

4.2.2 Scale and scope of CCVA

Setting the spatial boundaries of the CCVA is critical as it guides the analytical process including data or information requirement and involvement of stakeholders. CCVA can be conducted at national or subnational or regional scale. The following considerations are important for defining the spatial scope of the analyses:

- *Specify geographic scope:* Clearly defining the relevant geography or system spatial boundaries is important for determining the scope of the CCVA process. If a specific area such as a country, sub-national unit or is specified as the scope of a CCVA, it forms the spatial extent of the analysis. It is important to include areas that are contiguous with or close to the species' present range and those that may become climatically suitable for the species in future (i.e. both realized and fundamental niches for coral reefs, mangroves, and seagrass)
- *Specify System Boundaries:* In any system, there are several factors impacting on vulnerability. For example, within a coral reef socio-ecological system, assessments of ecological vulnerability may consider several factors that impact on coral reefs including the Crown of Thorns (CoT), sediments and nutrients, temperature, and Ocean acidification, among others. In evaluating the exposure of a coral reef socioecological system, one would need to define the boundaries of the pressure/stress factors to consider. This decision is usually informed by the data available, and other resources including system processing time and personnel, and ecological knowledge. For example, while CoT are major stressors on reefs, they might not be an issue in the location of interest.
- *Specify Spatial resolution:* Taking climate change into account will often require consideration of spatial and temporal scales. Resolution refers to the smallest unit of area that can be identified from the map/image or data. Resolution determines how accurately the location and shape of spatial features and data can be depicted at a given scale. Spatial resolution is closely related to the region of interest. It also defines the unit of analyses. Socioeconomic data tend to be highly resolved i.e. at household scale, while environmental data tend to be of relatively lower resolution, for example, temperature data at 1km or 100km grid size. When the CCVA input is gridded data, spatial resolution refers to the area or linear dimension(s) of the grid cells used. The appropriate grid size will often be determined by the resolution of the available data. In general, the highest resolution will determine the limit to which the grid size/unit of analyses can be resampled or adjusted to. For example, whilst most Global Climate Models operate on course grid size (100 x 100

km), most ecosystems e.g. coral reefs are gridded at relatively high resolution (i.e. 1 km). In this case, gridded climate data can be downscaled either statistically or dynamically.

In dynamic downscaling, course resolution outputs are used to drive a higher-resolution regional numerical model, enabling simulation of local conditions in greater detail but at an exorbitant computational and financial cost. In comparison, statistical downscaling is possible and is far less resource-intensive. The scale of spatial heterogeneity in the region being considered will also influence the appropriate grid size; a coarser grid may present few problems in areas of relatively low spatial heterogeneity (e.g., flat terrain or uniform land-surface properties), whereas finer grids may be necessary for areas of higher spatial heterogeneity (e.g., topographically complex, varying land-surface properties).

- *Specify time frame:* CCVA is dynamic over both space and time. Given that climate and other input data vary over time, there is a need to specify the timeframe for the risk screening or the time frame represented by CCVA. Selection of the timeframe for the analysis depends on the CCVA objective. The selected timeframe will also influence the climate change scenario(s) applied for the analysis.

4.2.3 Putting a team together

Understanding who key participants and partners are (both internal and external), their information needs, and their roles and responsibilities provides a context for designing a successful CCVA and its implementation process. Choosing participants is key to aligning the final outcomes to the CCVA goals and objectives.

4.2.3.1 Whom to engage?

The following stakeholder groups may be necessary to involve in a CCVA process:

- Decision-makers (e.g. regulators and managers).
- Resource users (e.g., fishermen)
- Opinion leaders (influential and respected individuals within the region or sector of interest)
- Climate change adaptation planners
- Information specialists (e.g., scientists, sociologists, etc.)

Time allocated to thoughtfully identifying and engaging stakeholders in the vulnerability assessment will usually be more than worth the effort if the vulnerability assessment is to be part of a longer-term engagement on climate change issues.

4.2.3.2 Engaging CCVA Stakeholders

The level of stakeholder engagement in vulnerability assessment varies widely. On one end of the spectrum, it could involve simply providing information along the way, while on the other end it could involve guiding the entire process. It is generally the case that the more deeply engaged stakeholders are, the more committed they will be to a climate change vulnerability assessment and to applying the results in subsequent adaptation planning and projects.

4.2.4 Justification, Budget & Authority

More generally, conducting a CCVA must be scaled to fit within the limitations of the available resources, including:

- The costs of conducting a CCVA depend on the time, data and information, and expertise needed to achieve the outcomes. Therefore, identifying potential budget before starting the CCVA process will keep expectations realistic. For example, while desktop reviews can be completed in as little as a few weeks, collection and/or analysis of primary data requires a greater investment of time. Furthermore, one person could accomplish a basic desktop CCVA by working to integrate existing information over a period of days to weeks, while an in-depth assessment may require a multi-member team working for months. Hence funding may be needed to hire researchers, analysts, and writers; to pay for travel and other logistical support; to acquire data and equipment; to conduct workshops; and, to prepare and disseminate reports.
- Data and information requirements for CCVA is influenced by the type of decision (e.g., strategy, project, activity), the timeframe, scale of decision making (e.g., subcounty, country or regionally). There is also a need to align the data needs to the stated CCVA goal and objectives.
- Expertise needed for a CCVA depends on the assessment objective as well as time and cost considerations and desired outputs. CCVA process requires a multi-disciplinary team of experts. For example, a marine park manager may be able to conduct a strategy level climate risk screening with limited input from an expert using available guidance and resources such as the reef resilience toolkit (ref). However, a more detailed examination of how climate variability and change may affect activity outcomes may require the engagement of individuals who understand climate modeling and can use climate predictions appropriately

4.3 Step 3: Evaluating vulnerability dimensions (i.e. exposure, sensitivity, and adaptive capacity)

4.3.1 Exposure dimension

Evaluating the exposure of a system to climate change requires an understanding of the ecosystem under study, in terms of how it is impacted and how it is likely to respond to climate change indicator (e.g., temperature, precipitation, and many others). Evaluating exposure involves identifying climate change indicators that may affect the ecosystem of interest. Exposure dimension of vulnerability can also be conducted based on historic observed changes in climate (retrospective assessment), on future climate projections (prospective assessment), or a combination of the two (Hayhoe et al. 2011, Lawler et al. 2011). Historic changes will generally give an indication of the current exposure of the ecosystem as compared to the past, while the future climate projections will give an assessment of how much change might be expected to impact on a given ecosystem. Depending on the objectives of the assessment, one or the other may be more appropriate.

4.3.1.1 Selecting and accessing climate indicators

Selecting climate indicators is one of the most important activities in CCVA (Snover et al., 2013). Determining what climate indicator may be appropriate to use in a CCVA depends on one's

geographic scope and boundary, the required levels of spatial and temporal resolution, and on the level of expertise available to apply and interpret the climatic data. Annex Table B provides examples of climate data freely available from online archives. While the list is not exhaustive, it provides a good starting point. However, data may need to be pre-processed for synthesis using basic statistical methods. The most commonly used statistical methods include computation of mean, anomalies, median, and standard deviation, and trend analysis. Therefore, data analysis requires good statistical practice.

Some of the variables that may need to be derived from specific indicators include those that address the following questions:

- How high is the inter-annual variability of climate variables?
- What is the frequency, intensity, timing, and duration of extreme events?
- What are the observed key climatic hazards in the system of interest?
- Where are the hotspots, i.e. where have the largest changes occurred in climate variables from past to present conditions?
- What is the projected change in key climatic variables? (e.g. change in inter-annual or inter-seasonal variability of the climatic variable, change in the average, change in the maximum or minimum value)
- What is the projected change in extreme events? (e.g. occurrence and timing of floods, dry spells, thermal stress, coral bleaching)
- Which climate change scenarios are relevant?

Therefore, selecting scenarios for exposure assessment requires identifying the primary local and large-scale climate drivers (such as El Niño-Southern Oscillation and Indian Ocean Dipole) and determining appropriate sources of information for historical and future scenarios. To understand historical changes in climate and what the future is likely to be, gridded in-situ, satellite, three-dimensional models, or Ocean and Atmospheric General Circulation Models (OAGCMs) are used (Annex Table B). It is important to recognise that future climate scenarios are not predictions but simply ‘plausible futures.

In general, several rules apply when using climate models:

- One should not rely on a single model run – use an array of model runs as the basis to identify a ‘best-guess’ scenario
- Always keep in mind that models provide a probable scenario – a likely or plausible future – and not a prediction. The reality maybe be better, worse, or just different.
- Use climate model output accordingly as a basis to explore system sensitivities and vulnerabilities, and to identify appropriate adaptation options and their timing.
- Always remember, precision does not equal accuracy.
- Some climate variables are better simulated by climate models than others. For example, one can be more confident about some variables, such as sea-level rise and temperature.
- The skill and knowledge of the model data user is an important factor. The user must make choices, for example, about which greenhouse gas pathway to use.

4.3.2 Sensitivity dimension i.e. impacts (and response) of climate exposure on the system of interest

The sensitivity of a system describes the dose-effect relationship between its exposure to climatic stimuli and the resulting impacts (Füssel & Klein, 2006). For example, the sensitivity of coastal communities who rely on marine ecosystem goods and services is largely dependent on how strongly they depend on the specific goods and services, which will be affected by climate change.

Indicators of sensitivity can encompass geographical conditions, land-use, demographic characteristics, dependency on fisheries (Annex Table C). Below questions can help in assessing how sensitive the system of interest is to climate change.

- How do climate conditions/indicators affect the system of interest? (e.g. direct/indirect, long term/short term)
- How do current climatic variability and extremes impact on the system of interest?
- Which climate variables impact on non-climatic stresses? for example, non-climatic stressor on mangroves of human deforestation may be compounded by climate change drivers of precipitation and temperature.

4.3.3 Adaptive capacity dimension

While *exposure* and *sensitivity* determine the potential impact of climate-induced change, *adaptive capacity* is the ability or potential of a system to respond successfully to climate variability and change, and includes adjustments in both behaviour and in resources and technologies. This dimension is about the capacity of the system of interest to respond and adapt to climate change. Observations of how the system has adapted or is adapting to current climate variability and extremes and assessing underlying capacities that may allow further adaptation in the future can be used to quantify the adaptive capacity. Indicators for the adaptive capacity of a socio-ecological system may include economic capability, physical infrastructure, social capital and institutional capacity (Annex Table D). Economic capability represents the economic resources available to reduce climate change vulnerability. It includes human resources and technological alternatives.

In determining the indicators of adaptive capacity, some of the considerations include:

- How have various measures addressed the key environmental, socio-economic and developmental issues? (e.g. policies, programmes, local adaptation measures)
- What response measures do exist to deal with climate variability and hazards?
- Have the response measures specifically addressed the identified hotspots? (e.g. regions, sectors, groups)
- What factors have determined the effectiveness of identified response measures?
- What institutional arrangements have helped with adaptation to climate variability and extremes?
- What natural resources have been conducive for adapting to climate variability and extremes?
- What economic resources have been conducive for adapting to climate variability and extremes?

4.4 Step 4: Synthesis and evaluation

Having explored and established the climate change impacts on preferred ecosystems, climate sensitivity, and the capacity to adapt, the synthesis of the dimensions to obtain the overall vulnerability is the final step. Synthesis is usually done by scaling the dimensions to values between 0-1, before summing exposure to sensitivity and subtracting the adaptive capacity. The overall vulnerability is then evaluated to qualitatively and quantitatively describe the ecosystems that are more vulnerable than others for prioritization. It is rather difficult to differentiate current and future vulnerability because, as Schauser *et al*. (2010) point out, there is a lack of data for projections of sensitivity and adaptive capacity.

One way to illustrate vulnerability for easy interpretation and communication to the managers is using a vulnerability rating scale (Table 4). Vulnerability rating scale presents overall vulnerability of a system as matrix of a simple categorical index (for example low, medium, high) or semi-quantitative ranking (i.e. 1 to 5). The information must be synthesized to identify level vulnerability associated with each combination of exposure/sensitivity and adaptive capacity of resilience or exposure/sensitivity (Table 4).

Table 4: Example of a simple vulnerability rating scale (color shades represent degree of vulnerability). Adapted from Marshall et al. (2009).

Adaptive capacity	**Sensitivity**		
	Low	**Medium**	**High**
High	Low	Low	Medium
Medium	Low	Medium	High
Low	Medium	High	Extreme

In a system with low adaptive capacity and high sensitivity, vulnerability is likely to be high and the adaptation is unlikely to occur without management intervention. Conversely, when a systems capacity to adapt is high and exposure or sensitivity is low, that ecosystem will likely adapt to climate change.

4.5 Step 5: Operationalizing and mainstreaming vulnerability

CCVAs are often part of a continuum of activities that, together, enable adaptive capacity and resilience to be assessed and enhanced (Lim and Spanger-Siegfried, 2004). As described in previous sections, a CCVA is designed to explore who or what is vulnerable; where, when, why and how they are vulnerable. Findings from CCVAs can help determine which sectors of an ecosystem or locations should be the focus of adaptation activities; which vulnerabilities should be reduced and how; and how any such efforts should be combined with other types of interventions that manage other stressors. For example, an assessment may show that certain types of ecosystems located within MPAs are less exposed to climate stressors, making them less sensitive and thus high adaptive capacity. This type of information will be helpful in determining whether similar actions (setting more MPAs) may reduce projected impacts.

Assessment results can also help to manage adaptation options to increase their effectiveness. For instance, CCVA results can be helpful in defining baseline exposure, sensitivity, and adaptive

capacity before any adaptation action; and developing plans to monitor important indicators of exposure, sensitivity, and adaptive capacity during implementation.

5 Existing CCVA studies in WIO

Examples of vulnerability assessments conducted in the WIO are illustrated in Table 5.

Table 5: Examples of climate change vulnerability assessments conducted within the WIO region.

Approach	Dimensions of Vulnerability considered	Scale of documented output	Reference
Examine vulnerability of coastal communities to the impacts of coral bleaching on fishery returns.	Exposure, sensitivity, adaptive capacity	Coastal societies are vulnerable to a range of climate-related impacts. For example, levels of exposure was low in Mauritius and high in Kenya and Seychelles, respectively.	Cinner et al. (2011)
Assess ecological components of vulnerability between government operated no-take marine reserves, community-based reserves, and openly fished areas.	Exposure, Sensitivity, Recovery potential, and Adaptive capacity	Fished sites were marginally more vulnerable than community-based and government marine reserves.	Cinner et al. (2013)
Identify global spatial gradients of thermal and eutrophication stressors.	Exposure	Corals are exposed to radiation and reinforcing stress. Based on exposure grades, the WIO region is composed of moderately to highly exposed regions with moderate to high scores in both radiation and reducing factors	Maina et al. (2011)
Modelling susceptibility of coral's to thermal stress and how coral communities will change with environmental variables associated with climate change.	Exposure	Regional gradients in environmental stress were identified for example, half of the strictly no take zones in the region are situated in locations with medium to high susceptibility.	Maina et al. (2008)

Provide an improved framework for assessing the vulnerability of coastal communities across cultures, oceans and scales, and suggests ways in which adaptation strategies can be conceptualized and implemented more effectively	Exposure, Sensitivity, Adaptive capacity	Coastal communities in Madagascar and South Africa are most vulnerable to change in the marine environment.	Aswani et al. (2018)
Apply a novel analytical framework that considers the interactions between adaptive capacity and environmental susceptibility to assess a range of conservation strategies.	Exposure and Adaptive capacity	Conservation strategies did not reflect adaptive capacity and are, therefore, ill prepared for climate change.	McClanahan et al. (2008)
Assessing vulnerability of the fishing communities to climate variability using selected fin fish species in Ungwana Bay and the Lower Tana Delta, north coast Kenya.	Exposure, Sensitivity, and Adaptive capacity	The Ungwana Bay and Lower Tana Delta ecosystem experiences both high exposure to climate variability and increased pressure to fisheries resources. In addition, artisanal fishing communities are characterized by low adaptation capacity.	Dzoga et al. (2018)

6 CCVA Methods:

6.1 Information & data

In some cases, information and data for the assessment will be readily available. In most cases, however, significant data gaps or limitations exist, which must be acknowledged and assumptions formulated when designing the assessment and reporting results. Most CCVA process will include:

- Evaluation of exposure, sensitivity, and adaptive capacity of the ecosystem or ecological process.
- Evaluation of historical changes, driven by both climate and non-climate factors. Where possible, attribute these changes to either climate or non-climate drivers.

- Analyses of observed and projected data on climate, land use, demography, and other key climate and non-climate drivers.
- Evaluation of relative vulnerabilities of ecosystems or processes based on an objective scoring system.
- Estimation of uncertainties. There are various ways to estimate uncertainly using expert knowledge or technical methods such as computer models, future emissions scenarios, and statistical variation.
- An analysis of spatial information on vulnerable areas and potential climate refugia.
- Narratives that describe key information sources, relevant ecological and geographical contexts, and justifications for rankings.

Common methods used for conducting a CCVA generally fall into the following categories (adapted from Chaudhury et al 2014; GIZ, 2014):

6.1.1 Desktop reviews

Desktop reviews are studies that draw on existing information. They do not require fieldwork or additional analysis. A desk review can help in the understanding how climate impacts have affected a particular ecosystem, or particular region in the past, or how they may be affected in the future. A variety of information sources can be included in the review, such as:

- Other VAs that have been done including regional/global reports
- Sources of climate data, including downscaled projections from climate models that were generated for other assessments
- Hazard and/or risk maps
- Storm damage assessment reports, which document whether and how extreme events previously affected a system
- Disaster risk reports, which provide information on risks of weather hazards in a given region
- Sector-specific historical records from past events, which can provide useful information about vulnerability; for example, a record of coral bleaching and mortality following elevated SST

A desktop review of existing information acts as a scoping step and is a good way of identifying and involving stakeholders who may have supporting information or expertise.

6.1.2 Stakeholders consultations and workshops

Broad, representative consultation is important to ensure a wide range of perspectives. Experts can also provide substantive information and analysis for a CCVA. For example, marine park managers can provide information about exposure based on historical events and the ecosystems that they oversee. Scientists may be able to provide information or analysis related to sensitivity, relevant to climate impacts, and adaptive capacity information.

Along with individual consultations with stakeholders and experts, stakeholder workshops can be an excellent way to understand vulnerabilities. By getting different perspectives in the same room,

one may also uncover new dimensions of vulnerability, identify cross-sectoral linkages, and fill gaps in knowledge.

6.1.3 Analysis

Additional or specialized analysis may be needed depending on your scope, the decisions you are trying to influence, and your ecosystem of interest. For example, a climate impact assessment might look at the specific type and severity of impacts expected for a particular ecosystem (either corals, mangroves or seagrass) depending on projected climate change. Global Climate Models[6] may help to understand likely changes in a particular area or ecosystem based on potential future climate conditions. If downscaled climate data is required but not readily available (based on your desk review and consultations), you may consider generating such data as part of the VA.

6.2 Analytical methods

With the purpose, emphasis and dimensions of an assessment specified, the analytical method for conducting CCVAs can vary depending resources and information available. The methods may be quantitative or qualitative.

Sensitivity matrices are applied for many scientific purposes (e.g. for identifying causal processes and explaining attributes of vulnerable systems, for linking system attributes to vulnerability outcomes, and for mapping, ranking and comparing vulnerability across regions), at many scales (from local to global), and with different policy objectives (e.g. more realistic assessment of climate change risks, aiding the allocation of resources across regions, monitoring the progress in reducing vulnerability over time, and identifying suitable entry points for interventions) (Füssel & Klein 2006). IPCC report highlights the need for metrics to assess adaptation, vulnerability and risk (Christensen et al. 2013). An increasing body of literature is available no building metrics for the key determinants of climate change risk, to design index assessing the climate change impacts, vulnerability and risks, to support tools for planning for adaptation, implementing measures and monitoring and evaluating climate adaptation. However, no common reference metrics exist for assessing the main components of climate change risk. This is due to many factors such as: the conceptual confusion around the key elements as vulnerability, adaptation and resilience due to different scientific communities that have tried to resolve it (Fussel, 2007).

Qualitative ranking helps to clearly communicate information on the relative level of vulnerability. When a ranking system is used, a description or definition of each category is typically provided, along with data uncertainties. Qualitative ranking is typically categorical (e.g., high/medium/low or on a scale).

Mapping is useful for assessing and communicating the spatial nature of vulnerability including changes in spatial aspects over time (Edwards et al. 2007). Maps can rely on a variety of inputs, ranging from qualitative stakeholder knowledge to quantitative Geographic Information System (GIS) analytics. They can be used as a tool throughout a VA, including during stakeholder consultations, during the technical assessment itself, or as a communication tool to explain the assessment results.

Projections are estimates or forecasts of future situation based on present trends (Hayhoe et al. 2017). Climate projections are typically presented for a range of plausible pathways, scenarios, or

[6] For more information on climate modeling and recent projections, see the website of the Intergovernmental Panel on Climate Change (IPCC) (www.ipcc.ch)

targets that capture the relationships between human choices, emissions, concentrations, and temperature change.

Institutional analysis explicitly analyses institutions, i.e. laws, schemes, conventions, shared practices, habits or traditions, as independent variables, dependent variables, intervening variables or several of these. This is increasingly seen as essential to advancing adaptation particularly with respect to integrating societal and ecological dimensions (Paavola and Adger, 2005). Therefore, a particular approach to institutional analysis influences the development of knowledge on institutions in adaptation.

Decision/probability trees integrates utility theory, probability, and mathematical optimization in a procedure designed to select the best pathway to facilitate adaptive management (Mitchell et al. 2007). It could help policymakers and planners to prioritize adaptation measures, tailored to the needs of species or habitats, for integration into the development or delivery of nature conservation legislation, regulation, incentives strategies and plans.

Delphi method is a structured and interactive process to collect opinions from a group to facilitate problem-solving, forecasting, planning, and decision-making (Neuman, 1994). Delphi is designed to reap the benefits, but reduce the liabilities, of group problem-solving.

Multi-criteria analysis provides one systematic way for decision makers to make sense of the wide range of information that may be relevant to making adaptation choices (Van Ierland et al. 2013). This method allows consideration of both quantitative and qualitative data in the ranking of alternative options.

6.3 Integrating results across disciplines

Previously, vast majority of research on global climate change had focused on climate change itself, rather than the resulting ecological and social impacts (Clark et al., 2000). Most recently, Aswani et al. (2018) proposed an integrative construct of vulnerability at the interface of biological and social structure, and their relationships in shaping vulnerability (either as producing or mitigating it). Social structure is understood as any social unit (e.g. household, community, organization) and its functioning (e.g. role, decision-making) while biological structure (or environments) refers to the multiple biophysical and social dimensions an organism, population or ecosystem is related to. This description of vulnerability attempts to be at the interface of the two broad conceptual traditions of vulnerability.

For example, McClanahan et al. (2008) applied a novel analytical framework to examine conservation actions in five western Indian Ocean countries. They integrated results from oceanographic-environmental model and a socioeconomic survey of coastal households to quantify indices of bleaching environmental susceptibility and adaptive capacity. Each indicator was normalized then combined as a weighted score to provide a scale of adaptive capacity that also ranged from 0–1. In their results, they found that conservation strategies do not reflect adaptive capacity and are, therefore, ill prepared for climate change.

7 Communicating CCVA results

Effective communication of CCVA results requires thought and care. Just as for the vulnerability assessment analyses, such communication should ensure that uncertainties are clearly explained, vulnerabilities explicitly described, and results presented in ways that facilitate their use in developing adaptation strategies.

First step is to identify the audience or audiences that you wish to target. Although a CCVA can often have multiple stakeholders, communication products should be tightly targeted at specific audiences, potentially necessitating multiple products from a single assessment. Table 6 lists examples of possible CCVA audiences, the information that will likely be most relevant to them and suggestions about appropriate methods and media for communicating results to each.

It is important to note that several different media and methods are often needed for effective communication, even for a single audience, and that this is almost always the case when addressing different audiences. In summary, targeting your audience necessitates tailoring methods, media, and content for your target group by understanding biases and other concerns that the audience might have with the results of a CCVA.

Table 6: Examples of CCVA target audiences, the types of information they require, and some of the communication media that are useful for communicating CCVAs and their results to them.

Audience	Relevant information	Appropriate communication methods
General public or multiple stakeholders	Broad conclusions and take-home messages about key vulnerabilities; basic data and analyses	Oral presentations/meetings with Q & A sessions; press releases targeting mass media; social media; popular articles
Conservation managers	Specific conclusions; suggestions for adaptation strategies for specific species, sites and site networks; in-depth data and analyses; areas of uncertainty; data deficiencies	Meetings; publications (both grey and peer-reviewed literature); guidelines documents
Policy makers, donor agencies	Broad conclusions; take-home messages; policy implications	Oral presentations/meetings with Q and A session; press releases and letters to the editor targeting mass media, policy forums; social media; briefing papers
Scientists and researchers	Specific conclusions; data and analyses; methodological problems and limitations; suggestions for CCVA improvement; areas of uncertainty	peer-reviewed scientific publications; oral presentations at scientific meetings; social media

Second step is to consider what to communicate which depends on the audience. authors may wish to describe the methods used, data gaps encountered and uncertainties associated with the results in addition to describing the degree of vulnerability of the assessed ecosystem and the implications for species-focused and site-focused conservation interventions. For scientists and researchers, the details of complicated models may be appropriate, while just a brief description of such models would form part of a briefing paper or talk to a community group. For conservation practitioners, spatially explicit results are also likely to be valuable for developing adaptation strategies, and maps depicting these results should include a spatial context (political boundaries, roads, park boundaries and populated areas) that the audience can relate to.

Third step is that authors need to think about how to communicate, and to make effective use of available media and visual aids (e.g., graphs, tables, maps and figures) for dissemination. Use of color in graphics to indicate relative vulnerability of the species assessed and error bars to indicate the limits of uncertainty can be powerful means of communication (Dubois et al., 2011).

It is important to be aware of the problems inherent in communicating CCVA results. Two particular kinds of content that need special attention are those of uncertainty and vulnerability. Scientific uncertainty is vastly different to the common use of the term, and this point needs to be clearly refreshed for certain audiences. Where possible it is important to quantify uncertainty and provide descriptions of what is known and what is uncertain.

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9 Annex

Annex Table A: Lists trend in SST from 1981 to 2017 for all the EEZs in the WIO.

EEZ	SST trend (°C/decade)	SST trend category
Madagascar	0.20	fast warming
Kenya	0.19	Moderate warming
Comoros	0.11	Moderate warming
Mayotte	0.11	Moderate warming
Mauritius	0.13	Moderate warming
Chagos	0.14	moderate warming
Somalia	0.07	Slow warming
Tanzania	0.09	Slow warming
Mozambique	0.05	Slow warming
South Africa	0.08	Slow warming
Seychelles	0.09	Slow warming
Reunion	0.10	Slow warming
Europa	0.08	Slow warming
Bassas da India	0.09	Slow warming
Juan de Nova Island	0.09	Slow warming

* These trends were estimated from linear regressions of annual mean SST (from 1982 to 2017).

Annex Table B: Examples of the most widely used and generally available climate datasets representing historical (baseline or recent past) climatic conditions.

Dataset name	Spatial extent	Temporal extent	Variables/exposure factors	Spatial resolution	Data available at: (URL)
Datasets using meteorological station data interpolated with respect to longitude, latitude and elevation					
WorldClim (Hijmans et al., 2005)	Global	1950-2000 (Period means)	- temperature - precipitation - solar radiation - wind speed - water vapor - pressure	30 seconds (~1km)	http://www.worldclim.org/
CRU TS v.4.02 (Harris et al., 2014)	Global	1901-2017	- temperature	0.5 degrees (~50km)	http://www.cru.uea.ac.uk/cru/data/hrg/
Datasets using satellite remote-sensed data, usually processed through some form of model					
MODIS	Global	2002–present	Land Surface Temperature SST Chlorophyll a	Varies depending on variable e.g. 4 & 9km SST	

NOAA AVHRR v 5.3	Global	1981–2014 (daily)	SST	0.04 degree (~4km)	http://data.nodc.noaa.gov/pathfinder/Version5.3/L3C
NOAA Coral Reef Watch (CRW) (Liu et al. 2014)	Global	1985 to present (daily)	SST	0.05 degrees (~5km)	ftp://ftp.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/coraltemp/v1.0/nc/
CHIRPS v2.0 (Funk et al., 2014)	50°S–50°N (Rainfall only)	1981–present (daily, 10-day, monthly & annual data)	Precipitation	0.05 degrees (~5km)	http://chg.geog.ucsb.edu/data/chirps/#plus7
TRMM/3B42	50°S–50°N (Rainfall only)	2000–present (daily, 10-day, 30-day)	Precipitation	0.25 degrees (~25km)	http://pmm.nasa.gov/data-access/
Sentinels	Global		Land Surface Temperature SST Chlorophyll a	10 m to 60 m	https://scihub.copernicus.eu/dhus/#/home
Model simulation datasets					

HYCOM + NCODA Reanalysis	Global	1995-2012	- SST - Sea surface elevation - Ocean mixed layer thickness	0.083 degrees (~8km)	ftp://ftp.hycom.org/datasets/GLBu0.08/expt_19.1
CMIP5	Global		- Surface air temperature - Precipitation - Ocean temperature - pH etc.	Varies with variable but 1 degree (~100km)	https://esgf-node.llnl.gov/projects/esgf-llnl/

Annex Table C: Indicators of sensitivity (based on Roy et al. 2001, McClanahan and Hicks, 2011, Cinner et al. 2013,)

Dimension	Illustrative questions
Coral bleaching susceptibility	- Which species (e.g. branching corals) are often severely affected by disturbance. High abundance of these species confers higher sensitivity.
Reef fish susceptibility	- Which species (e.g. branching corals) are often severely affected by disturbance i.e. coral bleaching/mortality
Species composition	
Abundance	- Which species have higher productivity (i.e. Fecundity–egg production, Recruitment period–successful recruitment event, Average age at maturity). Therefore, higher productivity species may be less sensitive (more resilient) to longer term climate change stressors and low productivity species more sensitive(and less resilient) over the longer term.)
Phenology	- Which environmental variables (e.g. salinity, temperature, currents, & freshwater flows) act as a phenological cue for spawning or breeding–cues.
Livelihood activities (e.g. fishing, selling marine products, mariculture, tourism, farming etc.)	- Which livelihood are important in the household or community?
Fishing gear susceptibility	- Which gears are often impacted by effects of coral bleaching on the fish species targeted by each?

Annex Table D: Indicators of adaptive capacity (based on Maina et al. 2015; McClanahan et al 2008a; Cinner et al. 2011)

Dimension	Illustrative questions
Human capital- knowledge and skills	- What is the education level of the populations? - What traditional knowledge or practices relevant to addressing climate are available in communities - Do people know about available adaptation options? - Do communities have access to relevant information, such as forecasts or early warming? - Is the information presented in languages and formats that are understood?
Social capital – informal and formal support structures	- Are there strong social networks and relationships? (the more communities and households exhibit connectedness, social participation, equality, and inclusivity, the more likely they will be able to respond to both climate and non-climate stressors) - Do government institutions effectively serve local communities? - What other institutions are relevant for adaptations? - Do social factors like age, gender, marital status and others affect the options available to people to adapt to climate change?
Natural capital – ecological assets	- Do people depend in natural resources (e.g. mangroves, corals, seagrass etc.) for their livelihoods? - Are ecosystem services valued and safeguarded? - Are these ecological assets able to adapt to consequences of climate change? - What mechanisms do these ecological assets have to adapt (e.g. plasticity, dispersal abilities)? - Are these ecological assets found within protected area? - Are the protected areas adequately managed to maintain the supply of ecosystem services or biodiversity that supports livelihoods (e.g. fishing, tourism)
Physical capital – built environment	- Is there a good system of roads and other physical infrastructures (e.g. hospitals, schools, piped water etc.)
Financial capital – financial resources	Do people have access to savings to respond to extreme events? Are government budgets available to invest in longer term adaptation options?

10 Case study 1: Climate Change Vulnerability Assessment for Coral Reefs

This section summarizes and communicates the methodology used in the case study for coral reefs vulnerability assessment in the WIO. In the IPCC's widely adopted vulnerability assessment framework, vulnerability is a function of exposure to climate and non-climate threats and sensitivity to these threats, which yields potential impacts that are moderated by adaptive capacity (Turner et al. 2003).

To assess and understand thermal history trends and possible future projection patterns at the approximate scale of reefs one would need very high resolution satellite data (for example, the 5km NOAA coral reef watch data) and downscaled multimodel projections from the CMIP5 data. From this, several metrics could be developed to pinpoint areas where corals have been exposed or are at risk for bleaching including (1) rates of change in annual, cool-season (non-bleaching months) and warm-season (bleaching months) SST; (2) the percentage of reefs exposed to bleaching-level thermal stress each year during the study period; and (3) projections of coral bleaching conditions (i.e. exposure to the primary climate threat to coral reefs).

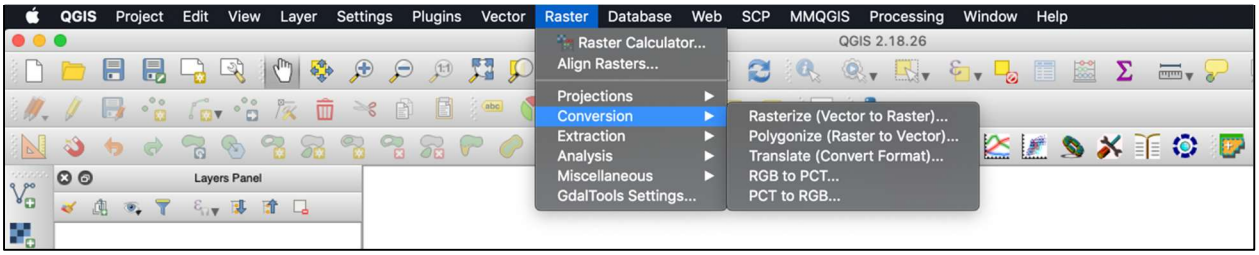
Steps used:

Step 1: Obtaining Reef locations

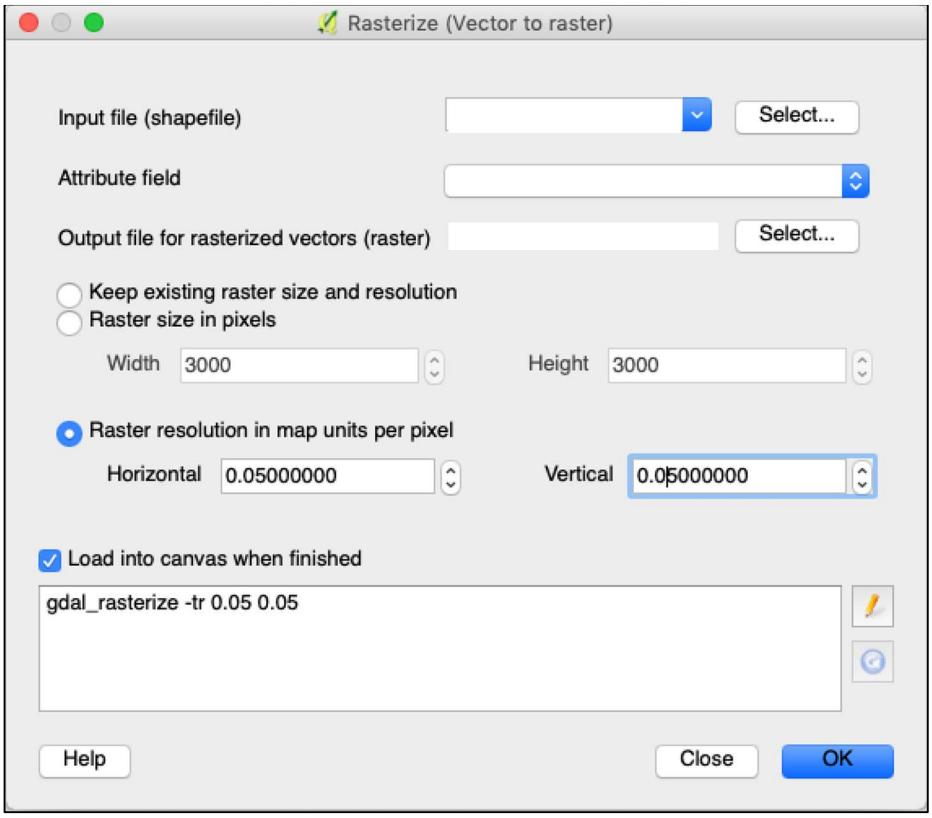
Coral reef locations can be extracted from the Global Distribution of Coral Reefs dataset (UNEP-WCMC et al., 2010) which is set at 1 km resolution. To match the resolution of satellite and downscaled multimodel projections data, the reef layer needs to be gridded onto a 5 km grid using GIS tools (e.g. QGIS or ArcGIS) as elaborated on the following paragraph.

Begin with a projected vector layer clipped over the region of interest and the follow the process described below either in QGIS or ArcGIS

In QGIS, click on Raster ▸ Conversion ▸ Rasterize (Vector to Raster) to start this tool, as in the screenshot below:



then set it up as in the screenshot below:



in ArcGIS this can be done with Feature to Raster tool.

ArcToolbox > Conversion Tools > To Raster > Feature to Raster

from dialog box, do following instructions.

The vector dataset

The field to assign values to features

The output raster name and location

The cell size for the output raster dataset

Step 2: Downloading archived SST and climate projections datasets

One would need to download sea surface temperature from NOAA coral reef watch which provides continuous and consistently derived temperatures over recent decades, currently available from 1985 to 2017. The fact that the data spans both previous coral bleaching events e.g. 1998, 2005, and 2010, and is of high resolution makes it key supporting its use to develop a range of historical thermal metrics e.g.

- Trends (SST rates of change)

To calculate SST trend one would need the long-term historical trajectory of either annual/decadal mean temperature then apply a linear generalised least squares model (after Weatherhead et al. 1998) to estimate SST trend as illustrated in the equation below:

$$\mathbf{SST_{trend} = \mu + \omega_{ann} t + N_t} \qquad 1$$

Where μ is constant, ω_{ann} is the slope, t is time in years and N_t is the residual assumed to autoregressive of the order of 1.

- Climatology (long-term average conditions)

Coral bleaching is caused by unusually warm sea surface temperatures. Therefore, looking for areas at risk of bleaching, one would define the "usual/average" temperatures calculated as long-term mean SST, or climatology (historical baseline temperature). Monthly climatologies are calculated from 27 years (1985-2012) of satellite data. The Maximum of the Monthly Mean SST climatology would then be defined as the warmest monthly mean value for each pixel indicating the upper limit of "usual" temperature.

- Sea surface temperature anomaly

SST Anomaly is produced by subtracting the long-term mean SST (for that location in that time of year) from the current value. The SST Anomaly product detects anomalous thermal conditions, indicating

whether current temperatures are cooler or warmer than the long-term mean temperature at each location for the time of year. Warm anomalies can lead to the development of bleaching thermal stress; this is especially useful when monitoring oceanic conditions prior to a bleaching season. The formula for obtaining anomaly is:

$$\mathbf{SST_{anomaly} = SST - climatology} \quad 2$$

- Degree Heating Weeks (DHW)

The degree heating week (DHW) index developed by the National Oceanic and Atmospheric Administration Coral Reef Watch (NOAA CRW; Liu et al., 2003; Liu et al., 2005) has been widely used to predict coral bleaching. Glynn and D'Croz (1990), showed that temperatures exceeding 1 °C above the usual summertime maximum are sufficient to cause stress to corals. This is commonly known as the bleaching threshold temperature. Only thermal stress (HotSpots) values that are ≥ 1 °C are accumulated over a 12- week window in the DHW (Liu et al. 2014). DHWs over 4 °C-weeks have been shown to cause significant coral bleaching; values over 8 °C-weeks have caused widespread bleaching and some mortality. The formula for obtaining the anomaly is:

$$\mathbf{DHW} = \frac{1}{7}\sum_{\mathbf{i=1}}^{84} \mathbf{HS_i}\ \mathbf{if HS_i} \geq 1℃ \quad \mathbf{3}$$

- Degree Heating Months (DHM)

Satellite based hindcast and nowcast only provide information as to how bleaching thermal stress has evolved and the present likelihood of bleaching. With coral reefs being among the most sensitive ecosystems to climate change, sea surface temperature (SST) data from Global Climate Models (GCMs) can be retrieved from the World Climate Research Programme's CMIP5 data sets (Moss et al. 2010) for relative concentration pathways experiments (e.g. RCP2.6, RCP4.5, RCP6.0 and RCP8.5) archived as monthly files.

Projecting future thermal stress on corals is estimated using the accumulation of Degree heating months. The monthly timestep is better suited on temporal course resolution archived climate models output. DHM index is calculated as anomalies above the warmest monthly temperature (MMM) from the climatology and summed for each 3-month period (van Hooidonk et al. 2015, 2016) or over a four month rolling window (Donner et al. 2009) using the formulae below:

$$\mathbf{DHM} = \sum_{\mathbf{i=1}}^{\mathbf{12}} \mathbf{HS_i}\ \mathbf{if HS_i} \geq \mathbf{1}℃ \qquad \mathbf{4}$$

Where i is month and HS is the thermal stress or HotSpots.

One DHM (in °C-month) is equal to 1 month of SST that is 1°C greater than the maximum in the monthly climatology. DHM total of 1°C is the best proxy for the lower intensity bleaching threshold (DHW>4) and DHM total of 2°C is the higher threshold, for severe coral bleaching with more associated coral mortality (DHW>8). Degree heating months can be converted into DHW by multiplying by 4.35 (Donner 2005 and van Hooidonk et al., 2013, 2014).

- Stress Frequency

The number of bleaching stress events is quantified through the time period, describing the historical incidence of DHW

11 Results

This section illustrates how the methods discussed above were used for vulnerability assessment for corals. In summary, the analysis of thermal history at coral reef locations revealed warming trends. The following key points are identified from each set of thermal history parameters.

11.1 SST trend

Annual averaged reef SSTs warmed an average of 0.14°C/decade during the study period with nearly 85% (1961 pixels) showing positive trend above 0.1°C/decade while 3% of reef locations show a cooling trend (0.04°C/decade) all in southwest of Madagascar. Frequency distribution of reef SST trend is shown in the inset. Compared to reef SSTs in other regions Middle East has warmed by 0.32°C/decade, Great Barrier Reef has warmed by 0.08°C/decade while Southeast Asia has warmed by 0.11°C/decade (see Heron et al. 2016). With bleaching typically observed during warms months (January-May), warming during this period was 0.28°C/decade compared to an average 0.42°C/decade during cool months (June-October). This shows that cool months are warming faster therefore, with this trend there is a possibility of bleaching being observed during these months.

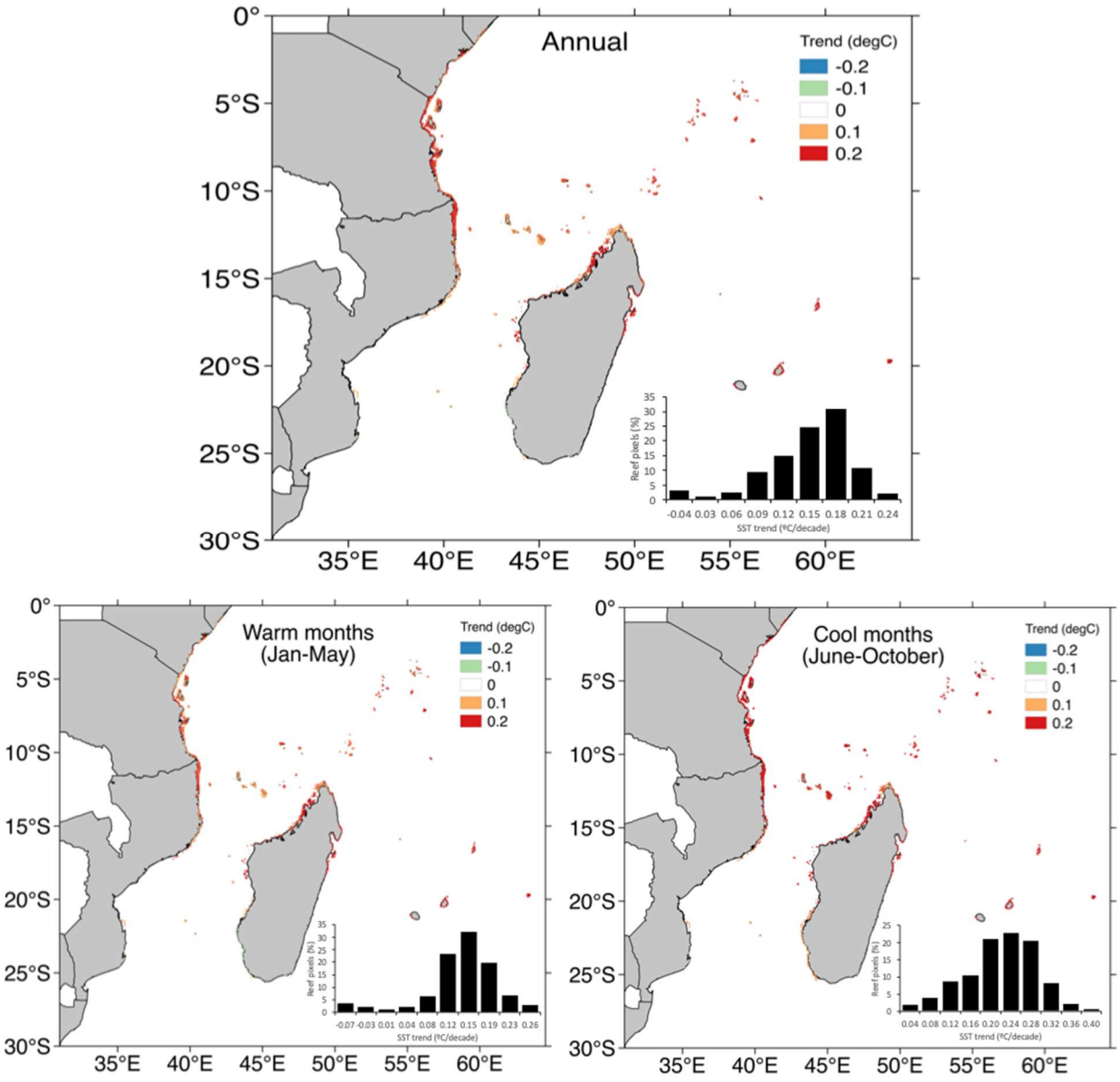


Figure 1: Trends in annual, warm months (Jan-May) and cool months (June-October) sea temperature at reef scale calculated from NOAA coral reef SST (1985-2017). The trend values are in °C/decade and the histograms show the distribution of SST trend in the region.

In each year of 1985–2017, accumulated thermal stress was observed somewhere across reefs in the region.

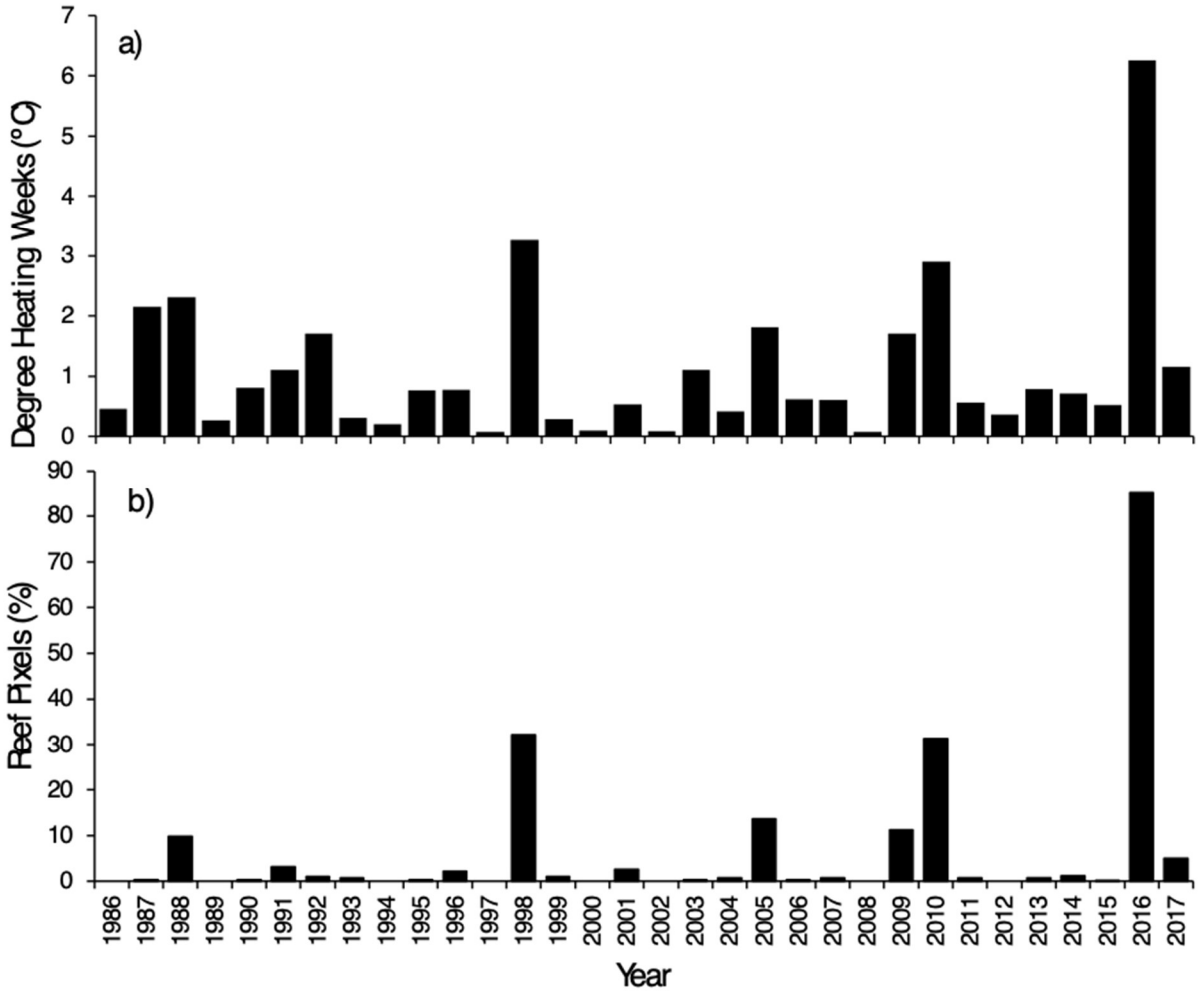


Figure 2: a)Histogram of accumulated heat stress defined as Degree Heating Weeks from 1986-2017, (b) frequency of bleaching level thermal stress defined as DHW ≥ 4 °C-weeks showing the average percentage of reef pixels affected by bleaching-level thermal stress.

11.2 Projection under RCP4.5

11.2.1 SST anomalies

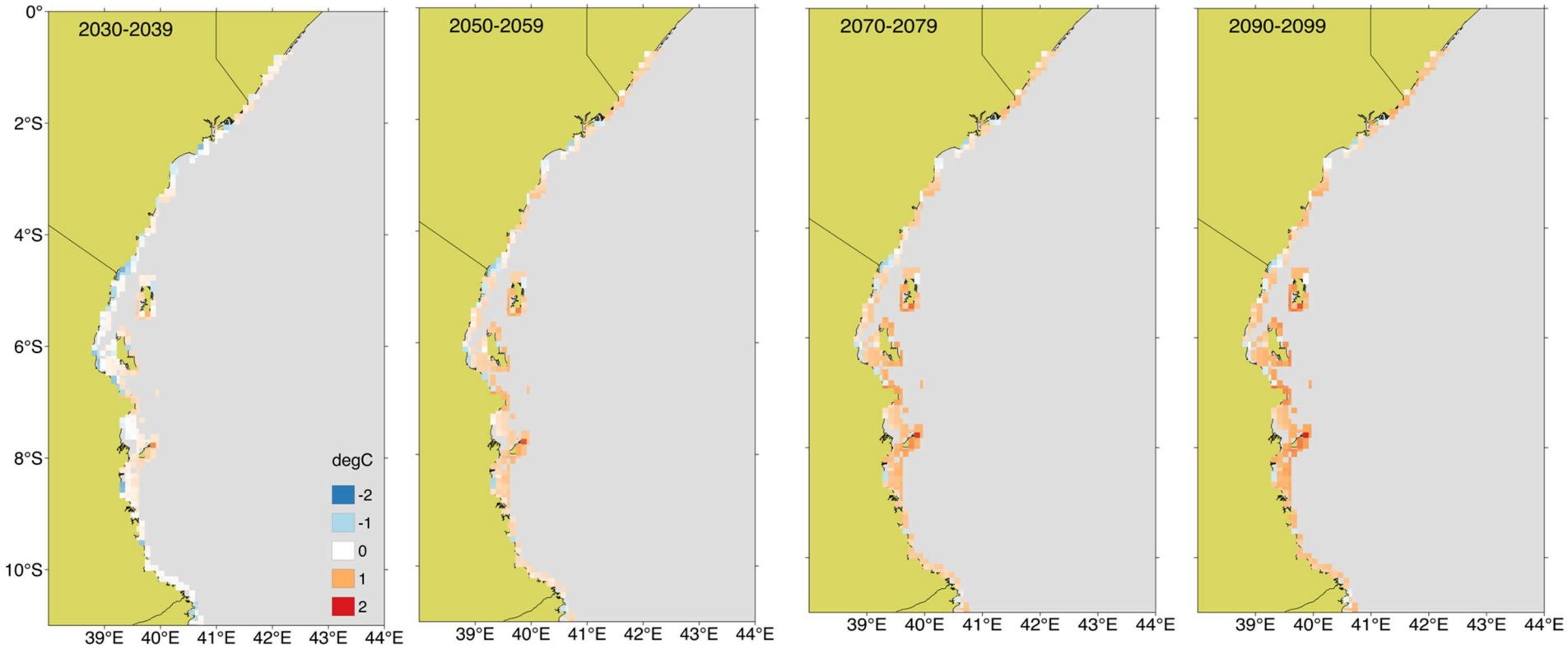


Figure 3: Projected SST anomalies for coral reefs along east African coast

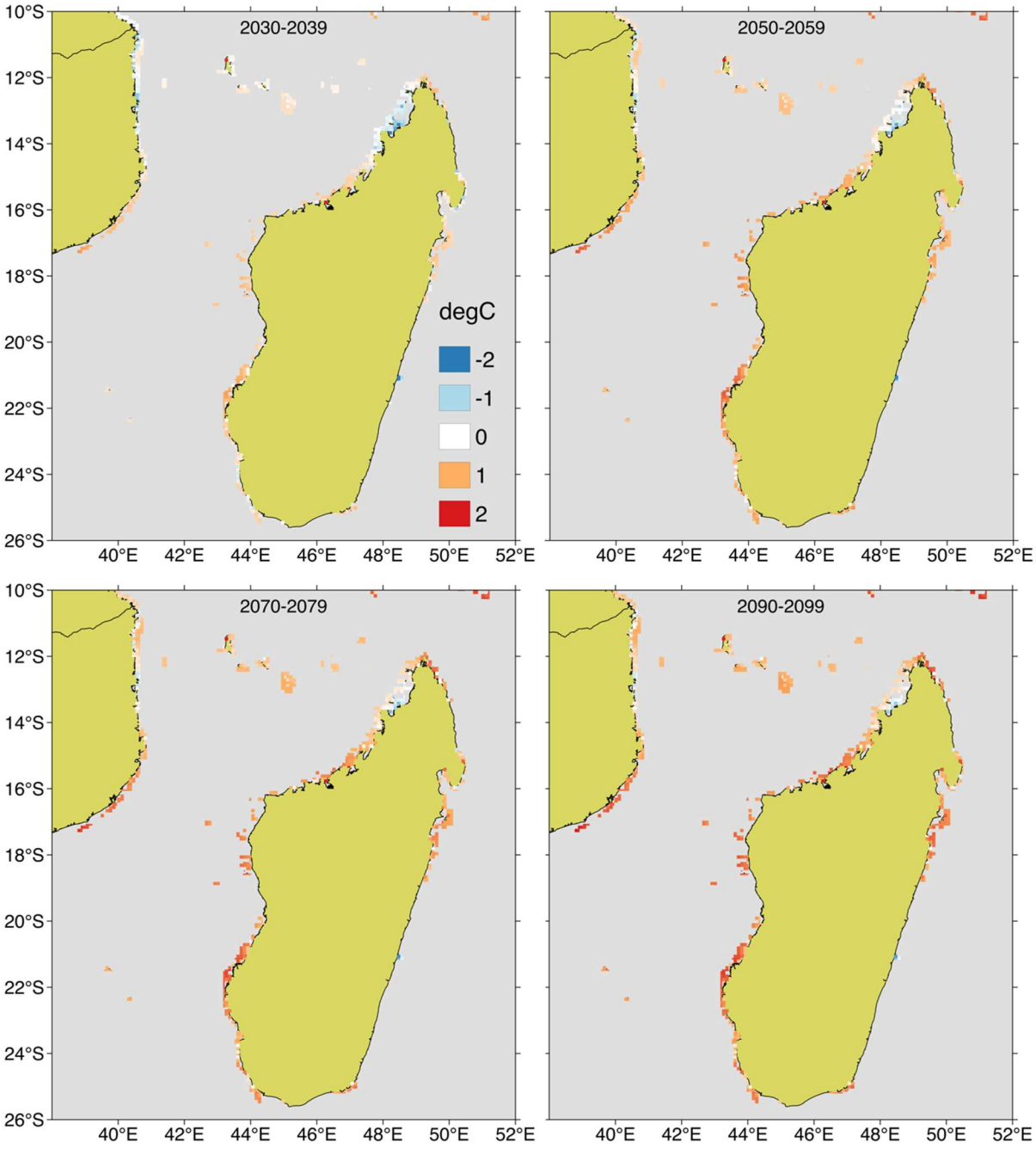


Figure 4: Projected SST anomalies in north Mozambique, Comoros islands and Madagascar

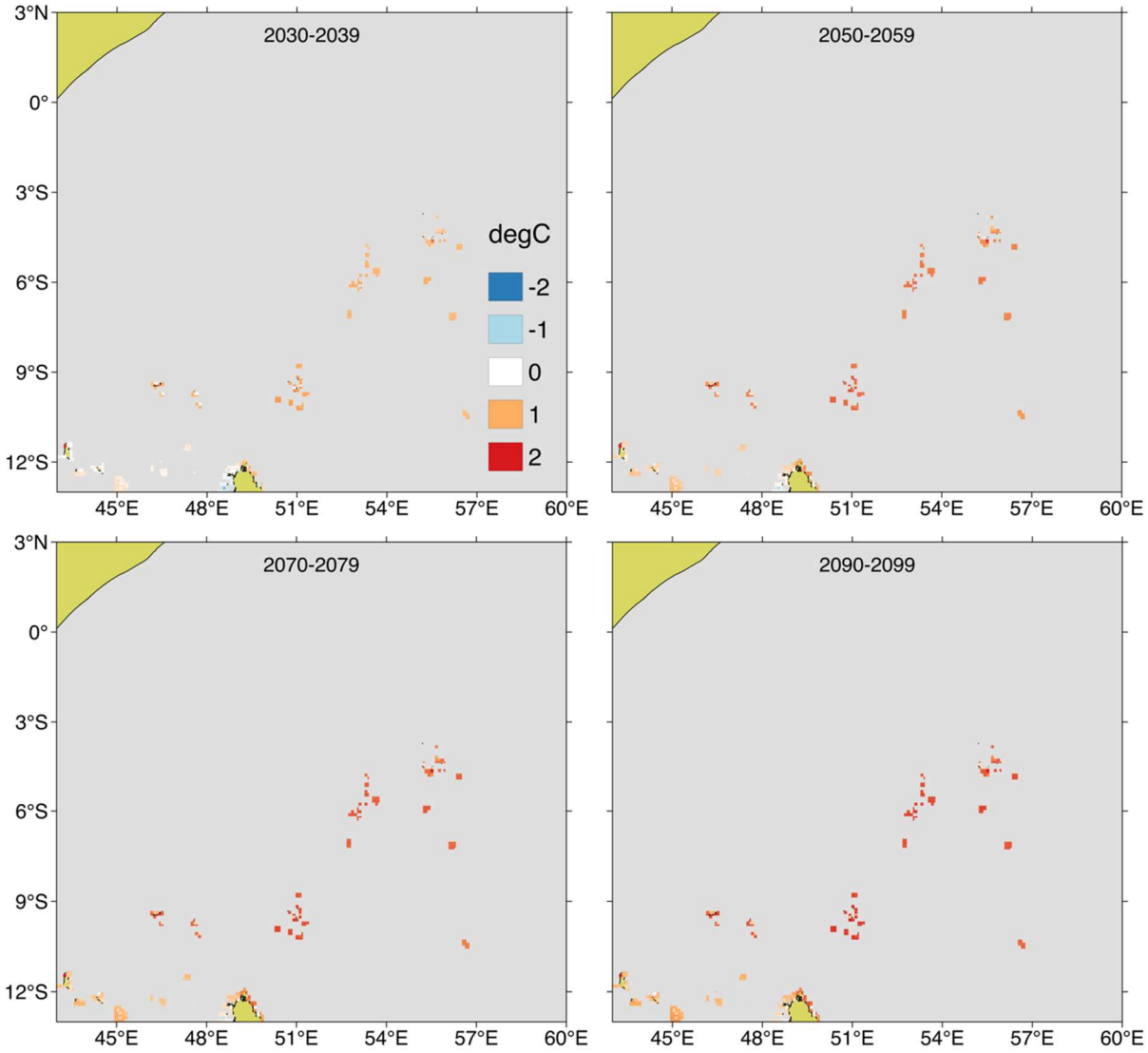


Figure 5: Projected SST anomalies in Seychelles archipelago

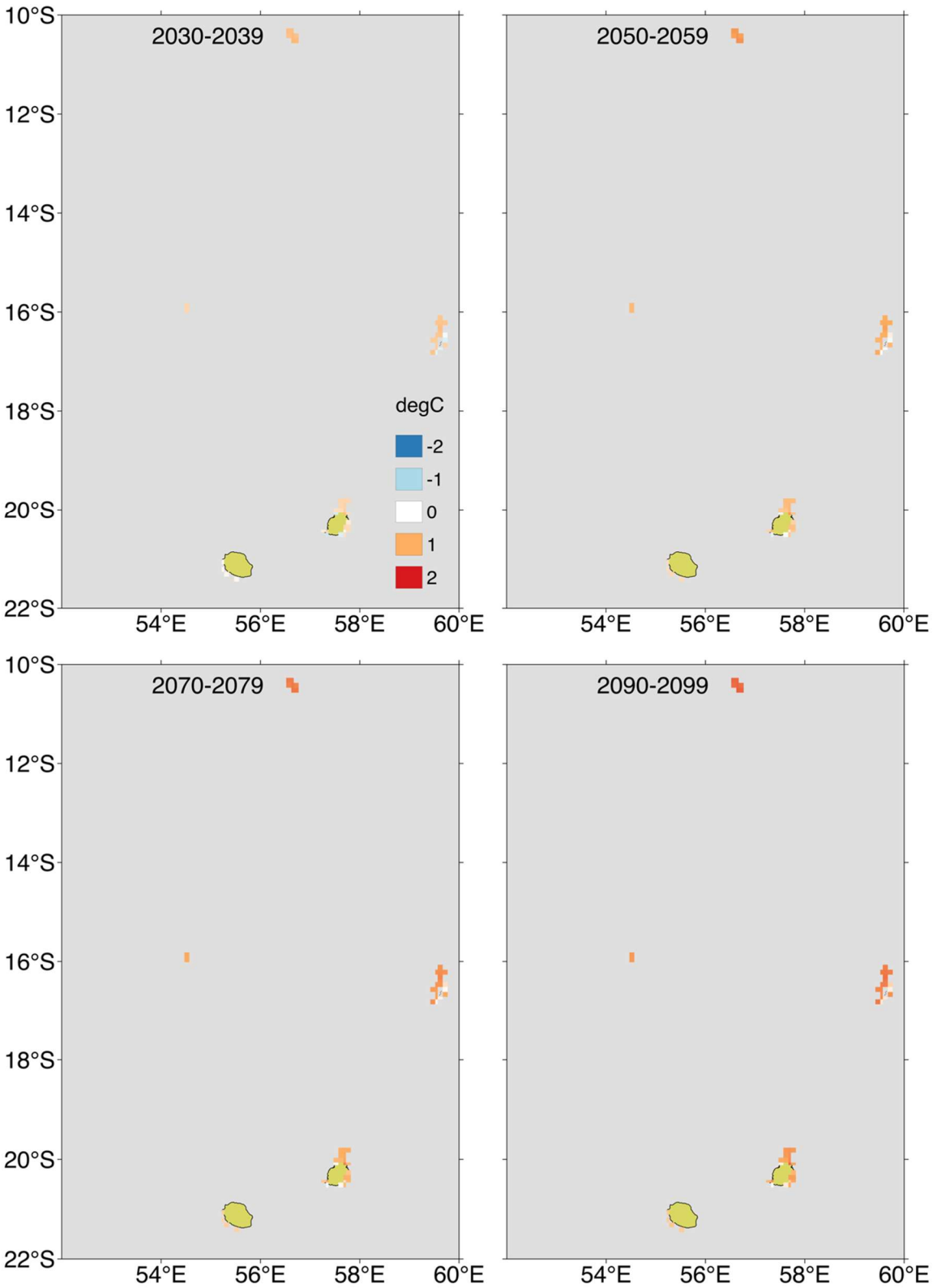


Figure 6: Projected SST anomalies in Mauritius

11.2.2 Projected timing of severe bleaching under RCP4.5 and RCP8.5

Coral reef futures vary greatly among countries in the WIO for the two RCPs. For example, coral reef along the East African coast seem to escape severe bleaching except a few reef areas south of Pemba Island (projected severe bleaching by 2080), south of Dar es Salaam (projected severe bleaching after 2040) and Mafia Island (projected severe bleaching by 2050). In contrast, under RCP8.5, severe bleaching is projected to occur in almost all reef areas between 2050 and 2080.

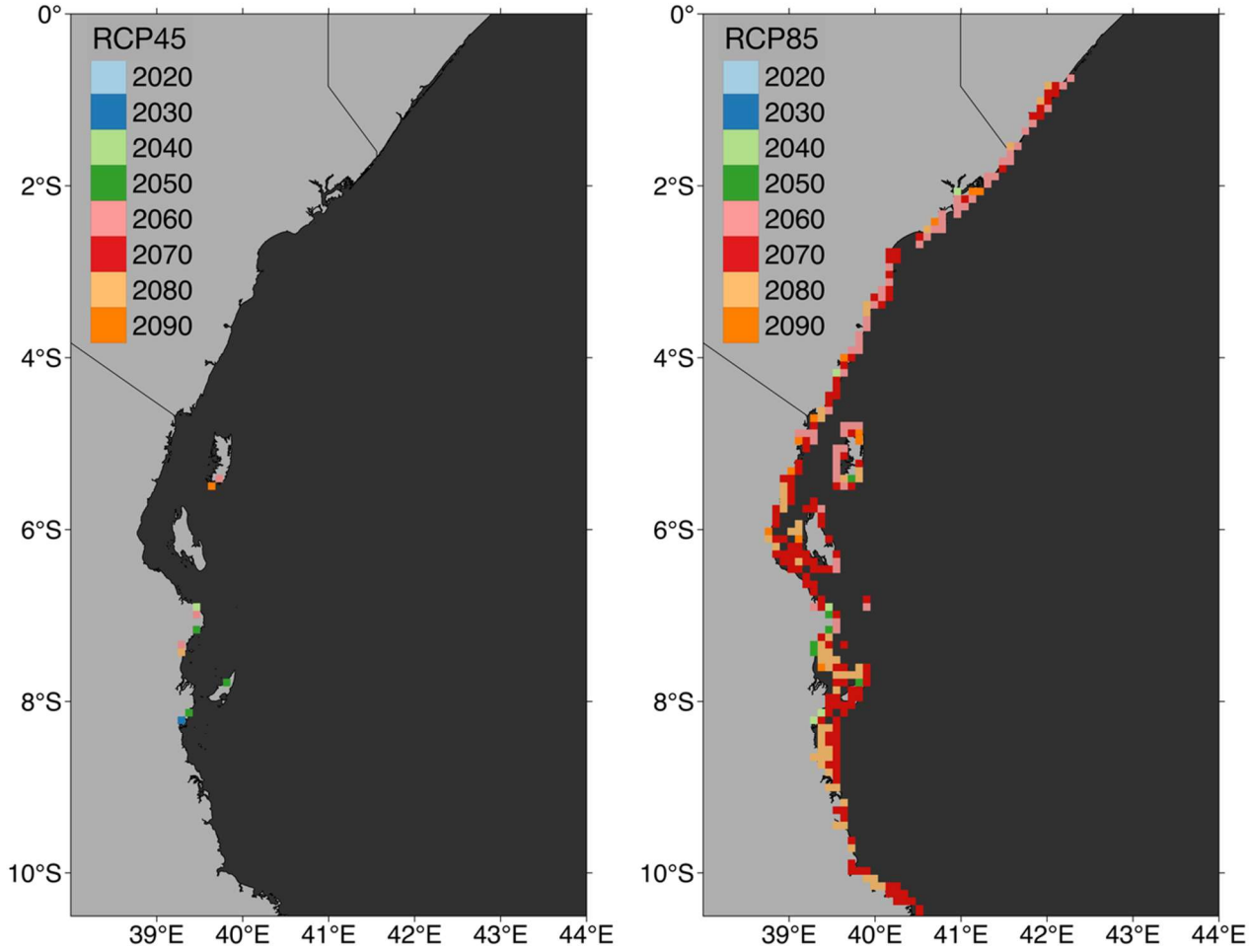


Figure 7: East Africa: Statistically downscaled projections of the timing of the onset of severe bleaching conditions defined as exceedance of DHM > 2 under RCP4.5 and RCP8.5

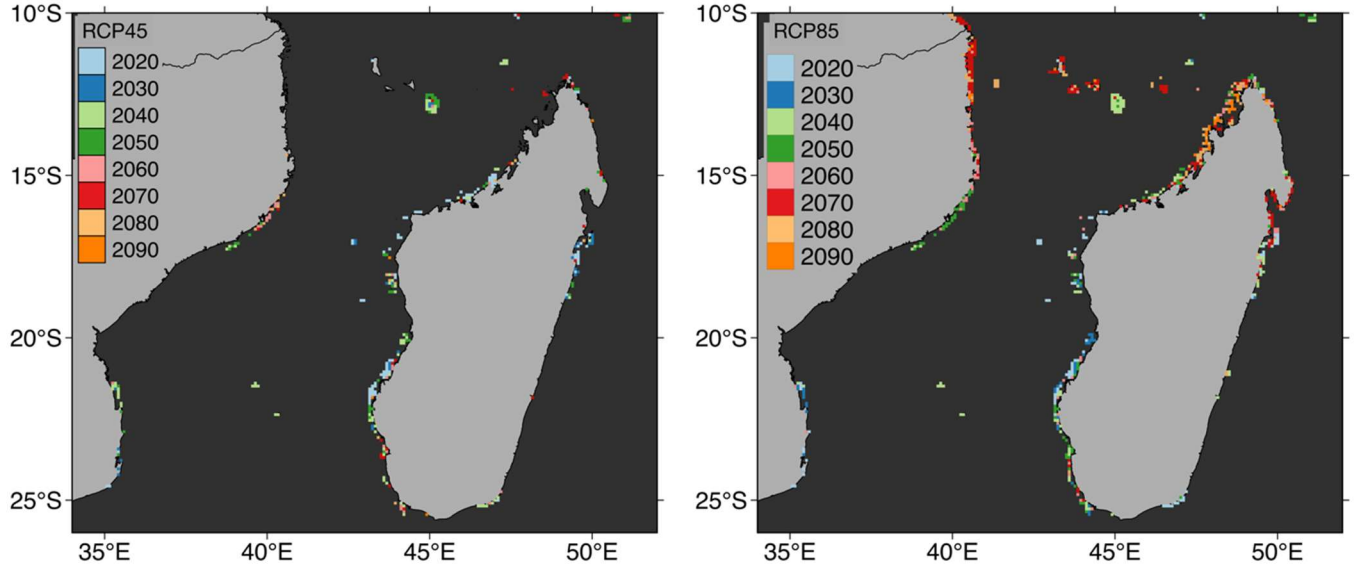


Figure 8: Mozambique, Comoros, and Madagascar: Statistically downscaled projections of the timing of the onset of severe bleaching conditions defined as exceedance of DHM > 2 under RCP4.5 and RCP8.5

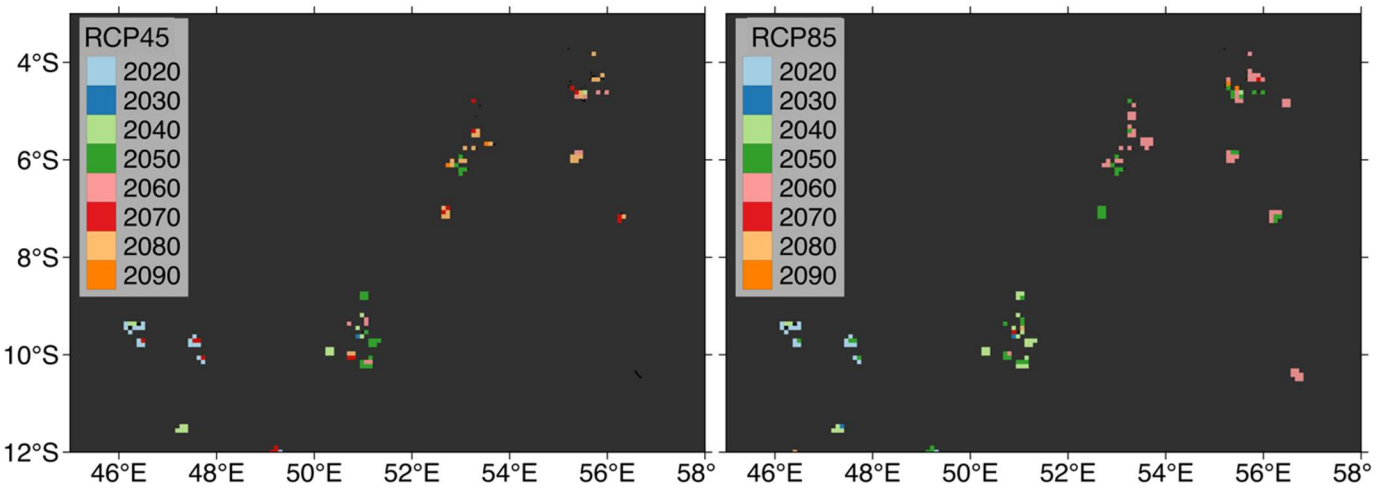


Figure 9: Seychelles: Statistically downscaled projections of the timing of the onset of severe bleaching conditions defined as exceedance of DHM > 2 under RCP4.5 and RCP8.5

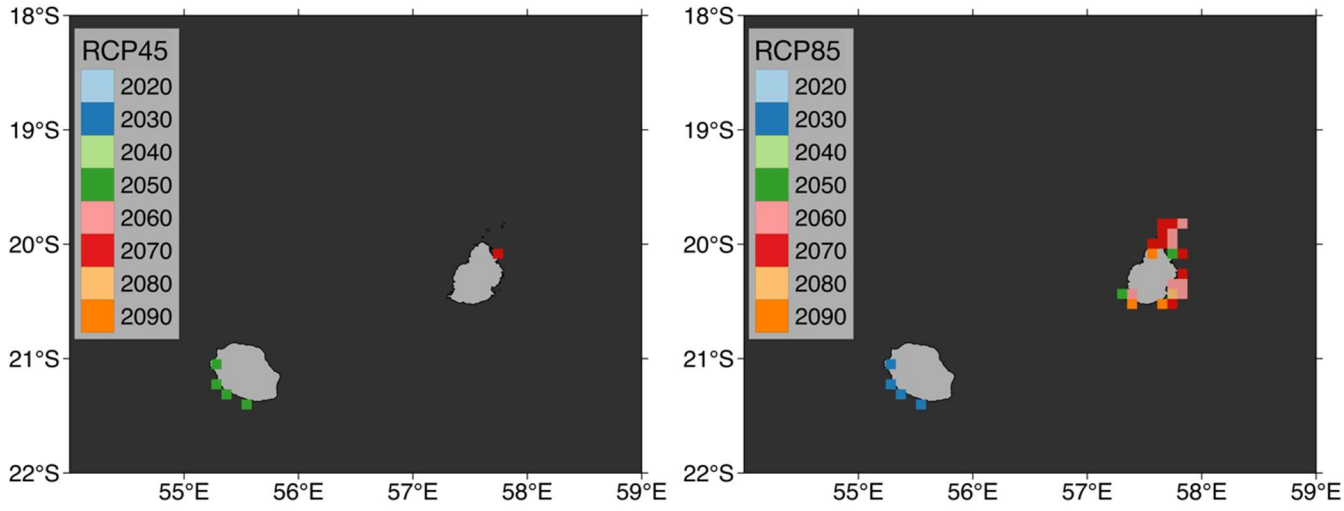


Figure 10: Mauritius: Statistically downscaled projections of the timing of the onset of severe bleaching conditions defined as exceedance of DHM > 2 under RCP4.5 and RCP8.5

11.3 Case Study 2: Conducting a Vulnerability Assessment for Mangroves

This section summarizes and communicates the methodology that could be used to assess vulnerability of mangroves in the WIO. The vulnerability assessment methodology outlined here is designed to identify which aspects of the mangrove system have already experienced climate change impacts and which aspects are most vulnerable to future impacts. Table 1 shows the approaches used to form a mangrove vulnerability assessment.

Table 1. Summary of the components of a mangrove vulnerability assessment, showing subsections of Section 3 where they are described.

Vulnerability assessment component	Approach
Initial review of existing information	Desktop computer searches and stakeholder inquiries
Land use intensity and sedimentation	Land development index
Geomorphological and sea level trends	Satellite altimetry data
Human pressure	Human pressure index
Ecological conditions	Mangrove vegetation cover

The VA components in Table xx are expanded below. Because vulnerability is a combination of exposure, sensitivity and adaptive capacity factors, the contribution of each component is so identified. For example, Tidal range, relative sea level trends, and sediment supply rates are all exposure factors, while sensitivity factors are ecological condition, seaward edge retreat, elevations within the mangroves, and sedimentation rates. Adaptive capacity factors include availability of migration areas inland from mangroves.

Steps used:

Step 1: Initial review of existing information

It is important and cost-effective to carry out an initial desktop compilation and assessment of existing data that may be relevant to the VA approaches. For example, sea level data from either tide gauge or satellite altimetry that can be analyzed to show relative sea level trends or downscaled climate models of future climate change scenarios for the region that may be available.
The desktop review of existing information acts as a scoping step and is a good way of identifying and involving stakeholders who may have supporting information or expertise.

Step 2: Estimate vulnerability of Mangroves using described methods below

- Land use intensity

To estimate exposure of mangroves to land use on would need to use the Land development index (LDI). The LDI is a land-use based index for intensity of land use (Brown and Vivas, 2005). The LDI coefficient is based on cumulative, non-renewable energy input received by each land-use type (Oliver et.al., 2011). LDI is calculated using equation 1:

$$\mathbf{LDI_{watershed}} = (\sum \%\mathbf{LU_i} \times \mathbf{LDI_i})/100 \qquad 1$$

Where LU_i is land use cover data developed by European Space Agency

- Erosion

To estimate watershed erosion, the Revised Universal Soil Loss Equation (RUSLE) is used. RUSLE calculates sheet and rill erosion from rainfall and the associated runoff for a landscape unit (Nam et al., 2003).

RUSLE is calculated using five parameters as follows:

$$\mathbf{A = K \times R \times LS \times C \times P} \qquad \mathbf{2}$$

Where A = mass of annual soil erosion (tonnes km-2); R = rainfall and runoff erosivity; K = soil erodibility (tonnes km^{-2} $hour^{-1}$); LS = slope

parameter; C = soil and crop management; P = conservation practice. Rainfall erosivity is a measure of the erosive force of rainfall. Indices used to estimate the rainfall erosivity include R-factor (Renard and Freimund 1994); the Fournier Index (FI) and the modified Fournier Index (MFI) (Vrieling et al. 2000). MFI was found to provide good spatial estimates of annual erosivity when used with the monthly satellite-based precipitation (Vrieling et al. 2000).

Soil erodibility factor (K- Factor) represents soil's susceptibility to erosion by rainstorms. It is an integrated average parameter based on several different erosion and hydrologic processes. K-factor is expressed as a function of sand, silt, clay and organic carbon concentration, which were derived using reclassification procedures using the soil database (FAO/ISRIC, 2009). K is computed as:

$$\mathbf{K} = \left[0.2 + 0.3\mathbf{exp}\left\{-0.026\mathbf{SAN}\left(1 - \frac{\mathbf{SIL}}{100}\right)\right\}\right]\left(\frac{\mathbf{SIL}}{\mathbf{CL+SIL}}\right)^{0.3}\left(1 - \frac{0.25\mathbf{C}}{\mathbf{C+exp}(3.7-2.9\mathbf{C})}\right)\left(1 - \frac{0.7\mathbf{SN1}}{\mathbf{SN1+exp}(-5.5+22.9\mathbf{SN1})}\right) \quad 4$$

LS Factor calculates the effect of slope length and steepness to erosion. Elevation data from the Shuttle Radar Topographic Mission (SRTM) 3 arc-second/90 metres Digital Elevation Model (DEM) (Jarvis et al.,2008) can be used to calculate slope steepness (S) and slope length (L) which are RUSLE parameters that adjusts erosion rates based on topography, assigning higher rates to longer or steeper slopes and lower rates to shorter or flatter ones (Nam et al. 2003).

The C Factor represents the effects of plants, soil cover and cover management practices that affect soil erosion. To calculate the C Factor, the land-use data of the region was reclassified into pertinent classes and assigned the C factor values adapted from NOAA in N-SPECT (Burke and Sugg, 2006).

To compute the land use and erosion mangrove exposure map, LDI and soil erosion maps are standardized using the increasing min-max fuzzy function. The output values are between 0-1; where 0 indicates relatively zero while 1 indicates high exposure respective to the conditions represented by respective layers. Standardized maps are then synthesized using fuzzy sum operator. Given two standardized layers A and B, the fuzzy sum operator produces a layer whose values are equal to or greater than each of the input layers A and B (An et al. 1991).

- Geomorphology and Sea level

The coastal setting and the geology control the geomorphology influenced by climate, wave and tidal regime, sedimentation and river discharge. The shore terraces correspond to eustatic movements of sea level. Retreat of the seaward edge of mangroves over time, if consistent along the coast, very likely shows vulnerability to sea level rise. Remote sensing and GIS analysis could be used to identify and quantify mangrove retreat at the seaward edge, recruitment inland (Lucas et al., 2002; Gilman et al., 2007b) or stability of mangrove distributions to demonstrate long-term resilience.

As a proxy of sea level rise, sea level anomaly (SLA) maps could be used To develop an index for mangrove exposure to sea level rise. To estimate exposure of mangroves to sea level rise, the optimal sea-level anomaly of 11.22m is calculated by taking the average sea level anomaly maps and adding 2SD (4.82 + 2*3.20). The maximum aggregated SLA layer is standardized between 0-1 using the increasing min-max function, with 1 representing maximum exposure and 0 representing no exposure.

- Inundation

Elevation and tidal data are used to determine the relative exposure of mangrove areas to flooding. To define the gradient of exposure of the elevation to flooding, the mangrove extent map and the elevation layers (from digital elevation model) are used to compute the average elevation where mangroves are found, and the standard deviation. These statistics are then utilized to calculate the threshold elevation of 21.11m by adding the average to 2SD (8.89 + 2*6.11). This value is then incorporated into the decreasing min-max function where 21.11 is used as the minimum and zero as maximum in the standardization process. The output is an inundation map showing relative exposure of mangrove areas to flooding, based on elevation.

- Land transgression

Slopes and land use types are some of the main factors affecting mangrove transgression. Hence, the slope layer and land use maps are utilized to define the suitability of land to mangrove transgression. Using slope layer and the mangrove extent layer, the

optimal slope for mangroves is calculated by adding the mean of the slope of all areas where mangroves are found to twice the standard deviation. The result, 3.31 degrees, is then used in an increasing min-max function to standardize the slope layer to values between 0 and 1. Further, the suitability of land area for landward transgression by mangroves is calculated using land use maps reclassified to 0 (land uses which would obstruct mangrove transgression) and 1 (land use types that would favour transgression). The land-use layer is first reclassified using a mask cropland map whereby all areas in the crop layer with pixels greater than 60% cultivation are used to assign cropland in the land-use layer. The modified land-use layer is then re-classed, with urban/artificial area assigned 0 (not favorable to mangrove transgression), while cropland, bare areas, forests and areas with permanently or semi-permanently submerged vegetation are classified as 1.

- Human disturbance

Human pressure index (HPI) is computed using population density and poverty indices (i.e. infant mortality rates and prevalence of child malnutrition) data. The Gridded Population of the World Version 3 (CIESEN, 2010), are gridded global population maps containing UN-adjusted population density grids (persons per sq.km.) at ~25km resolution. Data for Infant Mortality Rate and Prevalence of Child Malnutrition (children under the age of 5) at ~25km resolution are standardized using the increasing min-max function, and synthesized to generate a poverty index between 0-1. Population density data is similarly standardized, and used with the poverty index in a fuzzy sum function described above to generate a human pressure index, with values between 0-1 representing low and high human pressure respectively.

- Ecological conditions

Identification of spatial changes in mangrove vegetation cover is carried out through comparison over time of a series of aerial photographs and/or satellite images. Retreat of the seaward edge of mangroves and reduction in overall mangrove area over time are sensitivity factors. Sevral proxies are used to monitor and identify ecological conditions, for example, the Normalized Difference Vegetation Index (NDVI), such that high vegetation signals as

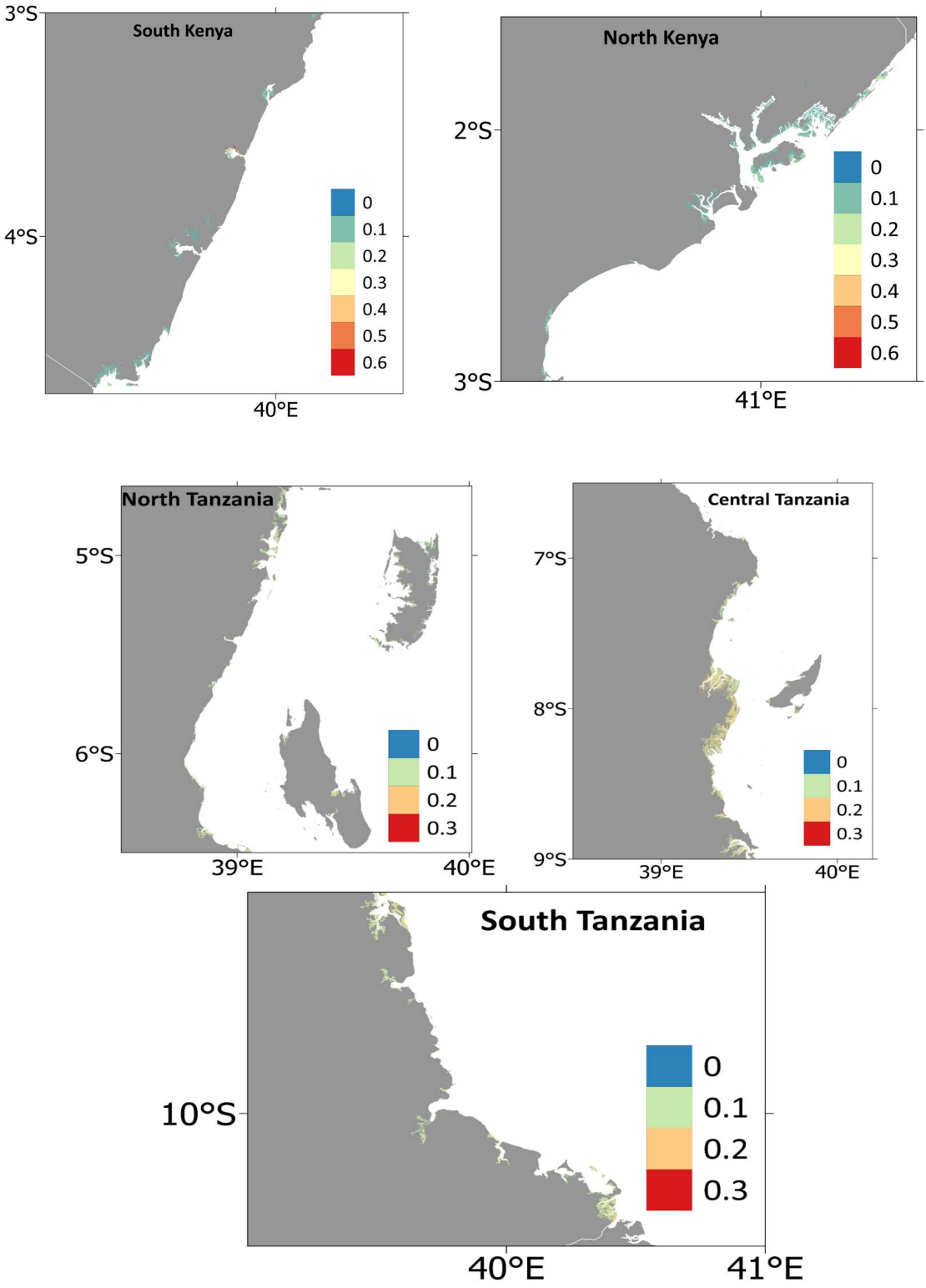
observed from satellite images indicate lack of fragmentation and good ecological condition, and vice versa. Table 7 lists satellite sources that can be used to monitor mangrove ecological conditions. NDVI values range from 0-1, with 0 indicating bare soil or no vegetation condition, and 1 indicating high vegetation. To reflect the ecological condition, the average NDVI layer is converted such that 1 represented high exposure due to ecological condition and 0 represented low exposure as a result of high NDVI values.

Table 7: Most commonly available optical satellite data sources

Data	Resolution	Period	Cost	Source	Notes
Landsat	30 m	1973–present	Open access	http://glovis.usgs.gov	Consistent sensor useful for long time series, change detection
Spot	2.5–20 m	1986–present	Open access	http://www.vito-eodata.be/	Long time series, good spectral resolution for mangrove mapping
Ikonos	<1–4 m	2001–present	US$7-30/km2	http://geofuse.geoeye.com/landing/	Highest resolution available for mapping species, zonation; can be tasked to collect images on demand
Modis	250 m	2002–present	Open access	https://lpdaac.usgs.gov/	Consistent sensor useful for long time series, change detection
AVHRR	8.3 km	1981-2015	Open access	https://ecocast.arc.nasa.gov/data/pub/gimms/	Moderate resolution for long time series data
Sentinels			Open access		
Quickbird	<1–2.6 m	2001–present	US$4-30/km2	http://browse.digitalglobe.com/	Highest resolution available for mapping species, zonation; can be tasked to collect images on demand

11.4 Results

11.4.1 Exposure to elevation



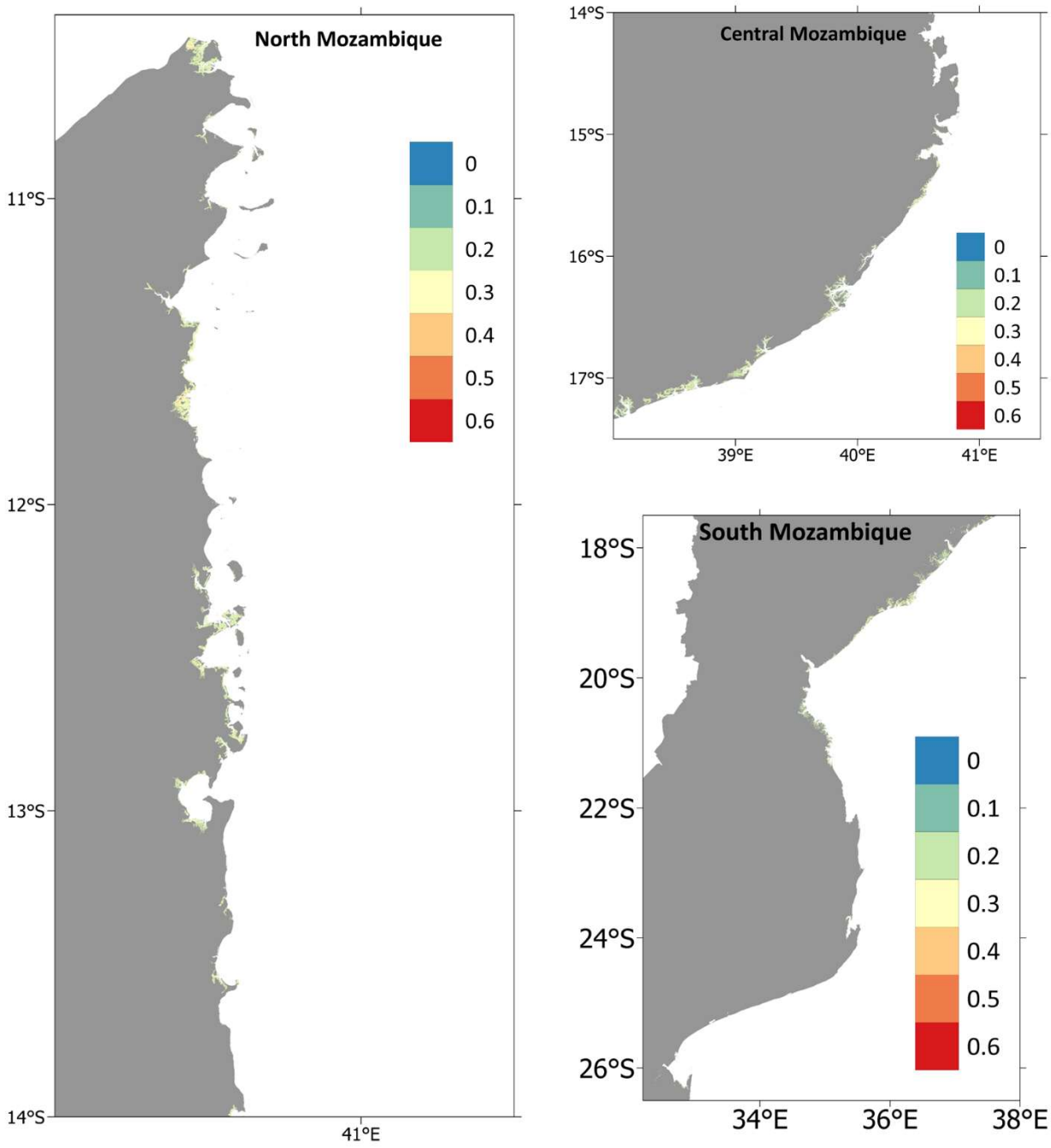
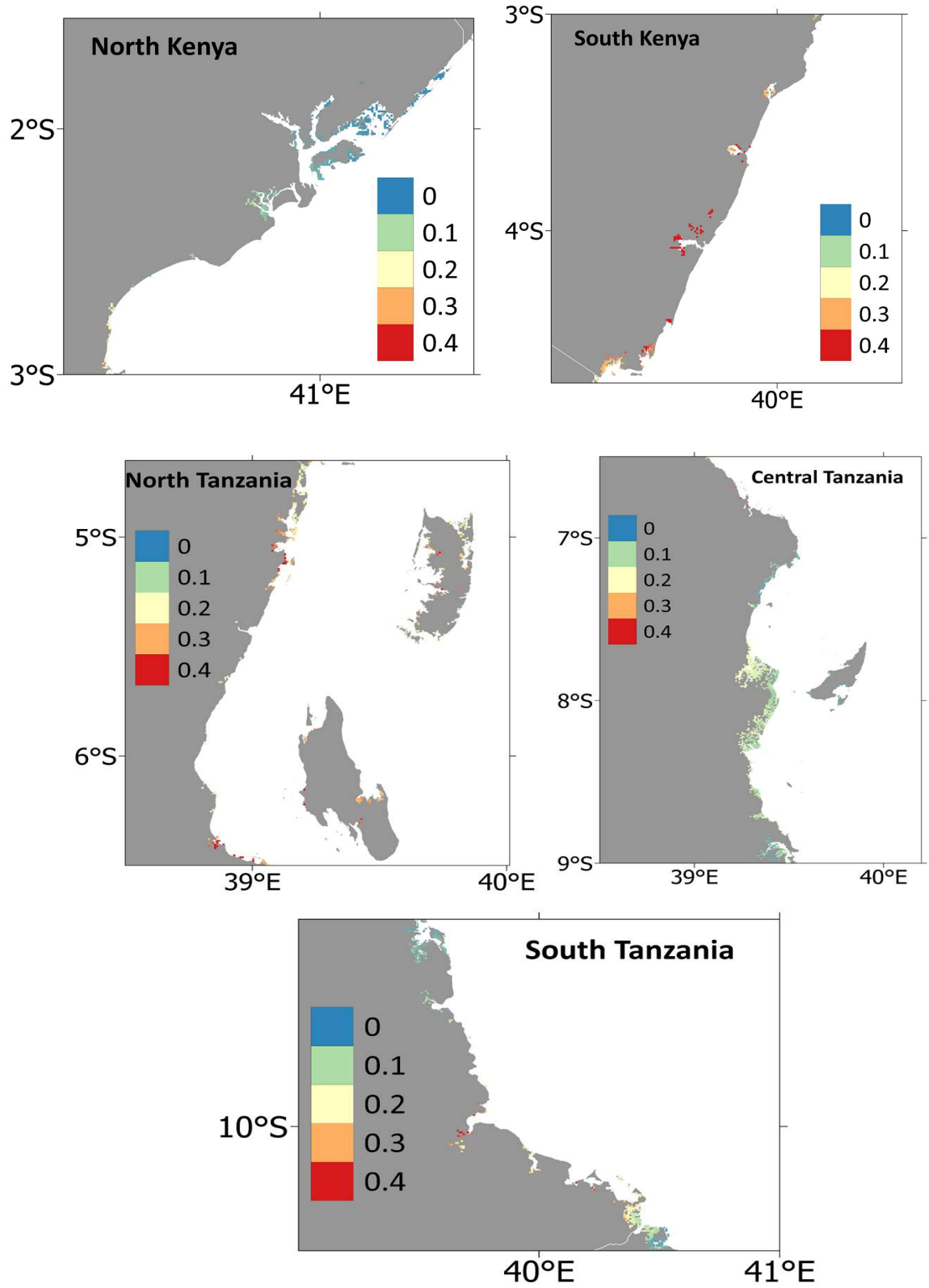
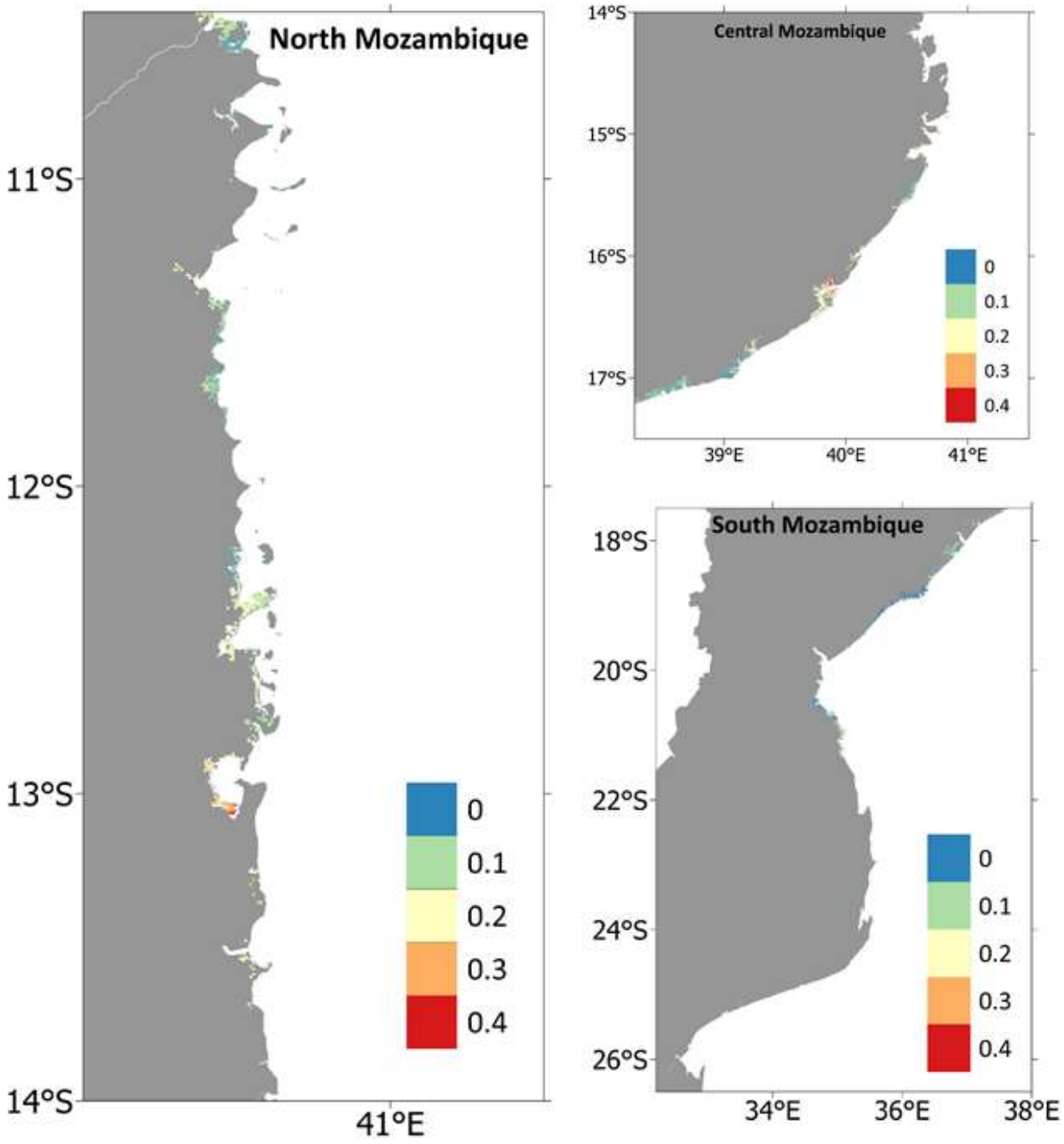


Figure 1: Exposure maps based on elevation

11.4.2 Exposure to Human pressure




North Mozambique
11°S
12°S
13°S
14°S
41°E
0
0.1
0.2
0.3
0.4
Central Mozambique
14°S
15°S
16°S
17°S
39°E
40°E
41°E
0
0.1
0.2
0.3
0.4
South Mozambique
18°S
20°S
22°S
24°S
26°S
34°E
36°E
38°E
0
0.1
0.2
0.3
0.4

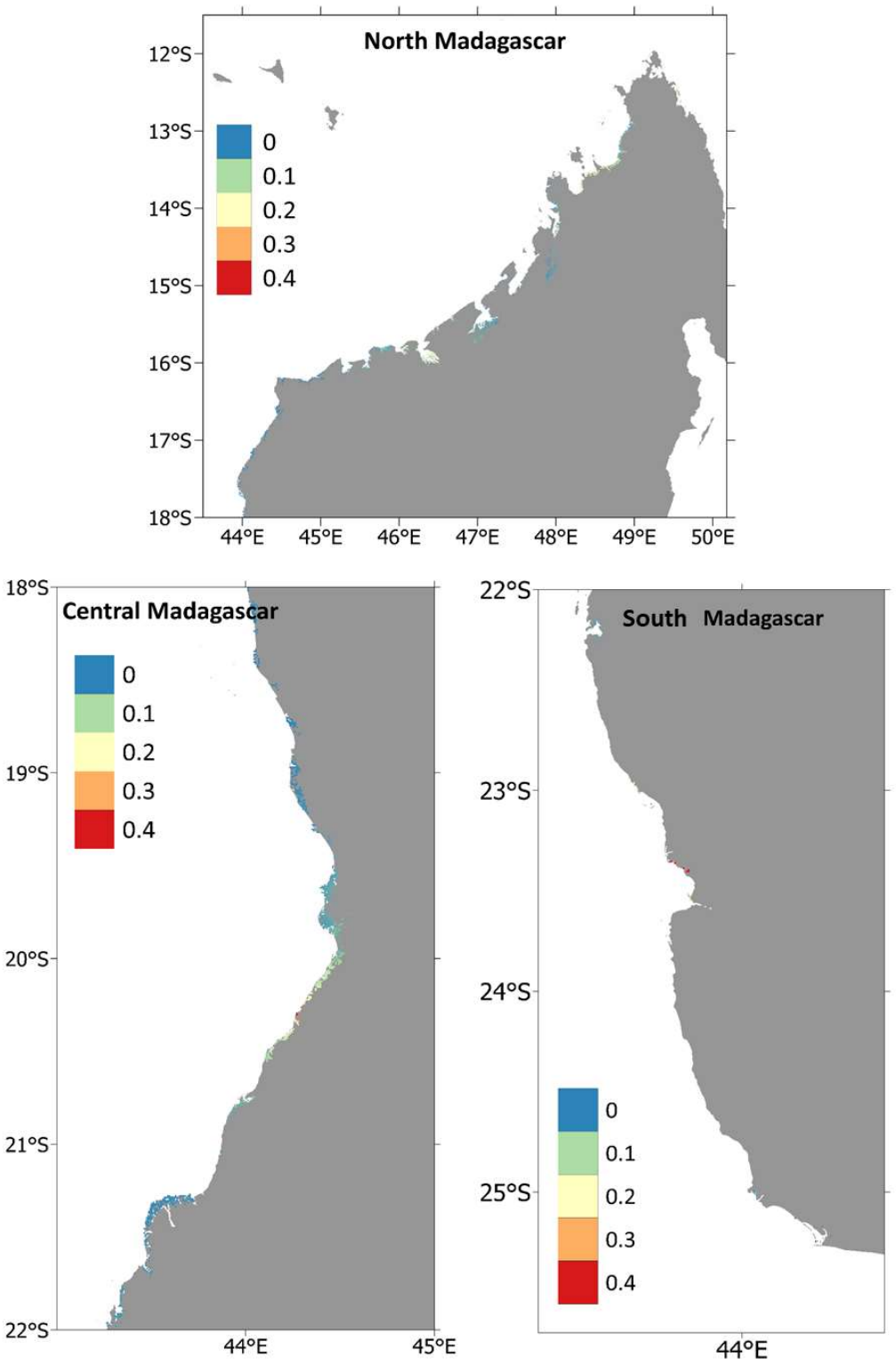


Figure 2: Exposure maps based on human pressure