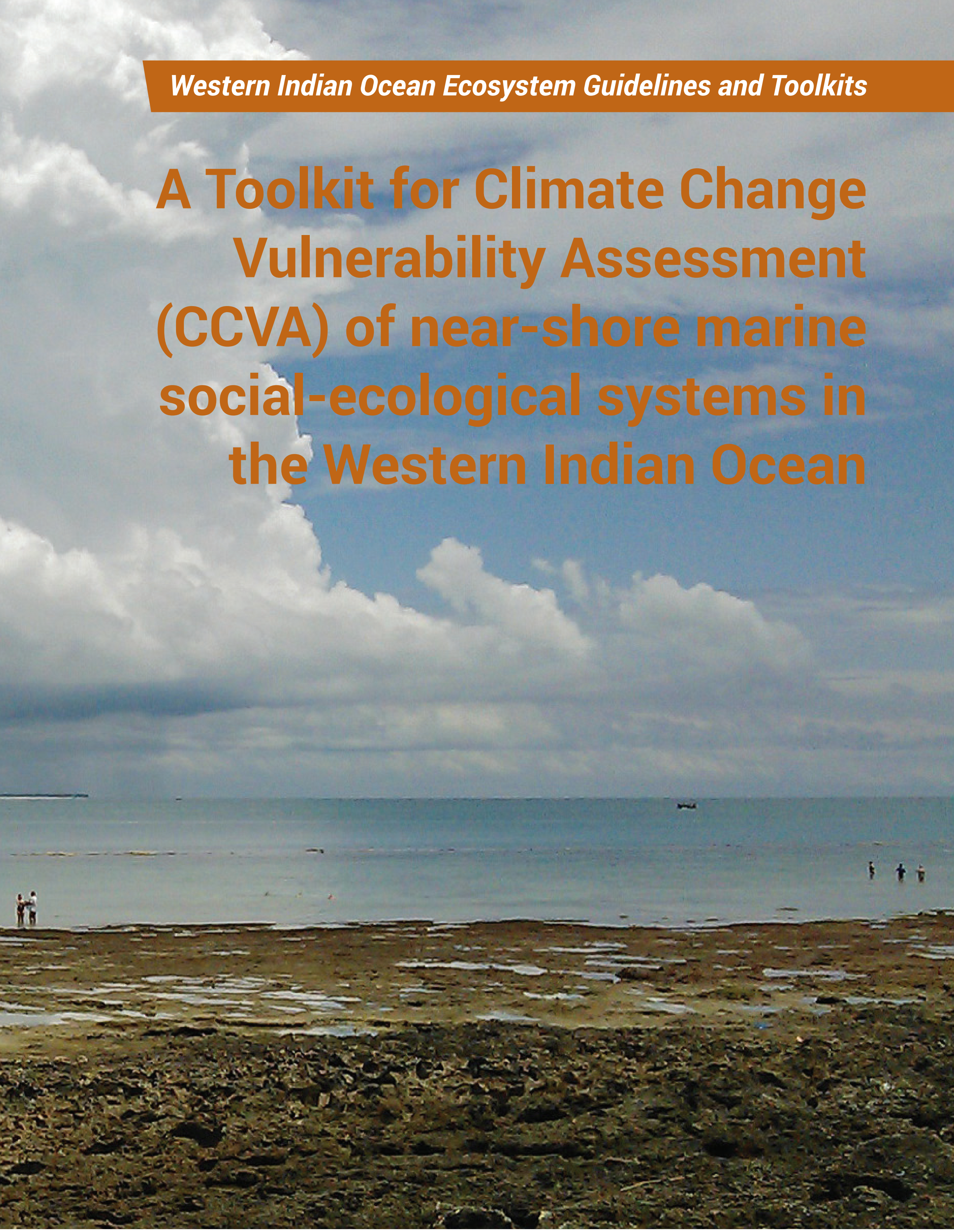

Western Indian Ocean Ecosystem Guidelines and Toolkits

A Toolkit for Climate Change Vulnerability Assessment (CCVA) of near-shore marine social-ecological systems in the Western Indian Ocean

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SYDNEY · AUSTRALIA

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A Toolkit for Climate Change Vulnerability Assessment (CCVA) of near-shore marine social-ecological systems in the Western Indian Ocean

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Preface

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Acronyms and abbreviations

AR	Assessment Report
CCVA	Climate Change Vulnerability Assessment
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
DUACS	Data Unification and Altimeter Combination System
EEZ	Exclusive Economic Zone
ENSO	El Niño–Southern Oscillation
GHG	Anthropogenic Greenhouse Gas
GIS	Geographic Information System
GLOSS	Global Sea Level Observing System
IOC	Intergovernmental Oceanographic Commission
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
MPA	Marine Protected Area
NAPA	National Adaptation Programmes of Action
RCP	Representative Concentration Pathways
SDGs	Sustainable Development Goals
SSPs	Shared Socio-Economic Pathways
SST	Sea Surface Temperature
UNFCC	United Nations Framework Convention on Climate Change
WIO	Western Indian Ocean

Glossary

Terminologies used in this document are derived from reports of the International Panel on Climate Change (IPCC).

Adaptation: Adaptation is an adjustment in natural or human systems to a new or changing environment. Adaptation to climate change refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities

Adaptive Capacity: It is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences

Climate Change: Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer)

Disaster: A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources

Exposure: The nature and degree to which a system is exposed to significant climatic variations. In this document exposure is considered as the characteristics and magnitudes of climate change, climate variability and associated hazards including the extreme events to which a system is exposed

Hazard: A dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage

Risk: Risk is the combination of the probability of an event and its negative consequences. The degree of risk is expressed in terms of monetary value in this document.

Sensitivity: Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli

Susceptibility: The state or fact of being likely or liable of a system or an element to be influenced or harmed by a particular thing or hazard (adopted from OED online)

Variability: It is the state or characteristic of a system of being variable, in this case that of the climate. In this document variability will be mostly associated with climate.

Vulnerability: It is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity

Background and context

This ***Toolkit*** for Climate Change Vulnerability Assessment (CCVA) of near-shore marine social-ecological systems in the Western Indian Ocean represents a set of guidelines and instructions for undertaking CCVA on coastal social and ecological systems, focused on mangrove, coral reef and seagrass ecosystems in the Western Indian Ocean region (WIO). The ***Toolkit*** comprises a background on climate change and climate change vulnerability, including conceptual and analytical vulnerability assessment frameworks. It provides a step-by-step procedural and methodological guide on conducting CCVA, including key datasets and detailed case studies on coral reefs and mangroves. This work is underpinned by the need to generate decision support tools to inform climate change adaptation strategies in the WIO. Therefore, this Toolkit aims to provide practical and scientifically sound guidance on climate change vulnerability assessments in coastal and marine social-ecological systems, including demonstrating the operationalization of CCVA and how outputs could be applied to prioritize climate change adaptation actions. The ***Toolkit*** is aimed at a wide range of stakeholders, including producers (those with technical capacity undertake a CCVA process) and users (policymakers and managers). They present various examples from within and outside the WIO region and contextualize the CCVA for the region to provide guidance 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 on climate change data, conceptual and analytical frameworks and regional case studies.

The *Toolkit* is structured as follows:

Section 1: Provides background to climate change vulnerability
Section 2: Describes common indicators of climate change vulnerability
Section 3: Explores linkages of climate change vulnerability framework with SDGs
Section 4: Provides a step-by-step guide for CCVA
Section 5: Reviews existing CCVA in the WIO
Section 6: Highlights challenges in undertaking CCVA
Section 7: Describes how to communicate CCVA outputs
Section 8: Conclusion

Annex

Tables A and B providing links to datasets and data sources important for CCVA
Two case studies

As part of the recommendations and in recognition that climate change vulnerability is dynamic in both space and time, the effectiveness of the ***Toolkit*** as a decision support tool can further be enhanced by embedding them in a dynamic environment. Using web and data analytics technology, the ***Toolkit*** can be formed into a dynamic web-based tool that can allow scenarios of adaptation strategies to be tested. Finally, capacity building on the application of this applying this ***Toolkit*** in the region is essential.

1. Climate Change Vulnerability

1.1 What is climate change vulnerability?

Climate change refers to significant changes in global climate, which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. Climate change is expected to drastically alter ecosystems and their capacity to benefit human society, as has been the case for centuries. The intensity and magnitude of change will vary over space and time, leading to differential impacts on ecosystems and community livelihoods. Furthermore, the nature of climate change impacts and the responses of the social-ecological systems (or simply put, humans in nature) complicates the management intervention to address the impacts of climate change. Systems, where social, economic, ecological, cultural, political, technological, and other components are strongly interlinked are known as social-ecological systems. Therefore, informing the management on strategies that can help both the social and ecological systems adapt, recover, or minimize the impacts is key to addressing climate change impacts on social-ecological and biophysical systems. One way of generating information that can inform spatially and temporally 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*., 2015). 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, single species or an entire ecosystem, a business enterprise, or an entire regional economy. In this *Toolkit*, vulnerability is described as a function of exposure, sensitivity and adaptive

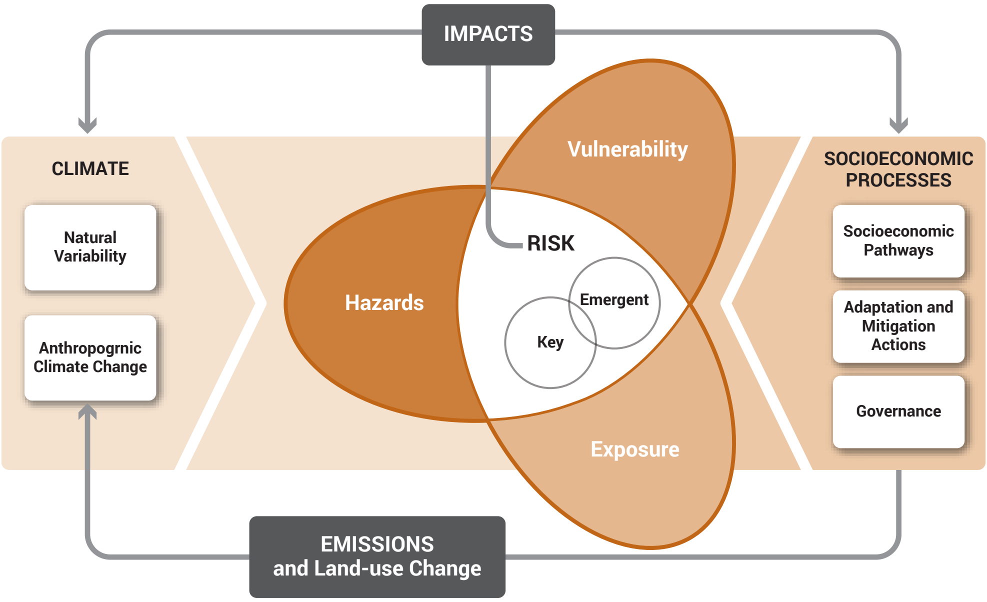

Figure 1. Schematic diagram illustrating the conceptual framework of interactions among the physical climate, exposure, vulnerability and risk. The keywords (exposure, vulnerability, risk and hazard) are defined in Box 1. Source: adapted from Oppenheimer *et al.* (2015).

capacity. In analyzing vulnerability, we emphasize the multidimensional aspect and the key elements that interact to amplify (or alleviate) the costs and risks that climate change can impose on a system. Furthermore, vulnerability index is defined as a metric describing the vulnerability of a system, generally derived by combining, with or without weighting, several indicators assumed to represent vulnerability (IPCC, 2014). CCVA's are typically conducted to identify appropriate measures that can support a system in adapting to climate change impacts and to enable practitioners and decision-makers to identify the most vulnerable areas, sectors, and social groups. In essence, they serve to identify opportunities for strengthening a system's ability to cope with external forces of change and minimize negative social or ecological outcomes (Thiault *et al*., 2021).

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 extreme and non-extreme climate impacts depends strongly on the degree of vulnerability and exposure to these events (Field *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 (Tim R McClanahan *et al*., 2019). Following this event, 30 percent of the exposed reefs in WIO bleached severely, while 10 percent experienced severe mortality (McClanahan *et al*., 2019; Obura *et al*., 2017). In addition, increasing temperature (and heatwave events) can cause detrimental changes upon seagrass growth, survival and distribution. The differential response of a system is primarily driven by the capacity inherent within the system to 'resist' the external pressure it is exposed to. Consequently, climate change impacts can be avoided if a population or ecosystem is exposed but has the inherent capacity (i.e., adaptive capacity) to avoid/resist harmful effects and recover from the impacts. In the social-ecological system context, vulnerability and exposure of ecological and social environments are interlinked.

Changes in the climate system and socio-economic processes (Figure 1) are central drivers of the three core components that constitute a risk. As illustrated in the conceptual framework (Figure 1), a *risk* is influenced by *hazard, exposure and vulnerability*. Risk can therefore be expressed as:

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

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

Using expressions 1 and 2 above, it can be deduced that a system is at high risk when:

$$Risk = \frac{Hazard x Exposure x Sensitivity}{Capacity to cope and adapt} \quad (1b)$$

1. Hazard is high – intensive and frequent in both spatial and temporal dimensions;
2. Exposure is high – Exposure to hazards during a particular period/time/season and in a particular geographic location. For instance, coral reefs, seagrasses, and mangroves around the globe were exposed to heatwaves during the strong El Niño event of 2016.
3. Sensitivity is high – An exposed unit is highly susceptible to being harmed or adversely affected. For example, the sensitivity of corals and seagrasses to temperature can determine the occurrence and degree of coral bleaching or whitening the coral skeleton, and mortality in seagrasses.
4. The 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:

1. Reducing hazard – hazard mitigation or reduction is any activity that reduces or alleviates the threat.
2. Reducing the exposure – keeping the elements/units/system away from the hazard areas and time or period of hazard

3. Reduce the sensitivity or susceptibility – minimize the weaknesses of the exposed elements, units, or systems through proper management strategies and policies

4. Strengthen the capacity to cope and adapt – enhance the strength or resistance of the exposed elements, units, or systems' strength or resistance if they cannot be removed from the hazard areas or period.

1.2 The Intergovernmental Panel on Climate Change (IPCC) vulnerability framework

The broader vulnerability literature, including IPCC reports, describe climate change vulnerability framework as being comprised of three dimensions, such 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.*, 2015). Quantifying each dimension for a system over varying spatial and temporal scales is key to estimating the system's spatially and/or temporally explicit vulnerability. This vulnerability framework 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 identify climate change threats to allow for the formulation of strategic actions that can facilitate threat reduction (Marshall, 2010) (see Box 1).

Box 1. Key definitions

Climate Change 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.

Climate Change 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.

Climate Change 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.

Climate Change 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 socio-economic distress and sediment plumes that can cause stress to coral reefs.

Climate Change 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.

Climate variability is deviation of climatic statistics over a given period of time (e.g. a month, season or year) when compared to long-term statistics for the same calendar period.

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 ecological adaptive capacity would consider how well the mangroves can resist and recover from perturbations.

1.2.1 Climate forecasts and greenhouse gas emission scenarios

Projections of future climate change play a crucial role in improving understanding of the climate system and characterizing societal risks and response options. Different sets of long-term emissions scenarios have been developed to coordinate climate change research and provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, and put forward adaptation and mitigation options. In the IPCC fifth Assessment Report (AR5), four climate change forcing scenarios, termed Representative Concentration Pathways (RCPs) were used to simulate future climate change. Projections used in the AR5 assessment were based on the radiation-based scenarios of Representative Concentration Pathways (RCP), and range from low/no climate mitigation (RCP 8.5) to high mitigation (RCP 2.6) (Moss *et al.*, 2010; van Vuuren *et al.*, 2011). Next, the Shared Socio-Economic Pathways (SSPs) were developed following the selection of concentration–emission scenarios, allowing mitigation and impact researchers to combine low- and high-emission futures with assumptions about population, gross domestic product (GDP), and other indicators (van Vuuren *et al.*, 2014). Climate models are now incorporating SSPs as important inputs to the IPCC's sixth assessment report (AR6) published in 2020-21. Researchers are also using them to examine how societal choices will affect greenhouse gas emissions, and, thus, how climate goals of the Paris Agreement might be met (Table 1). Understanding the assumptions underlying each emission scenario is necessary for comparing and matching future climate predictions across different generations of IPCC climate change scenarios (i.e., AR5, AR6) to allow the use of data from the diverse set of models and scenario. To inform the assessments, CCVA must explicitly state and describe the scenarios of mitigation potential (RCPs) and the storylines of mitigation challenges (SSPs) that are used to inform the assessments.

1.2.2 Adaptation to Climate Change

Adaptation refers to ecological, social, or economic systems changes in response to actual or expected climatic stimuli and their effects or impacts. Adaptation solutions take many shapes and forms, depending on the unique context of the ecosystem, community dependent on the ecosystem services, or region. There is no 'one–size–fits–all' solution–adaptation can include building flood defenses, setting up early warning systems, switching to drought-resistant crops, and government policies.

1.3 Social-ecological vulnerability

An increasingly critical aspect of sustaining ecosystems (e.g., coral reefs, seagrasses and mangroves) and the livelihoods of dependent

Table 1. Comparison and matching of two generations of IPCC climate change experiments, commonly referred to as SRES and RCP scenarios described in greater detail by Moss *et al.*, (2010) and van Vuuren *et al.*, (2011).

CLIMATE CHANGE EXPERIMENTS		**DESCRIPTION**
RCP	**SRES**	**Particular difference**
	SSP1-1.9	Holds warming to approximately 1.5C above 1850-1900 in 2100 "after slight overshoot" and implied net-zero CO2 emissions around the middle of the century.
RCP 2.6	SSP1-2.6	Stays below 2C warming with implied net-zero emissions in the second half of the century.
RCP 4.5	SSP2-4.5	Approximately in line with the upper end of combined pledges under the Paris Agreement. The scenario "deviates mildly from a 'no-additional climate-policy' reference scenario, resulting in a best-estimate warming around 2.7C by the end of the 21st century".
RCP 6.0	SSP4-6.0	A medium-to-high reference scenario resulting from no additional climate policy, with "particularly high non-CO2 emissions, including high aerosols emissions".
RCP 8.5	SSP5-8.5	A high reference scenario with no additional climate policy. Emissions as high as SSP5-8.5 are only achieved within the fossil-fuelled SSP5 socioeconomic development pathway.

people is the understanding of the vulnerability of the social-ecological system (Folke, 2006). A social-ecological system consists of ‘a biogeophysical unit and its associated social actors and institutions. Social-ecological systems are complex and adaptive an,d delimited by spatial or functional boundaries surrounding particular ecosystems. Approximately 60 million people live within 100 km of the coast across the WIO (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 well-being of coastal communities, are under threat from climate change. CCVA of coastal social-ecological systems as a management tool can inform management decisions on mitigating climate change impacts (Beroya-Eitner, 2016) and developing climate change adaptation strategies for coastal communities.

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

1. What threats or pressures are faced by the ecological and/or social system?
2. Are threats different across the different systems being considered, or are they similar?
3. What is the degree of exposure, how sensitive are the systems to perturbations, and what is the capacity for the system to adapt?
4. 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 socio-economic 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; Marshall, 2010, Thiault *et al.* 2021) idealizes two linked subsets of vulnerability: one subset represents the components of ecological vulnerability to the exposure to climate change, while the other represents a social vulnerability to changes in the ecological system (Cinner *et al.*, 2013). The ecological exposure, sensitivity, and capacity for adaptation are synthesized to represent the degree to which climate change will impact the continued supply of ecosystem goods and services (i.e., the ecological vulnerability). Therefore, in this framework, ecological vulnerability represents the exposure of the socio-economic domain to climate threats. The overall social-ecological vulnerability is derived from the sensitivity of socio-economic 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 social-ecological vulnerability from assessments based on the modified framework can be found in work done in the WIO (Cinner *et al.*, 2013) on coral reef fisheries social-ecological vulnerability assessment for resource-dependent communities in Kenya. They found that communities living near fished sites were marginally more vulnerable than those practicing community-based closures and those adjacent to 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 highly vulnerable to climate change due to high ecological exposure, low social adaptive capacity, and low social sensitivity. Based on these findings, adaptation strategies such as providing alternative livelihoods could be tailored for the vulnerable communities in Takaungu.

More recently, Aswani *et al.* (2018) developed an integrated vulnerability framework, which synthesizes ecological exposure, sensitivity and adaptive capacity (i.e., ecological vulnerability) with social livelihoods and food security approaches (Figure 2). In this framework, vulnerability comprised two high-level components representing biological and human subsystems. In this approach, environmental exposure is combined with biological/ecological sensitivity to estimate ecological vulnerability within the ecological subsystem (Pecl *et al.*, 2014). The ecological vulnerability is then integrated with the socio-economic subsystem to influence social-ecological vulnerability (Figure 2).

1.4 General approaches to conducting CCVA and concepts

Approaches to vulnerability assessments are based on two main interpretations of vulnerability, which have been conceptualized as *outcome vulnerability (or top-down)* and *contextual vulnerability* (or bottom-up) (Dessai and Hulme, 2004; Kelly and Adger, 2000; O'Brien *et al.*, 2007; van Aalst *et al.*, 2008). These are linked respectively to a *scientific focus/relevance* and a *human-security focus/relevance.* Each of these prioritizes producing 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 approach adopted in CCVA are dependent on management goals or the goals of the assessment and the data available.

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 in the future as it assumes a direct cause-effect relationship between

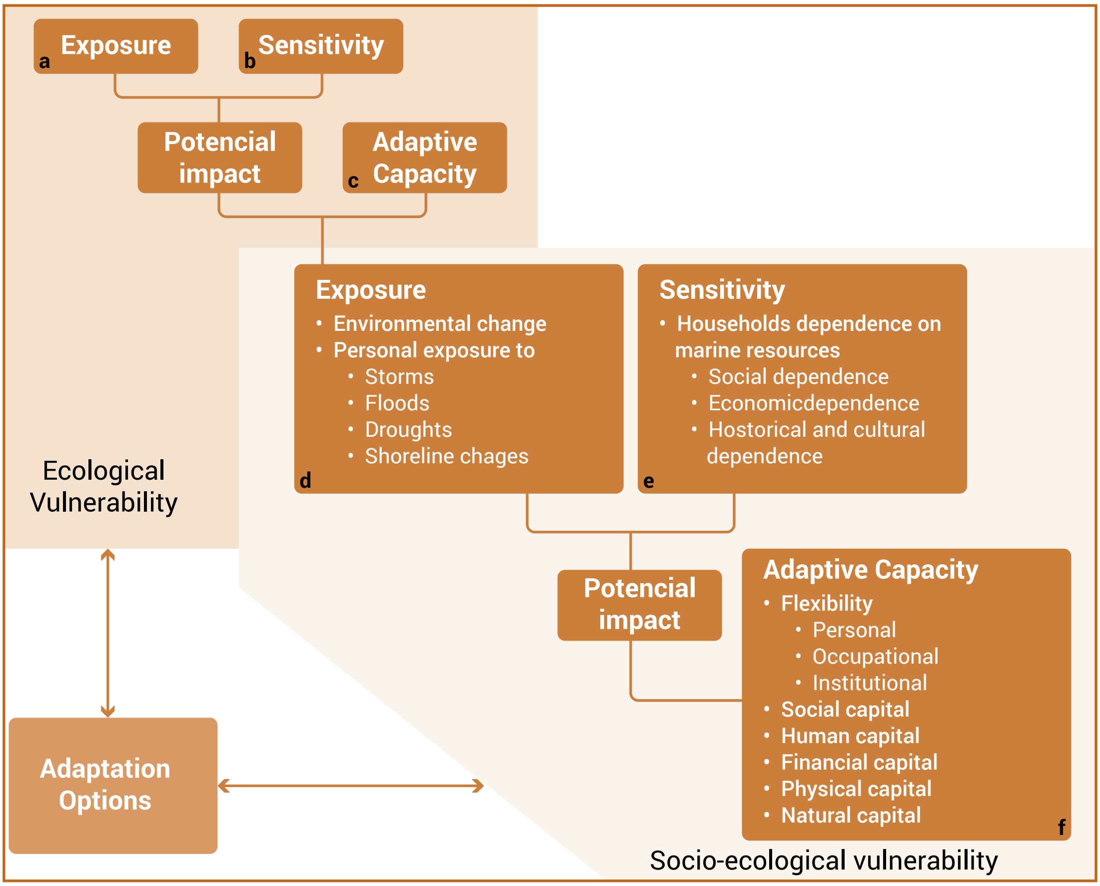

Figure 2. A conceptual CCVA framework for climate-sensitive social-ecological systems, which builds on the IPCC vulnerability framework. a – c describes ecological vulnerability dimension while d – f describes social vulnerability dimension with examples of indicators for each of the dimensions listed. Source: adapted from Aswani *et al.* (2018).

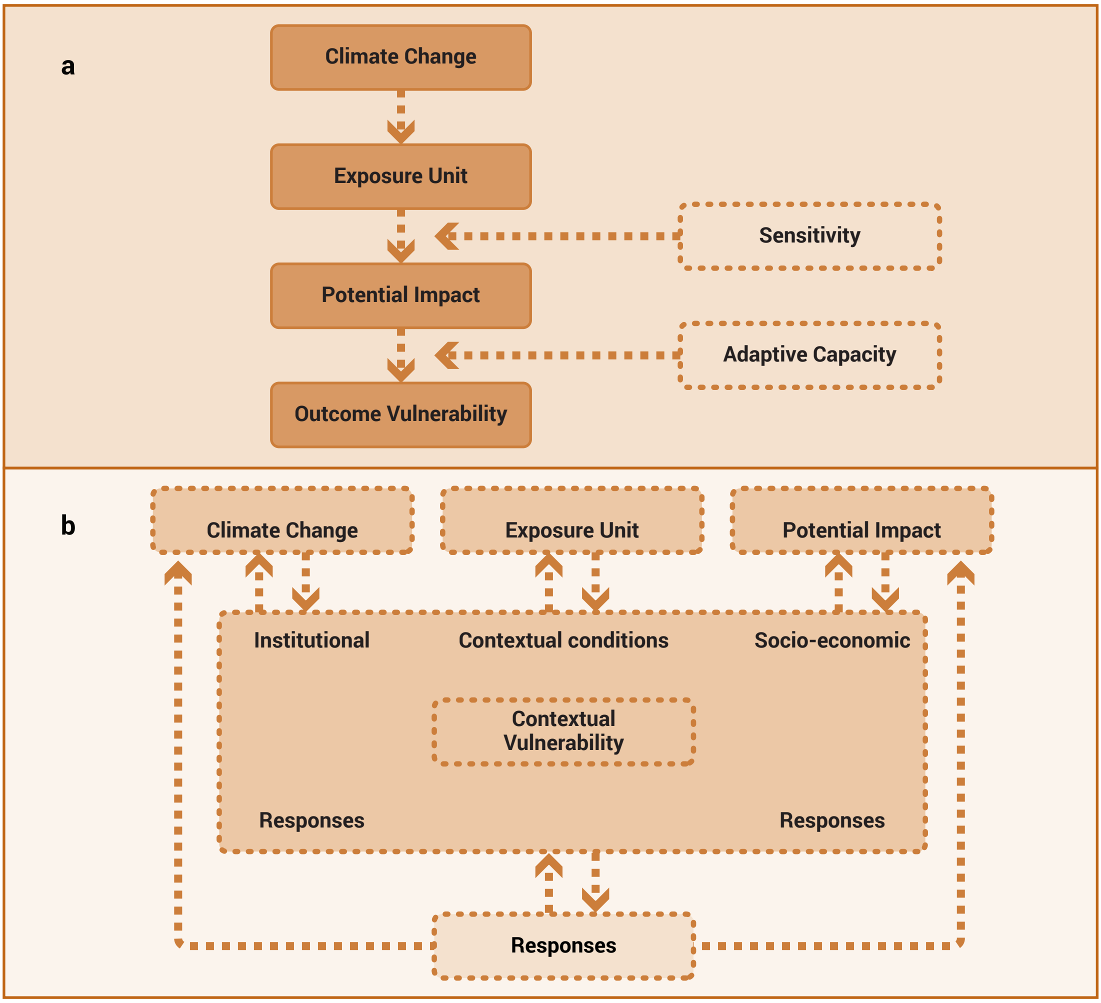

Figure 3. An illustration of the two climate change vulnerability interpretations, which can lead to different approaches to the assessments: (a) outcome vulnerability and (b) contextual vulnerability. Source: adapted from Füssel (2010); O'Brien *et al.* (2007).

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).

The contextual vulnerability approach (Figure 3b) considers 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 the 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).

Outcome and *contextual* vulnerabilities differ in their vulnerability descriptions (Table 2). Therefore, choosing one approach or concept over the other has implications on the resources required to execute a CCVA. Outcome or top-down approaches are usually applicable at global, national and regional levels. In contrast, the contextual or bottom-up 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, 2011; Mastrandrea *et al.*, 2010).

The CCVA approach presented in this guideline incorporates top-down and bottom-up elements and therefore represents a hybrid approach. For example, the construction of the exposure dimension utilizes global-scale data and indicators while estimating the adaptive social capacity applies village level demographic information.

Table 2. Diagnostic tool for identifying different vulnerability approaches. Source: based on Füssel and Klein, (2006); O'Brien *et al.* (2007).

APPROACH	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.

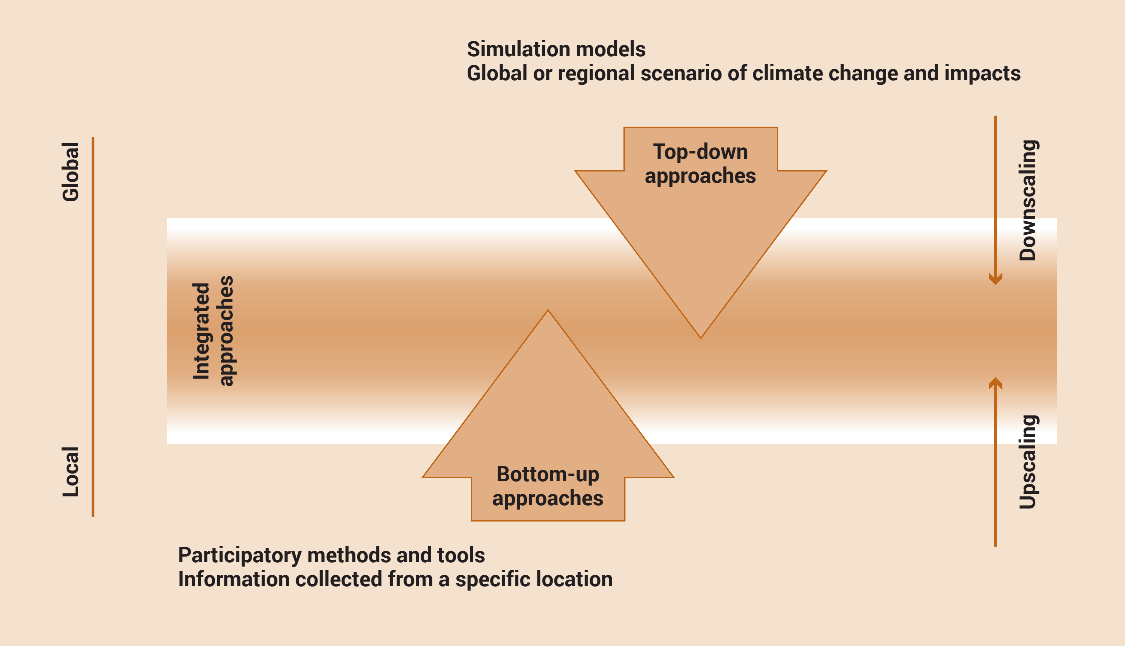

Figure 4. Schematic representation of how simultaneous upscaling and downscaling of the respective assessment types can lead to a realm in which integrated approaches can be developed. Source: adapted from Dessai and Hulme (2004).

2. Indicators of vulnerability

An indicator is a measurable variable used to represent an associated measurable or non-measurable of). For example, in social-ecological vulnerability assessments, the *multiplicity of livelihoods*, or the availability of livelihood options to communities, is considered an indicator for the social adaptive capacity of the local communities (Cinner *et al.*, 2013; Maina *et al.*, 2016). Vulnerability indicators can also be linked to specific actions 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 (i.e., sensitivity, adaptive capacity and exposure) (Hinkel, 2011). Indicators must be chosen with an understanding of how they affect or contribute to a social adaptive capacity. An overall measure of social adaptive capacity is derived after synthesizing indicators of social adaptive capacity. While common indicators of vulnerability dimensions are described herein, these are not exhaustive. In fact, if a variable is determined to be a good proxy or indicator of a dimension, it can be used with adequate justification. For example, considering heatwaves to measure extreme events might be deemed a better exposure indicator than simply maximum temperature. In the next subsection, details are presented of the indicators of the exposure dimension of vulnerability. Indicators for the other two dimensions are described in Section 4 Methods.

2.1 Indicators of climate exposure

In a vulnerability context, climate change indicators are primarily used to estimate a system's exposure to climate change. Climate change exposure indicators are a set of geophysical parameters that represent aspects of climate change and provide information on the most relevant domains of climate change impacting a system. Details are provided below for some of the indicators commonly applied in estimating exposure.

2.1.1 Mean air temperature

Temperature is a key metric for assessing the state of the climate. The last three decades were the warmest since the 1950s (IPCC, 2014). The warming is unequivocal and unprecedented (Pachauri *et al.*, 2014). Air temperature estimates are based on independently maintained global temperature (refer to Table A in Annex for freely available data sources).

The earth's average air temperature has increased by about 0.6 °C since 1980 compared to 1961 to 1990 (at 0.25 °C/decade). Nineteen of the hottest years have occurred since 2000, with the exception of 1998, which was helped by a very strong El Niño. The year 2020 tied with 2016 for the hottest year on record since record-keeping began in 1880 (source: NASA/GISS).

Relative to 1985 to 2005, in 2100, global mean surface temperatures are projected to increase by 0.3 °C to 1.7 °C under emission scenario RCP 2.6, 1.1 °C to 2.6 °C under emission scenario RCP4.5, 1.4 °C to 3.1 °C under emission scenario RCP6.0 and 2.6 °C to 4.8 °C under emission scenario RCP8.5 (IPCC, 2014). In the wider region, the temperature increase is likely to influence mangrove species composition, phenology, productivity, and ultimately the latitudinal range. For example, where temperatures exceed that of peak photosynthesis, productivity decreases. Furthermore, high temperatures increase evaporation rates, resulting in salinity increases; the synergistic impacts of salinity and aridity can influence species diversity, size, and productivity of mangrove forests. Temperature also affects sedimentation on reefs, mangroves and seagrasses through evapotranspiration, an important factor in the hydrological cycle. Examples of data sources for distribution of mangroves and other ecosystem, ecological, species and related parameters are provided in Table B in the Annex.

2.1.2 Sea Surface Temperature

The tropical Indian Ocean experiences strong, seasonally reversing winds. Strong southwesterly and northeasterly winds blow from and to the tropical western Indian Ocean during the austral winter (June to September) and summer (December to March).

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 led 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 Ocean and cooling in the eastern Indian Ocean (Hastenrath and Greischar, 1991; Mutai *et al.*, 1998; Gamoyo *et al.*, 2015).

The Indian Ocean has been warming over the past three decades (Figure 5). This has elicited interest among the research community due to 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 Ocean (Williams and Funk, 2011), eliciting more questions than answers on how this might impact social-ecological systems and global climate in general.

The increasing frequency of elevated warm water events has triggered widespread mass coral bleaching and mortality events across the region over the past three decades (Baker *et al.*, 2008; McClanahan *et al.*, 2007a; McClanahan *et al.*, 2007b; Obura, 2005). Differences in the susceptibility of reef-building corals to stress from rising sea temperatures have also resulted in changes to the composition of coral (McClana-

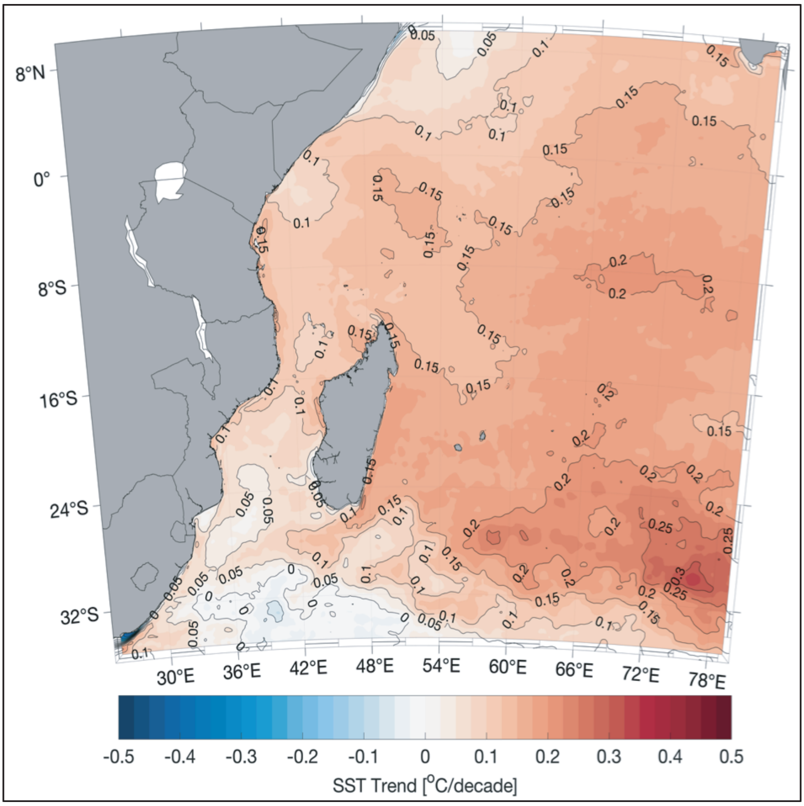

Figure 5. SST rate of rising (°C/decade) calculated from high-resolution coral reef watch SST data from 1982 to 2017. See Annex Table A for data sources.

han *et al.*, 2007) and associated benthic fish communities (Graham and Nash, 2013; Pratchett *et al.*, 2014).

Ocean warming can also lead to changes in the Asian monsoon circulation and rainfall and altering marine food webs (Roxy *et al.*, 2015). It is estimated that up to 20 percent of 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 climate models with anthropogenic greenhouse gas (GHG) forcing (i.e., CO_2 emissions) over the past century (Hoegh-Guldberg, 2014). Table 3 lists the observed trend in ocean warming from 1982 to 2017 for 15 exclusive economic zones (EEZ). These changes are based on linear regression statistics of annual mean SST.

2.1.3 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) experience 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 (Gamoyo *et al.*, 2015; Kijazi and Reason, 2012; Ogallo, 1988), but variations in Indian Ocean SST (phases of the Indian Ocean Dipole - IOD) are recognized as the dominant driver of eastern African short rain (Mutai *et al.*, 1998; Nicholson and Kim, 1997).

The long rains over the region are weakly correlated to global sea surface temperatures (SST) (Camberlin *et al.*, 2009). On the other hand, southern African countries receive most of their annual precipitation during the austral summer (December–February) and are strongly influenced by sea surface temperature (SST) anomalies across the global oceans (Hermes and Reason, 2009; Rouault and Richard, 2003) as well as by the El Niño–Southern Oscillation (ENSO) (Vigaud *et al.*, 2009). Although it is generally observed that El Niño events correspond to conditions of below-average rainfall over much of southern Africa (Giannini *et al.*, 2008), the ENSO teleconnection is not linear. Still, it behaves in a rather complex fashion in which several regimes of local rainfall response can be identified (Fauchereau *et al.*, 2009).

Overall, rainfall in the WIO has decreased over the decades by around -1.5 mm per decade between 1960-2017 (Figure 6), which implies that the climate is getting drier. Changing rainfall patterns are likely to influence mangrove forests' distribution, extent, and growth rates (Gilman *et al.*, 2008), particularly in mangroves at the edge of their tolerance limits. For example, a decrease in rainfall and an increase in evaporation may lead to an increase in soil salinity, resulting in a decrease in seedling survival, productivity and growth rate (Duke *et al.*, 1998).

Table 3. Lists the trend in Sea Surface Temperature trend from 1981 to 2017 summarized across for all the EEZs in the WIO.

EEZ	SST RATE OF RISE (°C/DECADE)	LINGUISTIC DESCRIPTOR
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

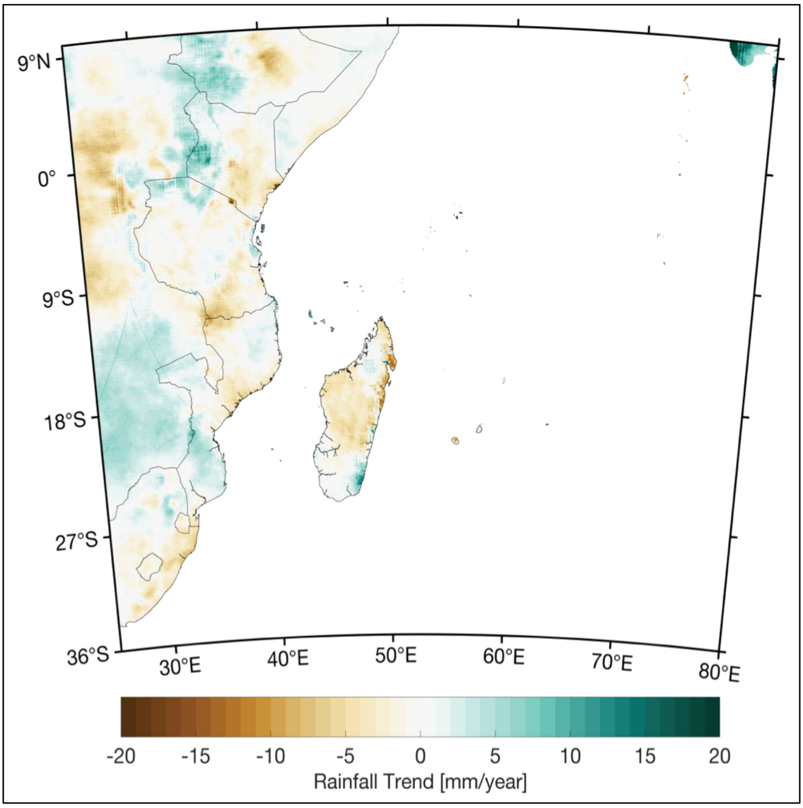

Figure 6. Spatial trends in annual rainfall from 1981-2017. Source: based on CHIRPS dataset (Climate Hazards Group InfraRed Precipitation with Station data), (Funk *et al*., 2015). See Annex Table A for data sources.

Furthermore, coral reefs and seagrasses may be impacted by salinity changes and sediment and nutrient regimes that are partially driven by precipitation.

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 and Schimel, 2007). During this time, the pH of surface ocean waters has fallen by 0.1 pH units from approximately 8.21 to 8.10 and is expected to decrease a further 0.3–0.4 pH units in coming decades (Orr *et al*., 2005). Like the Richter scale, the pH scale is logarithmic, so this change represents an approximate 30 percent increase in acidity. This process is known as ocean acidification.

Changes in pH are linked to shifts in ocean carbonate chemistry that can affect the ability of marine organisms such as molluscs 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 WIO region lacks long-term observation data on ocean acidification.

2.1.5 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*., 2011). The instrumental record of sea-

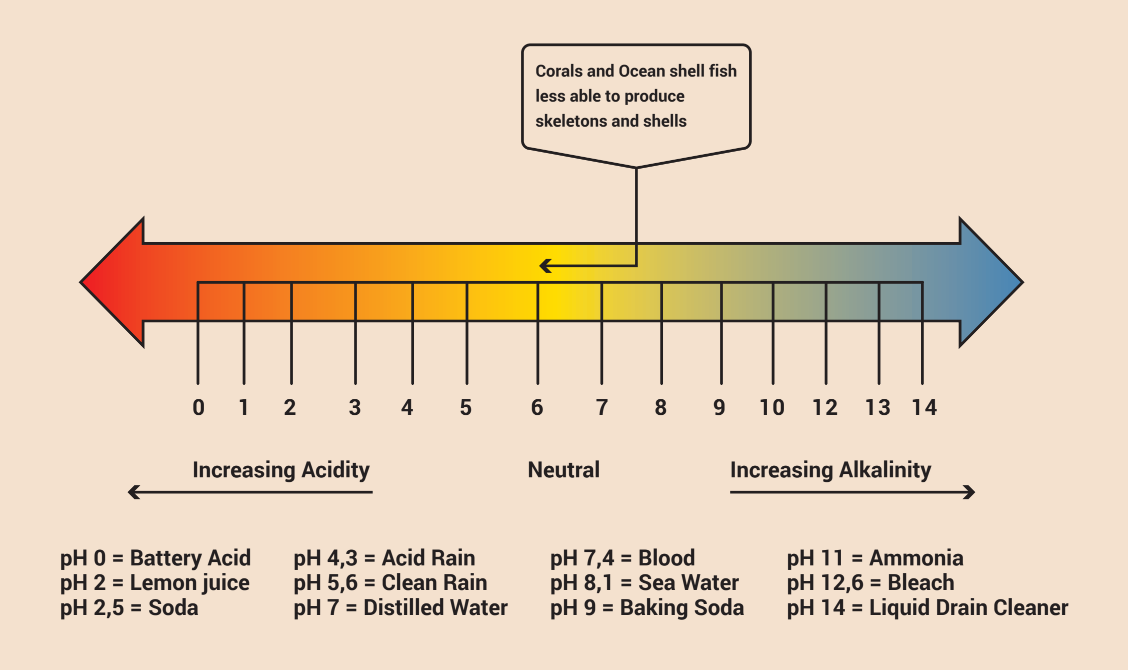

Figure 7. Acidity and alkalinity were measured using a pH scale where 7.0 is neutral; pH < 7 is acidic; while > 7 is alkaline (Kleypas *et al.*, 2008). Adapted from https://www.epa.gov/climate-indicators/oceans

level change mainly comprises tide gauge measurements[1] and, since the 1990s, satellite-based altimetry measurements[2].

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. GLOSS was developed to establish a well-designed, high-quality *in situ* sea level observing network to support broad research and an operational user base. Globally, about 300 tide gauge stations provide an optimal sampling of the global ocean (Figure 8). Tide gauge data can be obtained from http://www.psmsl.org/data/obtaining/

Using data from satellite altimetry missions, mean sea level trends can be estimated (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 trend patterns observed by satellite altimetry are transient features. These data are freely available for download and can be applied for vulnerability assessments. For example, see Annex Case Study 1 for extended data and Table A.

Sea level rise is a potential climate change threat to the long-term sustainability of valuable ecosystems such as corals, reefs and mangroves (Nicholls and Cazenave, 2010). Mangroves, for example, are sensitive to changes in inundation duration and frequency. Low sea level can lead to mangrove die-back associated with increased soil salinization (Lovelock *et al.*, 2017). An 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.*, 2011). The rise, however, is not globally uniform as the

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[1] The Global Sea Level Observing System

[2] AVISO (https://www.aviso.altimetry.fr)

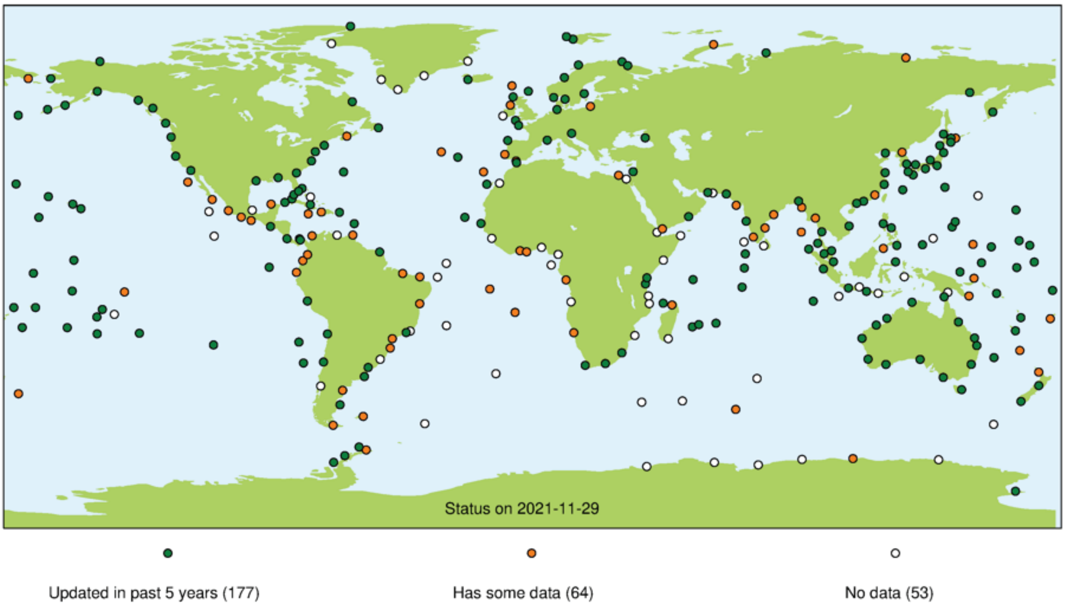

Figure 8. Map of the Global Sea Level Observing System (GLOSS) showing active stations and those with no data stream. Source: https://www.psmsl.org/products/gloss/status.php.

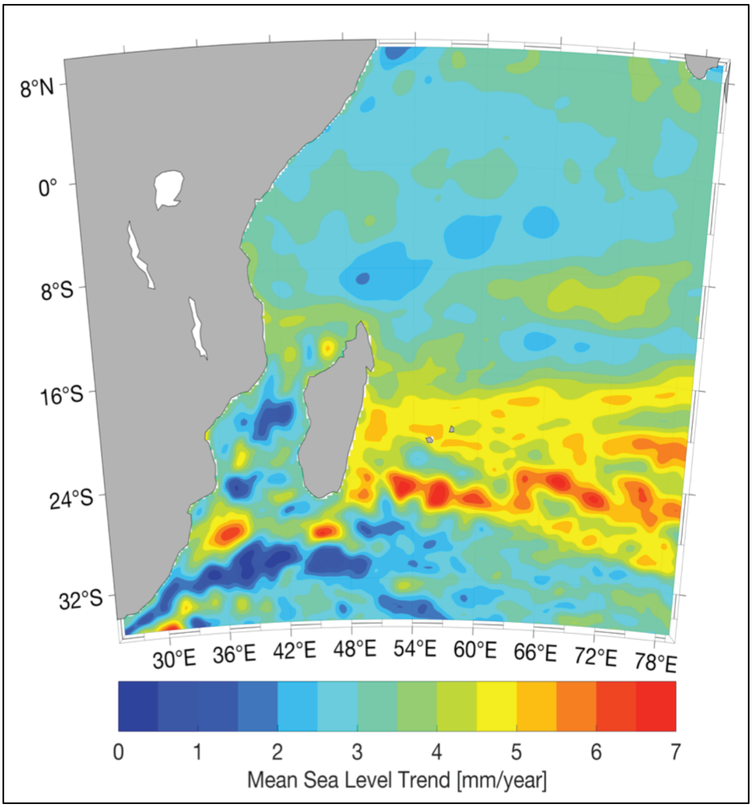

Figure 9. Map of regional patterns of observed sea level trend (in mm/year). This map was created using gridded, multi-mission Data Unification and Altimeter Combination System (DUACS) data since 1993. Source: data from http://www.aviso.oceanobs.com/duacs/.

sea-level rise in some regions accompanies a fall in others. The 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, 2008).

Multi-model average predictions of sea-level rise for 2050 relative to a baseline period of 1986–2000, based on low emission (RCP2.6) and high emission (RCP8.5) experiments suggest a likely increase in sea level in the WIO region by 2050 (Figure 10). Under the low emission experiment, the sea level is expected to increase by up to 0.25 m in 2050, compared to an increase of between 0.25-0.35 m under the high emission scenario. More importantly, climate projections, as illustrated in Figure 10 suggest that sea-level rise for the region is expected to change regardless of the emission trajectory. As derived and summarized from climate models, these data are essential in evaluating the exposure and vulnerability of the relevant socio-ecological systems to future changes in sea level.

2.2 Ecological component of vulnerability

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

1. Physical habitat: e.g., water, sediment, rocks
2. Biological habitat: e.g., mangroves, seagrasses, coral reefs
3. Primary producers (plants): e.g. phytoplankton, macroalgae, aquatic plants (e.g. seagrasses), mangroves, terrestrial plants

Mangroves, corals, and seagrasses provide a wide variety of ecosystem services, such as preventing coastal flooding and sustaining fishing and tourism industries. Across the WIO, peoples' livelihoods and income are often inextricably linked to healthy functioning ecosystems. Nevertheless, once the health of these ecosystems (as measured by coral and seagrass cover, mangrove biomass, etc.) deteriorates, due to the combined impacts of local use and global threats such as

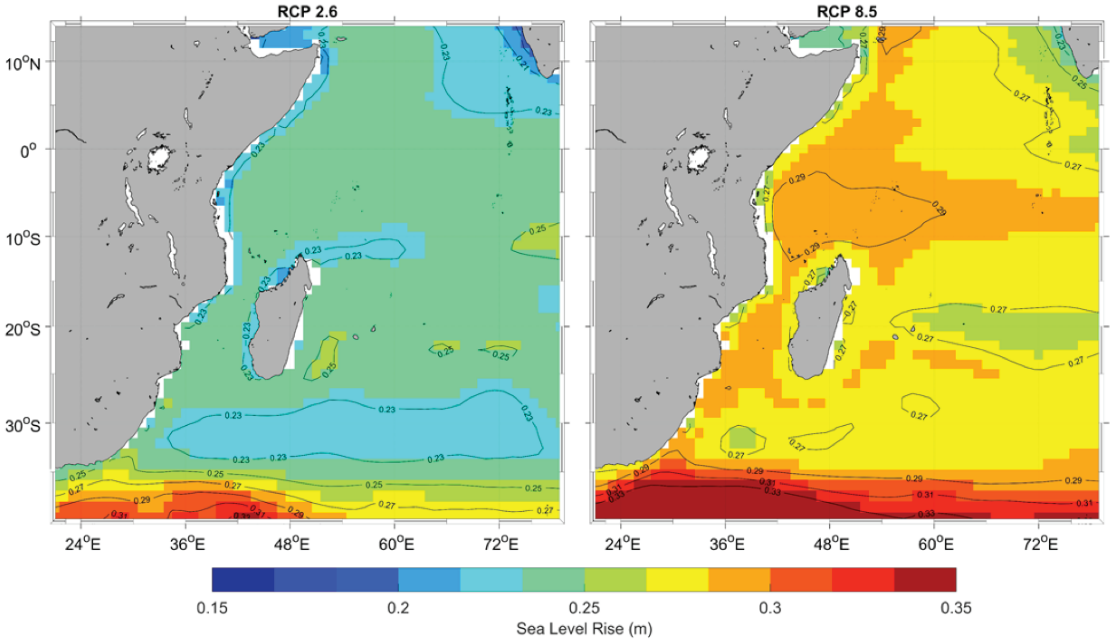

Figure 10. Multi-model average sea-level rise predictions for 2050 relative to a baseline period of 1986–2000, based on low emission (RCP2.6) and high emission (RCP8.5).

climate change and surpasses the "tipping point", the natural capital of the WIO region will be eroded, undermining its value for future and present. The tipping point is the critical point in a system or process, beyond which an unstoppable effect or change is likely to take place.

2.2.1 Coral reefs

The fate of coral reefs on a warming planet has been of great interest to 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 colourful flagellate *Symbiodinium* (Rowan, 1998) that reside in coral tissue (Brown, 1997).

Episodes of mass coral "bleaching" in the WIO since the early 1980s (Figure 11) have led to widespread coral mortality and have raised questions about the viability of coral reef ecosystems during this period of rapid climate change. Several studies have used climate models to predict coral bleaching, using different approaches across time and scale (reviewed by Donner *et al*., 2018), including vulnerability to thermal stress and local anthropogenic impacts and a combination of frequency and severity of coral bleaching, resilience and human impact (Donner *et al*., 2005; Donner, 2009; McLeod *et al*., 2010; Van Hooidonk *et al*., 2013; Van Hooidonk *et al*., 2016

A 1.5 °C global warming by 2100 would significantly damage coral reef systems, according to recent reports. In a 1.5 °C warming scenario, tropical coral reefs are projected to decline by 70-90 percent, whereas virtually all coral reefs (more than 99 percent) will be lost by the end of the century if 2 °C warming occurs (Hoegh-Guldberg *et al*., 2018).

2.2.2 Mangroves

Mangroves are important coastal resources, which support the livelihoods of millions of people in the tropics and sub-tropics (Bosire *et al*., 2003; Kairo *et al*., 2002). 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). It is estimated that ~1.0 million ha (or 5 percent) are in the WIO region (FAO, 2007). The majority of these are found in Mozambique (Zambezi Delta), Madagascar (Mahajamba Bay), Tanzania (Rufiji Delta) and Kenya (Lamu) (Spalding *et al*., 2010). However, mangroves coverage has continued to decline due to multiple global and local pressures (FAO, 2007), thus rapidly altering the structure and func-

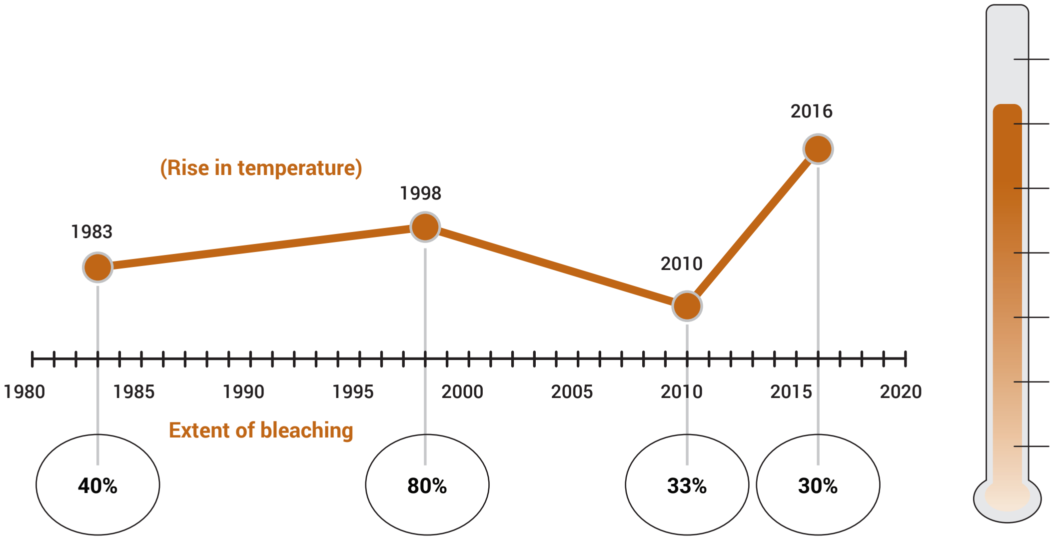

Figure 11. Rising sea surface temperature with corresponding mass coral bleaching years. Source: adapted from Obura *et al*. (2017).

tion of these ecosystems and their capacity to provide essential goods and services to millions of people in the tropics (Bosire *et al.*, 2003; Kairo *et al.*, 2002). Warming beyond 1.5°C may lead to mangroves being completely submerged before the end of the century in areas where sediment input is not enough for mangroves to grow (and extend landward, where space allows) at pace with sea-level rise.

2.2.3 Seagrasses

Seagrass ecosystems cover wide expanses of the intertidal and subtidal zones and are one of the most productive and diverse coastal marine ecosystems. The value of these ecosystems is estimated at US$ 20.8 billion (Obura *et al.*, 2017). Seagrass ecosystems are important as they provide nursery grounds and food for fish and invertebrates, which contributes to the livelihoods of coastal communities, coastline protection from erosion, carbon sequestration, and nutrient fixation (Spalding *et al.*, 2007). Despite their vital social and ecological value, seagrass communities are declining annually worldwide by over 7 percent (Cullen-Unsworth and Unsworth, 2013), with about 29 percent of the world seagrass stock having already been destroyed (Waycott *et al.*, 2009), mostly due to human activities, with further anticipated losses due to global warming and climate change (Short *et al.*, 2011). Although widely distributed throughout the region, the exact extent and coverage for the WIO region are unknown.

2.2.4 Rocky shoreline habitats

A rocky shore is an intertidal area that consists of solid rocks and often a biologically rich environment where different organisms occur (e.g. seaweeds, lichens, microscopic plants, molluscs, barnacles, etc.). Among the many factors that influence habitats, plants and animals on the rocky intertidal shores, energy forces (mainly as wave energy) and tidal inundation are significant. The wind, sunlight, and other physical factors create a complex environment. Thus, organisms living in rocky habitats are exposed to variable physical conditions that can easily adversely affect their health. For example, predicted changes in intensity and duration of temperature extremes (IPCC, 2014) will increase the likelihood of extreme desiccation events due to prolonged aerial exposure and temperature increase.

2.3 Social component of vulnerability

From a social perspective, vulnerability varies because 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 the 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 and identify adaptation actions.

2.3.1 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 percent of the marine catch and are the principal income-generating activity for many 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 *et al.*, 2002).

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

2.3.2 Migrant fishers

Migrant fishing is a major feature of fisheries in East Africa and an essential livelihood strategy for many fisherfolks due to the 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 (Westlund *et al.*, 2008). Often, they operate in remote locations that are less accessible to fisheries management authorities (Islam and Herbeck, 2013), rendering them more 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 individual and community levels (Wanyonyi *et al.*, 2016). For example, migration changes socio-economic, cultural and ecological conditions and changes 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 the migrants, those left behind, and those whose 'home' fishing grounds have been accessed by the migrants. Wanyonyi *et al.* (2016) demonstrated that migration leads to increased income and increased saving, thus improving the standard of living for the family and the overall adaptive capacity.

On the other hand, migrant fishers must leave the rest of their family members at home, forcing spouses to take on men's responsibilities such as farming. If there is a drought, the family experiences hard times due to low food production from farming. This increases the level of socio-economic vulnerability.

2.3.3 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 governance processes (how governments and other organizations address societal problems) 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 strategies include: Comoros, Madagascar, Mozambique, Tanzania, Kenya, Mauritius, Seychelles.

3. Linking vulnerability framework to other frameworks

While conducting a CCVA, it is also important to interlink with other global frameworks, e.g. the Sustainable Development Goals (SDGs), Sendai, Aichi and others (see Figure 12). This calls for a systematic pairing of the targets contained in each agenda based on their meaning to the CCVA. This can reveal actions that reduce vulnerability and, at the same time, address framework targets.

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[3]. Table 4 summarizes the relevant SDG goals and targets that link to CCVA.

Other complementary frameworks of importance include:

The Sendai framework for disaster risk reduction (Aitsi-Selmi *et al.*, 2015) 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)[4]. The Sendai framework focuses on four priorities of actions:

1. 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.

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

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

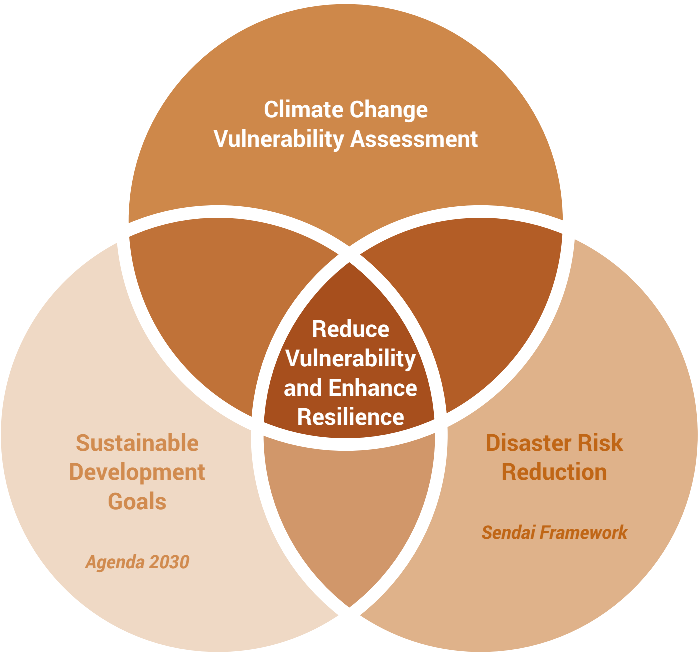


Figure 12. Vulnerability Assessments with the Sustainable Development Goals and the Sendai Framework. Source: adapted from UNFCC (2017).

2. Strengthening disaster risk governance to manage disaster risk at the national, regional and global levels for prevention, mitigation, preparedness, response, recovery, and rehabilitation.

3. Investing in resilience through structural and non-structural management measures.

4. Enhance disaster preparedness by ensuring capacities for effective response and recovery.

The Aichi targets on biodiversity, which has a set of five strategic goals:
1. Strategic Goal A: Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society.

2. Strategic Goal B: Reduce the direct pressures on biodiversity and promote sustainable use.

3. Strategic Goal C: To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity.

4. Strategic Goal D: Enhance the benefits of biodiversity and ecosystem services.

5. Strategic Goal E: Enhance implementation through participatory planning, knowledge management and capacity building.

Table 4. Relevant SDGs to climate change vulnerability assessment.

RELEVANT GOAL	RELEVANT TARGET
Goal 13: Climate action	**Target 13.1:** Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries
	Target 13.2: Integrate climate change measures into national policies, strategies and planning
	Target 13.3: Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning
Goal 14: Life below water	**Target 14.1:** By 2025, prevent and significantly reduce marine pollution of all kinds, from land-based activities, including marine debris and nutrient pollution
	Target 14.2: By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and taking action for their restoration to achieve healthy and productive oceans
	Target 14.3: Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels
Goal 1: No poverty	**Target 1.5:** By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters.
Goal 5: Gender equality	**Target 5.a:** Undertake reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property, financial services, inheritance and natural resources, in accordance with national laws.
Goal 12: Sustainable consumption and production	**Target 12.2:** By 2030, achieve the sustainable management and efficient use of natural resources
	Target 12.5: By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse
	Target 12.8: By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature
	Target 12.a: Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production
	Target 12.b: Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products

4. Methods for conducting CCVA

This section provides an overview of the methodological approach that can be adopted for a climate change vulnerability assessment exercise. It describes methodologies for evaluating each of the three components of vulnerability as illustrated in Figure 2, including methods for synthesizing the dimensions into overall climate change vulnerability estimates and applying adaptation planning.

Getting started with a CCVA - a step by step guide

The scope of a CCVA will vary according to the nature of the development challenges, including the geographic or jurisdictional area of concern (e.g. regional, national, municipal), expected project and decision lifetime (e.g. 5 years, 20 years, 50 years), and sector(s) of interest (e.g. cross-sectoral, a single sector, one aspect of a sector). In other words, for the information generated by an assessment to be relevant to key decisions, it should be largely contextualized or tailored for specific spatial, temporal, and sectoral scales.

The methodology described in this *Toolkit* involves five main steps, as illustrated in Figure 13. Each of these steps consists of a set of activities carried out progressively, with the outputs of each activity feeding into subsequent steps and activities.

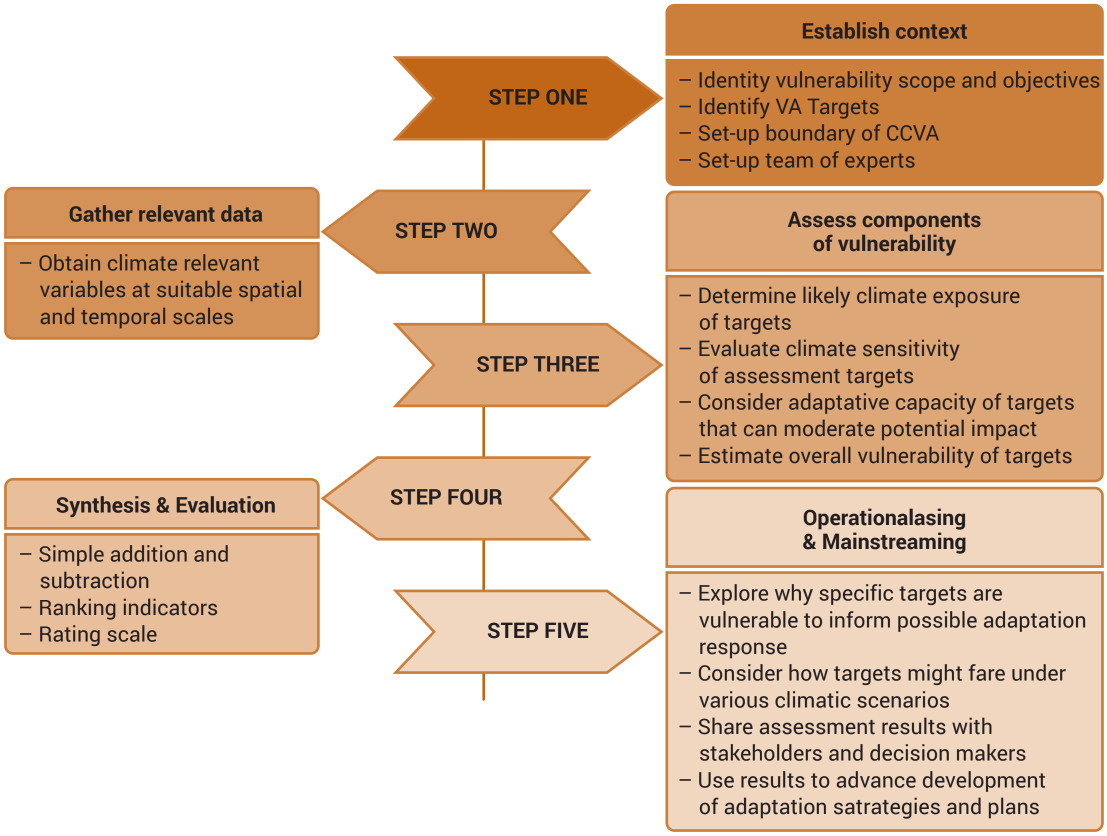


Figure 13. Flow chart of the five phases of a CCVA cycle and steps for conducting robust, context specific and policy relevant vulnerability assessments of socio-ecological systems.

Step 1: Establish context

The first step defines the framework of the CCVA and forms the basis for the subsequent steps. The following six activities are implemented as part of establishing the context:

Activity 1.1: Identify the objectives and scope of vulnerability assessment

There is a need to clearly define the purpose and the scope of the CCVA exercise. Having a well-defined goal(s) facilitates the establishment of well-structured CCVA whose outputs can effectively inform decisions on climate change adaptation. A well-defined goal should answer the following questions:

1. What is the purpose of the CCVA?

2. Who is the audience/who are end-users?

3. Which decisions can the CCVA influence?

With the goal(s) defined, objectives that describe specific actions towards achieving the broader goal(s) of the CCVA are formulated. Table 5 describes six broad CCVA objective categories to consider.

Activity 1.2: Define the assessment target

Once the objectives, physical boundaries and timeframe of the CCVA have been agreed upon, the CCVA targets need to be identified and explicitly defined. CCVA targets are those items/objects, places or issues that will be subject to detailed investigation in the CCVA. As illustrated in Figure 14 opposit, CCVA targets can broadly be categorized into ecological targets (species, ecosystems and habitats), ecosystem services targets and social targets (refer to sub-section 2.2 and 2.3 a for detailed description of coastal ecological and social systems). Often, CCVA involves more than one target. For example, social (e.g. fishing communities) and ecological (coral reefs) represent the coral reef fisheries socioecological system.

Activity 1.3: Conduct a desktop review

Conducting a desktop review can help understand how climate change has impacted a socio-ecological system in the past, or how it may be impacted in the future. The review includes an exploration of the system to identify assumptions about how components and stressors interact, as well as an exploration of potential system elements to be considered (Thialt *et al.* 20). It also involves a review of background information that can inform the CCVA. The background information can be derived from:

1. Existing CCVAs reports for both the study area and from other regions;

2. Sources of climate data, including downscaled projections from climate models that were generated for other assessments;

Table 5. Examples of CCVA objectives and their scope of focus. Source: adapted from Foden and Young (2016).

SCOPE	CCVA OBJECTIVE
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 do 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 to better assess the ecosystem's vulnerability to climate change?

Figure 14. Schematic illustration of a range of CCVA targets.

3. Existing hazard maps, risk maps, threat maps or sensitivity maps;
4. Damage assessment reports, which document whether and how extreme events previously affected a system;
5. Disaster risk reports, which provide information on risks of weather hazards in a given region;
6. Sector-specific historical records from past events, which can provide useful information about vulnerability; e.g. a record of coral bleaching and mortality following elevated SST; and
7. New/relevant indicators for a specific system in a given region.

Activity 1.4: Define the scope/boundary of the assessment

An appropriate geographic scale for the assessment and the time scales being considered must be defined. The following considerations are important for defining the scope of the analyses:

- *Specify geographic extent:* When defining the relevant geography or the system's spatial boundaries, it is important to include areas that are contiguous with or close to 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 seagrasses).
- *Specify spatial resolution:* Once the geographic extent is defined, the spatial resolution of data and information needed is defined. For example, socio-economic data tend to be highly resolved, i.e. at the household scale. In contrast, environmental data tend to be of relatively lower resolution, for example, temperature data at 1 km or 100 km grid size. The resolution of the data used can impact the overall outcome of the CCVA process.
- *Specify timeframe:* In determining the appropriate timeframe, it is important to consider the potential impact of climate change under multiple scenarios (e.g. 5, 20, or 100 years). Note that near-term projections of climate scenarios tend to have a higher degree of certainty than those looking further ahead.

Activity 1.5: Form a team

Understanding the key participants and partners (both internal and external), 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 outcomes to the CCVA goals and objectives. Box 2 outlines steps for identifying stakeholders.

When considering whom to engage it may be necessary to involve the following stakeholder groups in a CCVA process:

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

Time allocated to thoughtfully identify and engage with 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.

Activity 1.6: Justification, Budget and Authority

More generally, when conducting a CCVA the scope and objectives need to fit within the limitations of the available resources, including:

1. The cost of conducting a CCVA depends on the time, data and information, and expertise needed to achieve the outcomes. Therefore, identify potential budgets is vital before starting the CCVA process to 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 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 prepare and disseminate reports.
2. Data and information requirements for CCVA are influenced by the type of decision (e.g. strategy, project, activity), the timeframe, scale of decision making (e.g. sub-county, country or regional). Therefore, it is important to align the data needs to the stated CCVA goals and objectives.
3. Expertise needed for a CCVA depends on the assessment objective and time and cost considerations and desired outputs. CCVA process requires a multi-disciplinary team of experts. For example, a marine park manager may conduct a strategy level climate risk screening with limited input from an expert using available guidance and resources such as the reef resilience toolkit (https://cordioea.net/coral-bleaching/reef-resilience/). How-

Box 2. Steps to identify the appropriate team and stakeholders

Create a list of organizations, interest groups, and individual who may wish to be involved in the assessment process.

Set-up a meeting with representative of the groups

Take them through the principles of CCVA and the goals of the assessment in which they are being asking to engage

It maybe for the participants to select a mediator for the stakeholder engagement process, someone who is viewed as neutral and widely respected.

ever, 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 appropriately use climate predictions.

Step 2: Compile relevant data and resources

Climate data and other non-climate information needs for a CCVA are shaped by factors such as the type of decisions the CCVA would inform (i.e. goal(s) and objectives), the scale of decision making (e.g. country, ecosystem), and the timescale of the assessment. It is important to identify data needs based on the CCVA scope and objectives and better understand the available relevant data and information that is already available. This understanding will help determine whether additional analyses are required or if a desktop analysis will provide sufficient detail to move forward. Table 6 highlights the resources often required and/or desired to conduct a CCVA. Tables A and B in the Annex highlight examples of freely available resources/data that can be used. While the list provided on these tables is not exhaustive, it provides a good starting point.

Additionally, socio-economic data and information e.g. living conditions (housing characteristics) and health conditions (physical mobility), and economic (poverty levels), population growth and changing land use practices need to be considered as factors that impact on respective dimensions of vulnerability. Often, a socio-economic survey is necessary to elicit information that can inform the adaptive capacity and sensitivity from a social perspective (see details in the relevant sections). It may also be helpful to evaluate data and information on non-climate stressors as they can be important contributors to climate vulnerabilities. For instance, population growth and changing land use practices may increase the vulnerability of mangrove forest ecosystems.

Step 3: Evaluating vulnerability dimensions

Given that vulnerability is a composite index that integrates exposure, sensitivity, and adaptive capacity, each of these dimensions needs to be evaluated in ecological and or social settings (Figure 2, parts a-f). This section describes methods for operationalizing the integrated vulnerability conceptual framework illustrated in Figure 2, particularly parts a-f. Socio-ecological parameters are often closely linked; therefore, socio-ecological vulnerability assessments should be conducted in the same place at the same time. For example, monitoring of fish populations should be directly linked to surveys of fish markets, fishermen and their catches. Similarly, ecological parameters describe the natural state of the coral reef, which will impact socio-economic factors such as income and employment.

Activity 3.1: Evaluate the profile of the system of interest

When planning to evaluate vulnerability dimensions, it is important to evaluate the profile of the system of interest. A system profile presents the general current status of the system of interest. The following questions form a basis for conducting a system profile or a baseline survey of the system of interest.

Table 6. Summary of the data resources generally required by each CCVA approach.

RESOURCE TYPE	INPUT REQUIREMENTS
Species/ecosystem distribution data	Point localities; and/or gridded/raster distributions; and/or polygons/maps, rapid assessments and/or expert knowledge
Climate data	Distant past or paleoclimate (historical) projections; recent past/baseline climate projections; future projections, rapid assessments and/or expert knowledge
Ecological data	Spatial projections of land cover (reflecting ecosystem/habitat); data describing exacerbation of other threats (not caused by climate change), rapid assessments and/or expert knowledge
Technological requirements	Hardware (e.g. computer); software (e.g. GIS), or simply a spreadsheet for a rapid and basic assessments

1. What is the state of natural resources in the system of interest?
    a. Spatial distribution of natural resources (e.g. mangrove area or condition)
    b. Temporal trends of natural resources (e.g. change in forest cover and type)
    c. Quality of natural resources (e.g. degraded coral reef health/percentage cover)
2. What kind of socio-economic dynamics exist in the system of interest?
    a. Demographic profile (e.g. number and density of the population, population below poverty line, literacy rate)
    b. Livelihood profiles (e.g. main sources of livelihood, diversity of livelihood strategies, gender-specific livelihood strategies)
3. What are the main environmental issues in the system of interest?
    a. Identification of key environmental issues (e.g. bleaching, deforestation, water pollution)
    b. Sectorial implications due to identified environmental issues (e.g. impacts on mangrove-dependent or fisheries livelihoods)
    c. Temporal trends (e.g. percentage decline in mangrove forest or coral reef cover)
4. What resources are available?
    a. Expertise of the people to do the monitoring
    b. Cost of equipment and time.

Conduct a baseline survey

Different sampling designs are employed for the assessment of the different ecosystems. For example, in mangroves, transect line rapid assessment, permanent plots and mangrove litter productivity, leaf area index etc., could be used to evaluate ecological integrity of the system of interest (refer to Box 3). The use of accurate and validated methods for determining ecological integrity is a useful contribution to decision makers.

Examples of survey protocols that can be used for baseline assessments and monitoring of coral reefs and seagrass include:

1. A simple, rapid protocol for assessing coral bleaching: **https://c532f75abb9c1c021b8c-e46e473f8aadb72cf2a8ea564b4e6a76.ssl.cf5.rackcdn.com/2017/02/22/9mkks762mz_Bleaching_Survey_writeup_April2016.pdf.**
2. Seagrass monitoring manual: https://www.seagrasswatch.org/manuals/.
3. IUCN Rapid assessment protocol for coral reefs: **https://www.iucn.org/content/resilience-assessment-coral-reefs-rapid-assessment-protocol-coral-reefs-focusing-coral.**
4. Assessing coral reef resilience: https://cordioea.net/coral-bleaching/reef-resilience/.

The questions to be considered when studying the profile of the system of interest depend on the purpose of the vulnerability assessment. During the study of the profile of the system of interest, new questions that were not considered at the outset are likely to arise. At the end of this analysis, basic information about the biophysical and social status of the system of interest should have been gained.

Activity 3.2: Determine the exposure

The most basic and direct types of exposure are changes in climate indicators, including temperature (land and ocean), precipitation, wind and others. For example, for a coral reef ecosystem, exposure to higher-than-normal sea surface temperatures (ecological exposure; refer to Figure 2, part a) can be a major driver of mass coral bleaching and high coral mortality. Direct impacts on people include increased storm intensity, altered rainfall patterns and sea level rise (social exposure; refer to Figure 2, part d).

Box 3. Description of the different methods to assess mangrove

A rapid assessment establishes what mangrove forest community structure is present, and what condition the forest is in. It is good for a reconnaissance survey with local community members.

Permanent plot measurement gives quantitative forest assessment data that are most useful to the assessment of vulnerability and change

A mangrove litter productivity study gives more detailed information on mangrove health and phenology.

Therefore, evaluating the social and ecological exposure to climate change requires identifying likely or potential changes in relevant variables. These variables can be both direct climatic factors such as changes in temperature or precipitation and indirect such as shifts in ecosystem processes or demographic patterns.

Choosing indicators and accessing data

Choosing the indicators of exposure is one of the most important activities in CCVA (Snover *et al.*, 2013). Therefore, selecting scenarios for exposure assessment requires identifying both climatic and non-climatic variables. Data can be obtained from many different sources and utilize various techniques. Examples of different indicators and information required when evaluating exposure are provided in Table 7 (also see Case Study 1 in the extended data) while the process is illustrated in Figure 15. The process begins with identifying the indicators standardizing the indicators, weighting the indicators, and synthesizing the indicators into an overall composite exposure, sensitivity or adaptive capacity metric. These can be done in GIS if the analysis is spatial or on a spreadsheet.

The majority of these indicators are derived from time series. For example, maximum temperature and average rainfall may need to be derived by aggregating time series climate data. Some of the data sources in Table 6 consist of readily aggregated variables. Given the dynamic nature of climate over time scales, it makes sense to access time series data and perform aggregation to derive the variable of interest. This may require technical expertise in GIS (if the data is spatial) or basic statistics and the use of spreadsheets.

Evaluating exposure (i) standardizing variables

With exposure variables/indicators and data in place, the next step is standardizing the variables to bring them to the same scale (i.e. 0-1, 1-10, 1-100 etc.). This can be achieved using the maximum-minimum function (also technically referred to as right and left linear trapezoidal equations). Equations 2a and 2b below are then used to standardize each of the selected exposure indicators/variables, essentially converting a given variable to 'partial exposure' with a range between 0 to 1. For example, when high values of an indicator represent high exposure (e.g. mean ocean temperature in coral bleaching exposure), Equation 2a is applied.

$$X = \frac{x - min}{max - min} \tag{2a}$$

Conversely, when exposure decreases with increase in indicator values (e.g. mean annual rainfall in mangrove exposure), Equation 2b is applied in the standardization (of mean rainfall data in the example).

$$X = \frac{max - x}{max - min} \tag{2b}$$

Table 7. Example of indicators to assess exposure of mangroves and social systems.

SUBSYSTEM	INDICATOR	INFORMATION COLLECTED/ANALYZED	METHOD	DATA TYPE
Mangrove	Topography/ slope/sea level anomaly/rainfall/ temperature	Surface elevation (m); relative sea level rise (m); mean annual rainfall and maximum temperature (°C); future climate scenarios (RCPs)	Remote sensing; spatial analysis; digital elevation model	Quantitative
Fisherfolk	distance from village to the sea; gravity of markets; slope	location of fishing villages and proximity to the system of interest; relative sea level rise (m)	Collection of secondary information; interviews	Quantitative and qualitative

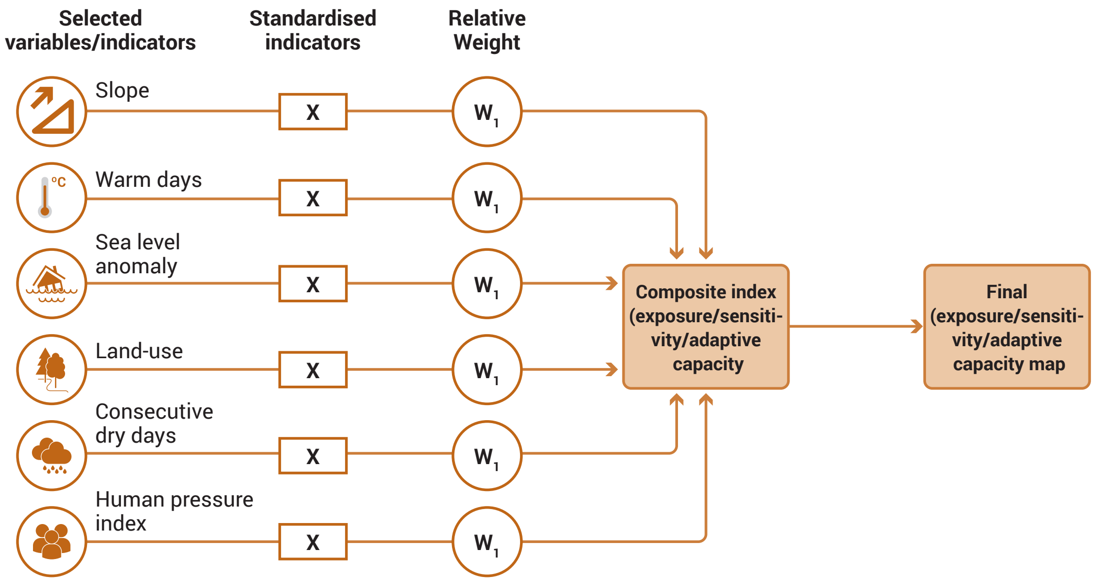


Figure 15. An illustration of analytical steps for evaluating any of the three vulnerability dimensions (i.e., exposure, sensitivity, and adaptive capacity).

Where X represents partial exposure of system of interest, with values ranging between 0 to 1; x represents a value among a range of indicator (e.g. max temperature of 30 C); *min* is the minimum value within the range, while *max* is the maximum value.

If a threshold value at which the variable (e.g. mean temperature) becomes detrimental, for example 30 °C for coral reefs, this threshold can be specified as the *max* in the equation. When threshold is not known the *max* and *min* of the population can be used (for example, maximum and minimum annual rainfall in mangrove system).

Evaluating exposure (ii) assigning weights

The next step is to assign relative weights to the variables/or indicators based on how important they are concerning the *exposure* of the system. In literature, there are several techniques to assign weights to variables. Two methods are described in this guideline: Analytical Hierarchical Process (AHP) (Saaty, 1980) and direct weighing methods. These methods are based entirely on expert knowledge; hence the final results are directly a result of the expert's judgments. To apply the direct weighting method, the relative importance of each exposure indicator is evaluated against other indicators and assigned a weight between 1-5. The weights are then scaled between 0-1. While direct weighting can be based on the knowledge of one expert, the AHP method should be applied if a wider consultation among experts on the weighting of indicators is preferred. Also known as pair-wise weighing, AHP is a general theory of measurement widely applied in decision-making processes. **A spreadsheet template is provided alongside detailed instructions on the AHP weighting process (extended data 2).**

Evaluating exposure (iii) Synthesize partial exposures from (i) above

The next step is to synthesize the partial exposure data (or maps if using GIS) into a single exposure index using the weighted linear combination equation described below in Equation 3 and illustrated in Figure 15.

$$S = \sum wi\ xi \qquad (3)$$

Where, is the weight factor indicator *i* and is the standardized value of the input data (or layer if using GIS).

Activity 3.3: Determine sensitivity dimension

Sensitivity is the degree to which a system is affected by changes in climate conditions or natural hazards (exposure). For example, the sensitivity of coastal communities that 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.

Evaluating ecological sensitivity

Evaluate ecological sensitivity (for ecological sensitivity dimension, refer to Figure 2, part b) by determining whether the system of interest is significantly affected by climate-related stimuli or not. If the system is affected by climate-related or non-climate stimuli, consider it sensitive. Questions in Table 8 can help evaluate the ecological sensitivity of the system of interest to climate change.

The analytical process for evaluating the overall sensitivity is similar to the procedures explained for exposure in Activity 3.2 (above). If more than one indicator of ecological sensitivity is selected, the processes of standardizing, weighting, and synthesis are described under this activity. The *relative weighting* and *synthesis* steps do not apply if only one variable is considered.

Evaluate social sensitivity

Estimating sensitivity in a social setting often involves social surveys to elicit information on indicators of social sensitivity (for ecological sensitivity dimension Figure 2, part e). The following questions can guide the formulation of survey questions to elicit information necessary for understanding the sensitivity of a social system:

1. How may climate-related changes in local resources affect human communities' use of those resources?

2. Which livelihoods are important in the household or community?

3. Which segments of human communities will be disproportionately affected and why?

The most frequently used socio-economic parameters include:

1. Household demographics – include age, gender, education level, religion, literacy, etc.

2. Employment – measures how people earn money or gather food. A special emphasis is on assessing people directly using marine resources, especially fishers.

3. Cultural/heritage– measures what areas or reef resources are of special interest to communities for cultural or religious purposes.

Table 8. Indicators of ecological sensitivity.

DIMENSION	ILLUSTRATIVE QUESTIONS
Coral bleaching susceptibility	Which coral species (e.g. branching corals) are often severely affected by disturbance? (e.g. branching corals). High abundance of these species confers higher sensitivity.
Reef fish susceptibility	Which fish species are often severely affected by habitat disturbances induced by coral bleaching/mortality?
Mangroves	Which mangroves areas or species are often impacted by disturbance e.g. change in forest structure, composition and productivity?
Seagrasses	Which seagrass habitat or seagrass species are often impacted by disturbance?

4. Traditional uses and activities – determine how communities used and managed reef resources in the past. This is used to compare with current practices.

5. Social networks and interactions – these are important in determining who the key decision makers are and how decisions are made in the community.

6. Community infrastructure – details how communities are governed and how they relate to higher levels of government.

7. Local perception of reef management and management success – this is essential for managers to understand and target methods of influencing perceptions in favor of resource conservation.

8. Level of understanding of human impacts to reefs – measures whether communities are aware of their damaging activities and concerned about sustainability.

9. Level of understanding and cooperation of marine protected area (MPA) regulations – managers need this information to develop education programs to increase support for MPA management.

Some of the methods and tools that can be used to collect social sensitivity information include:

1. Focus / Discussion Groups – involves a selected group of individuals, perhaps key stakeholders, meeting to discuss.

2. Surveys – involves distributing a survey to a randomly selected group of possible respondents to gain information.

Once the data from survey responses for questions relevant to sensitivity has been entered and qualitative responses quantified, Equation 5 below (Maina *et al.*, 2016) can be used to calculate social sensitivity index:

$$S = \frac{\sum_{i}^{N}{}_{\,i=1} V_i}{N} \times \frac{1}{t} \qquad (4)$$

where V_i is response for the variable/question considered (e.g. whether fishers recognized declining trends in the fishery status); N is the total number of respondents for each village/community; t is the number of categories of the responses (e.g. fishing, climate, adaptation options etc.). Equation 2a and 2b in Activity 3.2 are then applied.

Once all the sensitivity indicators are normalized and weights generated, the weighted linear combination Equation 4 can be applied to synthesize the sensitivity indicators into a composite index

Activity 3.4: Social and ecological adaptive capacity

While exposure and sensitivity determine the potential impact of climate-induced change, adaptive capacity is the ability or potential of a system or community to respond successfully to climate variability and change. It includes adjustments in both behaviour and resources and technologies. For example, for mangrove ecosystems, if net vertical accretion does not keep up with relative sea level rise, then adaptation is through inland migration, depending on suitable topography and available areas. Local communities and stakeholders also develop social adaptive capability through their management capacity, supported by effective legislation that enables mangrove protection from non-climate stressors. Box 5 summarizes key questions that can guide the assessment of adaptive capacity.

Evaluate ecological adaptive capacity

Indicators of adaptive capacity are based on diversity and flexibility across a range of traits (e.g. life history or behavioral) and organizational levels (e.g. genetic, species, populations) as well as access to and interactions with suitable habitats (see Table 9 below). Here, indicators can be quantitative measures of adaptability summarized as indices. Therefore, appropriate indicators for assessing adaptive capacity must be tailored to the case in question. With adaptive capacity variables and data in place, the next step is to standardize the variables, weight, and synthesize the partial adaptive capacity as described in Activity 3.2.

Box 5. Key questions to guide the assessment of adaptive capacity

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?

Evaluating social adaptive capacity

Most indicators of social adaptive capacity will comprise qualitative perceptions of individuals or communities about their capacity to adapt (e.g. social capital, innovation, institutional structures, governance strategies). This data or information is collected through surveys (e.g. research on the coastal communities based of their dependence on coral reef-based activities as the main source of livelihood). Having chosen the suitable variables, it is necessary to ensure that indicators are standardized (refer to *Evaluating exposure (i) standardizing variables*, Activity 3.2). As a next step, weights should be assigned to these indicators (refer to *Evaluating exposure (ii) assigning weights,* Activity 3.2). Finally, the partial adaptive capacity data (or maps if using GIS) needs to be synthesized into a single adaptive capacity index using the weighted linear combination equation described in Activity 3.2.

Step 4: Synthesizing dimensions into a composite index of vulnerability

Having determined the climate exposure, social and ecological sensitivity, and social and ecological adaptive capacity, the final step is to synthesize/combine the respective composite indices/ scores into the overall vulnerability index. This section explains the steps involved in creating a vulnerability composite using vulnerability dimensions from Step 3. There are several methods for achieving this, three of which are proposed here and can be applied depending on the level of complexity of the study.

Method 1: Simple addition and subtraction of composite indicators

The overall vulnerability can be computed by subtracting adaptive capacity estimates from the sum of exposure and sensitivity (Equation 5).

$$Vulnerability=(Exposure+sensitivity)-Adaptive\ Capacity \qquad (5)$$

This implies that a system with a high adaptive capacity and lower exposure/sensitivity is less vulnerable than a system with low adaptive capacity and high exposure/sensitivity. The latter is more susceptible to climate change impacts and has an overall high vulnerability (see Figure 16).

Method 2: Ranking the indicators

This method describes how to combine results from some or all the indicators used to obtain an overall vulnerability assessment for a given system. A score from one to five can be used for the indicators where 1 is no impact and 5 is severe impact (Table 10). Once the scores have been recorded, the systems vulnerability can be ranked on a scale as in Table 11.

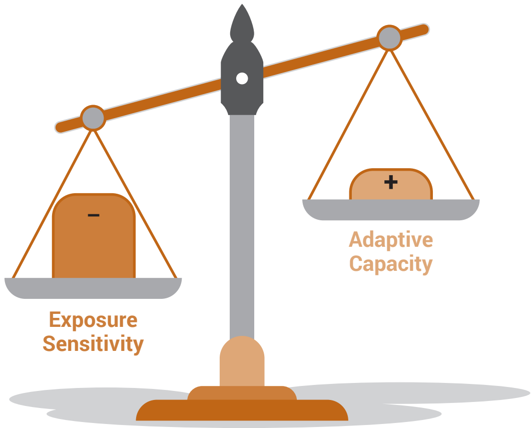
As shown in Table 11, the scores assigned to each variable should be collated into a single table to obtain an overall vulnerability assessment ranking. Table 11 gives an overall assessment of vul-

Table 9. Examples of social and ecological measures used in assessments of adaptive capacity. Source: adapted from Whitney *et al*. (2017).

CHARACTERISTICS OF SOCIAL ADAPTIVE CAPACITY		**CHARACTERISTICS OF ECOLOGICAL ADAPTIVE CAPACITY**	
Category	Indicator	Category	Indicator
Diversity and flexibility	Livelihood and income diversity Economic opportunities Level of dependence on natural resources Occupational mobility Place attachment Migration patterns Willingness to change	Diversity and flexibility	Species diversity Functional redundancy across species Response diversity across species Species' life history traits (e.g. metabolic rates, size, reproductive strategies such as generation time, fecundity) Broad habitat range and tolerance
Access to assets	Household material assets (e.g. boats, gear) Levels of education Financial status and access to sources of credit Access to markets Bridging social capital and institutional supports Equity, rights, and access to resources Cultural memory, traditions, and assets	Habitats and interactions	Habitat availability Habitat heterogeneity Habitat connectivity (opportunity) Rate and magnitude of habitat disturbance Habitat diversity Phenology
Learning and knowledge	Resource monitoring and feedback mechanisms Knowledge of disturbance (e.g. climate change) Perceptions of risk Spaces and platforms for learning Diversity of knowledge and information sources Ability to anticipate change Recognition of causality and human agency Intergenerational learning capacity	Capacity to adapt within species	Behavioural change (e.g. prey switching) and learning Phenotypic plasticity Tolerance limits Rapid genetic adaptation of traits through behaviour change and acclimation Reproductive rate and capacity for dissemination Dispersal capacity Migration capacity
Governance and institutions	Levels of trust, social capital, and networks Gender and race relations Levels of participation and quality of decision-making processes Planning capacity Presence of local environmental institutions and strength of social norms Quality of governance and leadership in environmental policies and agencies Accountability of managers and governance bodies Active risk management and adaptive governance processes	Self-organizing systems	Community structure and dynamics

nerability by averaging the ranks in the last row. The overall score is the overall vulnerability score, where 1 is low vulnerability and 5 is very high vulnerability. To calculate the overall vulnerability score, use the equation below:

$$\textit{Vulenrability score} = \frac{\textit{Total score}}{\textit{number of components}} \tag{6}$$



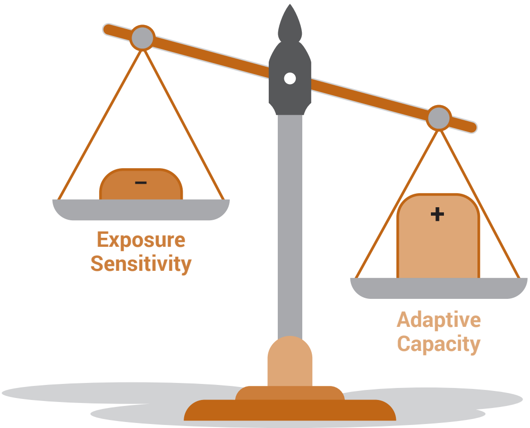


Figure 16. Vulnerability as determined by the relationship among three components: exposure, sensitivity and adaptive capacity.

Table 11 shows that the total score is17 while the total number of variables (i.e. sediment supply, sea level, rainfall etc) for all the vulnerability components is 8 (exposure =3), sensitivity =2), adaptive capacity =3). Therefore, the overall vulnerability score = 2.1.

Method 3: The vulnerability rating scale

Another method to illustrate vulnerability for easy interpretation and communication to managers is using a vulnerability rating scale (Table 12). The 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 the level vulnerability associated with each combination of exposure/sensitivity and adaptive capacity of resilience or exposure/sensitivity (Table 12).

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 *et al.*, 2005). As described in previous sections, a CCVA is designed to explore who is vulnerable; where, when, why, and how 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 having a higher ecological adaptive capacity. This type of information will

Table 10. An example of scores used to record coral reef conditions. Source: adapted from English *et al.* (1997).

SCORE	CONDITION	EXAMPLE
1	No or slight impact	Fairly continuous heathy reef
2	Moderate impact	Bleached corals and low recruitment
3	Rather high impact	Bleached corals with no recruitment
4	High impact	Low coral survival rate
5	Severe impact	Widespread coral mortality

Table 11. Example of ranking worksheet for mangrove vulnerability assessment results. Source: adapted from Ellison (2015).

	SCALE/DEGREE					
	1	**2**	**3**	**4**	**5**	**SCORE**
EXPOSURE						
Sediment supply	High	Fairly high	Medium	Fairly low	Low	2
Sea level rise	Uplifting	Slightly uplifting	Stable	Slowly submerging	Rapidly submerging	3
Rainfall	Wetter	Unchanged	Somewhat drier	Moderately drier	Significantly drier	2
SENSITIVITY						
Condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	1
Recruitment	All species recruiting	Most species recruiting	Some species recruiting	Just a few recruiting	No recruitment	1
Mortality	>25	15-25	10-15	5-10	<5	1
ADAPTIVE CAPACITY						
Community management capacity	Good	Fairly good	Moderate	Poor	None	4
Stakeholder involvement	Good	Fairly good	Moderate	Poor	None	3
Total						17

Table 12. Example of a simple vulnerability rating scale (color shades represent degree of vulnerability). Source: adapted from Marshall *et al.* (2013).

ADAPTIVE CAPACITY	**SENSITIVITY**		
	Low	Medium	High
High	Low	Low	Medium
Medium	Low	Medium	High
Low	Medium	High	Extreme

help determine 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 help define 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 the WIO region

Over the last 15 years in the WIO region there have been an increasing number of approaches and scopes aimed at assessing climate variability (Table 13).

Table 13. Examples of climate change vulnerability assessments conducted within the WIO region.

APPROACH AND SCOPE	DIMENSIONS OF VULNERABILITY CONSIDERED	SCALE OF DOCUMENTED OUTPUT	REFERENCE
Integrated approach; 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 were low in Mauritius and high in Kenya and Seychelles, respectively.	Cinner *et al.* (2012)
Integrated approach: focusing on 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)
Top-down approach: focused on identifying 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)
Top-down approach: focused on modelling the susceptibility of corals 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)
Bottom-up approach: to 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)
Integrated approach: apply a novel analytical framework that considers the interactions between adaptive capacity and environmental susceptibility to assess a range of conservation strategies.	Exposure and sdaptive capacity	Conservation strategies did not reflect adaptive capacity and are, therefore, ill prepared for climate change.	McClanahan *et al.* (2008)
Bottom-up approach: focused on 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 high exposure to climate variability and increased pressure on fisheries resources. In addition, artisanal fishing communities are characterized by low adaptation capacity.	Dzoga *et al.* (2018)

6. Challenges in undertaking CCVA

This section outlines some of the challenges in undertaking a CCVA. Undertaking a CCVA can be a challenging process primarily because:

a) The system under assessment is usually complex. Therefore, careful consideration of multiple risks, control variables and modulating influences is necessary.

b) There can be uncertainty when obtaining relevant data for different vulnerability drivers, including limited/unreliable data, unidentified or unknown interactions, with non-climate stressors, unidentified or unknown interactions among different elements of climate change and unidentified or unknown thresholds. Uncertainties make it difficult to establish baselines and validate proposed integrated vulnerability assessment frameworks and models. Uncertainty can be quantified by quantitative measures (e.g. a range of values calculated by various models) and/or by qualitative statements (e.g. reflecting the judgement of a team of experts)

c) CCVA can vary in scope and methodologies. The preference of these methodologies often depends on many factors like purpose, resource availability, timescale etc. For example, a seagrass ecologist may undertake a rapid vulnerability assessment by snorkeling over seagrass and using expert knowledge to rank different vulnerability dimensions using a rating scale.

d) Public perception and lack of political will. For example, lack of political will might be one of the primary factors characterizing weak governance in fisheries.

Plate 1. ?????????=?

7. Communicating CCVA results

To ensure that CCVA fulfils its purpose, communicating and reporting results should be a well-planned and integral part of the assessment process. This section provides suggestions about developing effective communication strategies for CCVAs and their results, by following the steps described below.

Step 1: Identify the target audience

Although a CCVA can often involve multiple stakeholders, communication products should be tightly targeted at specific audiences, potentially necessitating multiple products from a single assessment.

It is important to note that several different media and methods are often needed for effective communication, even for a single audience. This is almost always the case when addressing different audiences. In summary, targeting the identified audience necessitates tailoring methods, media, and content for the specific target group(s) by understanding biases and other concerns that the audience might have with a CCVA. For example, CCVA to support adaptation planning at the community level will require very different means of communication (e.g. community meetings) to CCVA to advance scientific knowledge (e.g. through scientific journals) and to those assessments to raise awareness at high policy levels (e.g. short briefs). Table 14 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.

Step 2: What to communicate

With a wide range of stakeholders, there is often a wide range of values, baseline knowledge, expectations and needs within and among audiences. Therefore, it is important to tailor the message in meaningful ways to the target audience's experience, values, and sphere of influence. Tailoring the message does not mean modifying the facts of climate change in any way, rather, it means considering the kind of knowledge the audience has, the information complexity that they are capable of understanding and the actions they are likely to take. In addition to describing the degree(s) of vulnerability of the assessed ecosystem, authors may wish to describe the methods used, data gaps encountered, and

Table 14. Examples of CCVA target audiences, the types of information they require, and some of the communication media 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 and 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); guideline 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

uncertainties associated with the results. For scientists and researchers, the details of complicated models may be appropriate.

In contrast, 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 valuable for developing adaptation strategies. Maps depicting these results should include a spatial context (political boundaries, roads, park boundaries and populated areas) that the audience can relate to.

Step 3: How to communicate

Authors need to think about how to communicate methods, results and uncertainties, and 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). Media such as brief reports, graphs and summary tables can quickly convey complexities that are hard to explain in other ways. It is important to pay attention to clear articulation of terms and avoidance of undefined acronyms or obscure technical jargon when writing.

Recently, social media has become increasingly useful for disseminating results to broad audiences. Twitter, Facebook, and Instagram posts that include striking images, graphs and videos, for instance, can direct audiences to more in-depth reports, briefing notes and media reports about vulnerability assessment results, while enabling the popularization of ideas that might otherwise be overlooked in decision-making processes.

It is important to be aware of the problems inherent in communicating CCVA results. Two kinds of content that need special attention are vulnerability and the associated uncertainty. Scientific uncertainty is vastly different to the common use of the term, and this point needs to be refreshed for certain audiences. Where possible it is important to quantify uncertainty and provide descriptions of what is known and what is uncertain. For example, there is no doubt that sea level will rise, but there is less certainty regarding its magnitude and which coasts will be impacted and when.

CCVA results should be communicated in a way that includes descriptions of the species, likelihoods of how those species or habitats may be affected, and the uncertainties regarding how a species will respond to new conditions where its preferred habitat(s) cannot be found. The uncertainty is not in the species' preferences, but in how the habitats will change and how the species will respond to a new climate. It may be helpful to emphasize what is known based on applied principles of ecology, physics and/or chemistry, with very little uncertainty, first and foremost.

8. Conclusions

Even best-case scenarios of climate mitigation suggest that climate change impacts are inevitable and will become the reality for centuries to come (for example, sea level rise in 2050 for as illustrated in Figure 10). Therefore, it is critical that strategies that can address vulnerability for coastal and marine social-ecosystems, including facilitating resilience and coping mechanisms, , are implemented. The approaches to CCVA described in this report are multidisciplinary and integrate biotic and abiotic factors. The procedural and methodological guide is presented as a step-by-step process. It integrates both the top-down approach involving analyses of climate data, and a more contextual bottom-up approach. It includes accurate and validated methods for determining ecological integrity and the extent and effect of human uses and impacts. It provides a baseline of indicators against which to monitor future change. Therefore, the *Toolkit* is a complete suite of necessary components for assessing the vulnerability of social-ecological systems. Adaptation and resilience-building require a suite of thoughtful, preventive actions, measures and investments that reduce the vulnerability of natural systems. One of the critical messages from this document is that conducting a CCVA should not be treated as a one-off exercise with an end point. An assessment as described in this report is only a starting point that should yield important yet provisional indications of climate change vulnerability and resilience. Much of the data and results obtained will effectively form no more than a baseline. Designing and establishing a long-term ongoing monitoring program, to continue observing and assessing the complex dynamics of climate change impacts should be an essential outcome of all CCVAs. As climate change vulnerability is dynamic in space and time, the effectiveness of this *Toolkit* as a decision support product can further be enhanced by integrating it in a dynamic environment. With advancement in technology, the *Toolkit* can be developed into a dynamic web-based tool with a functionality that allows scenarios of adaptation strategies to be tested. The *Toolkit* provides the background materials for such web-based product. Finally, capacity building is essential for an effective CCVA, such that every team member is conversant not only with the process but also with the envisaged outcomes.

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Annex

Table A. 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	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	Global	1901-2017	Temperature	0.5 degrees (~50km)	http://www.cru.uea.ac.uk/cru/data/hrg/
CRUTEM4	Global	1860-2019	Land air temperature anomalies	5 degrees (~500km)	https://crudata.uea.ac.uk/cru/data/temperature/
The Berkeley Earth Surface Temperatures	Global	1850-present	Land surface air temperature	1 degree (~100km)	http://berkeleyearth.org/data/
GISTEMP v4	Global	1880-present	- Surface air temperature - Land-ocean temperature	2 degrees (~200km)	https://data.giss.nasa.gov/gistemp/
Satellite remote-sensing data and derived indicators					
MODIS	Global	2002-present	- Land surface temperature - SST - Chlorophyll a	Varies depending on the 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)	Global	1985 -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	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

DATASET NAME	SPATIAL EXTENT	TEMPORAL EXTENT	VARIABLES/ EXPOSURE FACTORS	SPATIAL RESOLUTION	DATA AVAILABLE AT: (URL)
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/

Table B. Examples of other data sources important for CCVA.

DATASET NAME	SPATIAL EXTENT	DATA FORMAT	SPATIAL RESOLUTION	DATA AVAILABLE AT: (URL)
Species data				
Global Biodiversity Information Facility (GBIF)	Global	Point data		www.gbif.org
IUCN Red List Database	Global	Polygons		www.iucnredlist.org/technical-documents/spatial-data
Ecosystem				
WCMC (Coral, mangrove and seagrass)	Global	polygons	1km	https://data.unep-wcmc.org/datasets/1 https://data.unep-wcmc.org/datasets/4 https://data.unep-wcmc.org/datasets/7
Ecological data				
NASA (MODIS): Landcover	Global	Gridded		https://lpdaac.usgs.gov/data/get-started-data/collection-overview/
Sentinel (Landcover)	Africa	Gridded	20m	http://2016africalandcover20m.esrin.esa.int
MODIS (NDVI)	Global	Gridded	250m	https://modis.gsfc.nasa.gov/data/dataprod/mod13.php
Geomorphology				
SRTM (Elevation)	Global	Gridded	30m	
GEBCO (Bathymetry)	Global	Gridded	500m	https://www.gebco.net/data_and_products/gridded_bathymetry_data/

Case study 1.
Drivers and exposure of Mangroves to Environmental Change and the Implications for Management

Published as: Maina, J.M., Bosire, J.O., Kairo, J.G., Bandeira, S.O., Mangora, M.M., Macamo, C., Ralison, H. and Majambo, G. 2021. Identifying global and local drivers of change in mangrove cover and the implications for management. *Global Ecology and Biogeography*, 30(10): 2057-2069.

Mangrove forests are critical transitional forests between terrestrial and marine ecosystems. They fulfil important functions in providing wood, coastal protection, spawning and nursery grounds, and other habitat functions. Throughout the western Indian Ocean (WIO) countries, mangroves are under immense human-induced pressures, with over-exploitation of mangrove wood products, conversion of mangrove areas to other land uses, and pollution being the main pressures. These are compounded by climate change-induced pressures of elevated air temperatures, increased salinity, reduced freshwater input, increased intensity and frequency of storms, sea-level rise, and massive sedimentation due to increased precipitation.

This case study tries to elaborate and discuss ways to evaluate mangroves' exposure and sensitivity dimensions from multiple environmental and human pressures. Table A1 summarizes the approaches we used to assess mangrove vulnerability in the WIO region.

Step 1: establishing context

Activity 1: Objectives of the vulnerability assessment
The objective of this vulnerability assessment case study is to demonstrate how to evaluate the drivers of change of mangroves and their relative importance by applying established hypotheses on how mangroves are impacted by exposure to environmental stress.

Activity 2: Desktop searches

After setting up the objectives for mangrove assessment, we carried out literature to gather information on climatic and environmental variables important to mangroves.

Activity 3: Setting boundary

We focused the study on Kenya, Tanzania, Mozambique and Madagascar (Fig A1), which represents approximately 772,852 ha (~80 percent) of the total mangrove area in the WIO. This

Table A1. Summary of the components of a mangrove vulnerability assessment.

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

extent represents significant heterogeneity based on biophysical conditions, human impacts and management regimes. Consequently, the study extent was zoned into 38 geographical sectors based on biophysical conditions and in-country management unit regimes.

Step 2: Gather relevant data

After conducting literature review, relevant data and information were collected from different sources on natural resources (i.e. land-use intensity, sedimentation, geomorphological, sea-level trends, ecological conditions) and socio-economic variables (i.e. human pressure).

Step 3: Estimating exposure dimension

Activity 1: Exposure to land-use intensity

Exposure of mangroves to land use and erosion was estimated using:
Land development intensity (LDI) - LDI is a land-use based index for the 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). To compute LDI for the region, we downloaded watersheds from the Hydrosheds website and a 20 m grid land use data from http://2016africalandcover20m.esrin.esa.int.

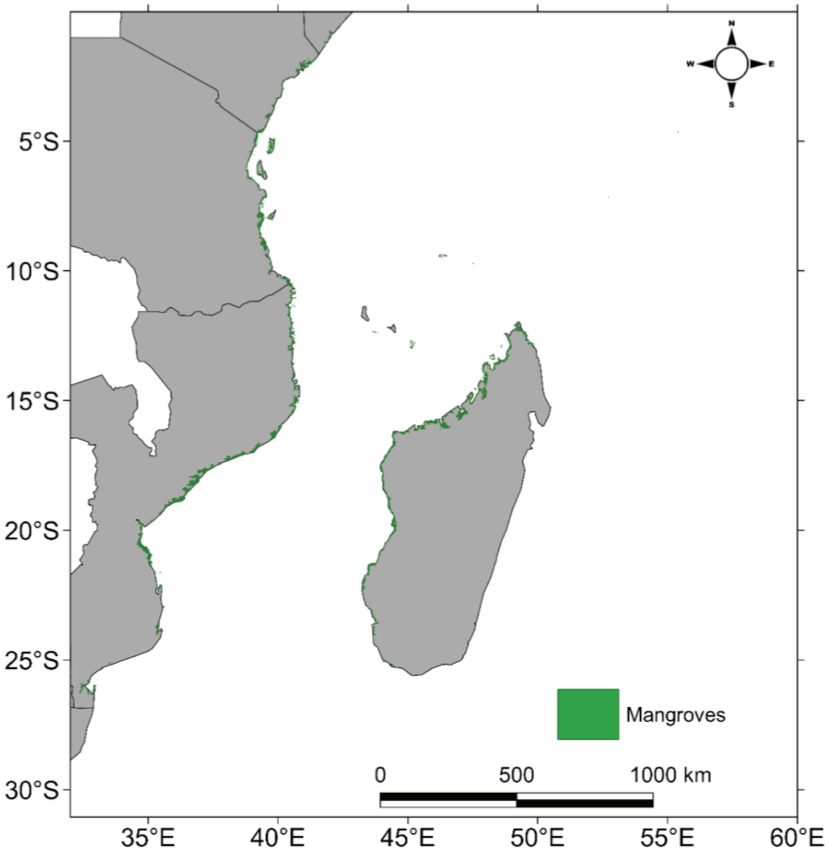

Figure A1. Mangrove distribution in coastal Kenya, Tanzania, Mozambique and Madagascar. Data source: Giri *et al*. (2011)compiled using disparate geospatial data sources and national statistics, need to be improved. Here, we mapped the status and distributions of global mangroves using recently available Global Land Survey (GLS.

Land use classes were harmonized with Brown and Vivas (2005) and assigned the LDI coefficients. An area-weighted LDI, as devised by Brown and Vivas (2005), was calculated using Equation 1

$$LDI_{watershed} = \Sigma(\%LU_i * LD_i) / 100 \qquad (1)$$

Watershed erosion - Watershed erosion data was downloaded from a recent high resolution (1 km grid) global estimates (Borrelli *et al.*, 2017) based on the Revised Universal Soil Loss Equation (RUSLE). RUSLE calculates sheet and rill erosion from rainfall and the associated runoff for a landscape unit (Nam *et al.*, 2003)landscape-scale estimates of carbon fluxes are uncertain and factors such as deforestation poorly resolved due to a lack of data. In this study, trends in vegetation cover and carbon for East Africa were quantified using moderate- resolution imaging spectroradiometer (MODIS.

To compute the partial exposure of mangroves to land-use intensity and erosion, LDI and soil erosion maps were standardized using the increasing min-max fuzzy function. The outputs were values between 0-1 where 0 in relative terms represents no exposure, and 1 indicated high exposure respectively to the conditions represented by respective layers. Standardized maps were then synthesized using a 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 the input layers A and B (An, 1991).

Activity 2: Exposure to human pressure

The human pressure index (HPI) was estimated using a mangrove accessibility map. Access to markets was used as a proxy for human impact on mangrove ecosystems. A map that quantifies the gravity at a spatial resolution of approximately one square kilometer was developed by integrating several data layers that characterize factors affecting human movement rates and urban centres or towns within an established geospatial-modelling framework. The gravity of the markets map for mangrove areas was standardized using a decreasing min-max fuzzy function to generate values between 0-1, representing low and high human pressure.

Activity 3: Exposure to geomorphology and sea-level rise

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

Activity 4: Exposure to inundation

The mangrove extent data and the elevation layers (from the digital elevation model) were used to calculate the average elevation at which mangroves are found and the standard deviation to determine the gradient of exposure of mangroves to flooding. These statistics were then utilized to calculate the threshold elevation of 21.11 m by adding the average to 2SD (8.89 + 2*6.11). This value was 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.

Activity 5: Exposure to climate extreme events

Here, we considered exposure pathways to include the physical exposure as represented by extreme temperature events). To analyze changes in the frequency of extreme temperature, we used a published database of historical and future climate indices computed using a consistent methodology across different modeled and observational data by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang *et al.*, 2011). ETCCDI has defined 21 indices that represent extreme events of temperature and rainfall as part of the efforts to facilitate the understanding of the observed and projected climate change (Sillmann *et al.*, 2013a & b). Among these, an air temperature index that represents extreme conditions/heatwaves, i.e. the exceedance in rates (%) above the 90 of temperature (TX90p) for the period 2050-2060, is used here for two climate change scenarios (RCP45 and RCP85).

Step 4: Estimating sensitivity dimension

To estimate the sensitivity of mangroves to climate and environmental changes, we used normalized difference vegetation index (NDVI) from MODIS 13 NDVI product of 16-day composites at 250 m resolution obtained for the years from 2000 to June 2017. The data was pre-processed and clipped to the mangrove extent to calculate the monthly and yearly averages. Statistical summaries were computed for each month and for the entire time series. We then used the maximum and minimum NDVI values to calculate the Vegetation Condition Index (VCI) using equation 2:

$$VCI = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \qquad (2)$$

Step 5: Estimating Adaptive Capacity dimension

Land transgression - Slope and land use type are some of the main factors affecting mangrove transgression. Hence, we utilized the slope layer and land use map to define land suitability to mangrove transgression. Using the slope layer and the mangrove extent layer, we calculated the optimal slope for mangroves by adding the mean of the slope of all areas where mangroves are found to be twice the standard deviation. We then applied the increasing min-max function to standardize the slope layer to values between 0 and 1. Further, we computed the suitability of the land area for the landward transgression by mangroves using a land-use map reclassified to 0 (land uses which would obstruct mangrove transgression) and 1 (land-use types that would favour transgression). The land-use layer was first reclassified using a mask cropland map whereby all areas in the crop layer that had pixels with greater than 60% cultivation were used to assign cropland in the land-use layer. The modified land-use layer was then re-classed, with urban/artificial area assigned 0 (not favourable to mangrove transgression). At the same time, cropland, bare areas, forests and areas with permanently or semi-permanently submerged vegetation were classified as 1.

Step 6: synthesis and evaluation

Having explored and established exposure, sensitivity and adaptive capacity dimensions, we applied geostatistical techniques with all the partial exposure data as the input to generate the overall mangrove vulnerability index for mangroves in the WIO. Here, we performed Spatial Principal Component Analysis (SPCA) (Li *et al.*, 2006) using the standardized layers as input. PCA involves calculations of eigenvalues and their corresponding eigenvectors of the covariance matrix to derive the new variables in decreasing order of importance in explaining the variation of the original variables (Tran et al., 2002). The outputs are uncorrelated bands and a report showing the proportion of the variance explained by each band. The first few components (PC's) often explain the bulk of the variance. It is often possible to ascribe meaning to what the trends represent by analyzing the factor loadings in each PC (Jackson, 2003). These proportions of explained variance by each PC were then used as weights in a weighted sum overlay of the PC layers to yield one map which incorporates all the elements of exposure considered. The final vulnerability map was summarized by sectors (mean and SD).

Results

Partial exposures

Exposure maps from the eight variables considered (S1 and S2) indicate variability within and among the mangrove sectors (Table 3 and 4). The partial exposure was highly variable spatially, with differential exposure to stressors. Human pressure is highest in the southern parts of Tanzania and Northern Mozambique, while the lowest values were recorded in Southern Mozambique. The exposure to sea-level rise indicates a north-south latitudinal gradient, with sectors in the north less exposed than sectors in the south.

Exposure composite

The principal component analysis outputs (Table A1) indicate that PCs 1, 2 and 3 explained most of the variance (46 percent,14 percent and 13 percent, respectively) in East Africa. Dominant variables in PC1 were **climate change (+ve), inundation (-ve)**, and **SLA (-ve)**. The same factors were also prominent in PCs 2 and 3 with SLA and climate and SLA and slope being dominant (+ve) in PCs 2 and 3. For Madagascar, LDI was the dominant contributor to PC1 (42 percent), while slope was dominant in PC2 (28 percent). Inundation and SLA were negatively correlated to mangrove conditions in PC3 (12 percent), where they dominated.

Table A1. SPCA output showing the principal component's factor loadings and contribution ratios.

		PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
	Contribution ratio	**0.56**	**0.15**	**0.14**	**0.08**	**0.03**	**0.02**	**0.02**	**0.00**
East Africa	**Factor loadings**								
	Climate (future)	0.56	-0.29	-0.73	0.22	-0.01	0.13	0.01	0.00
	Gravity of Market	0.09	0.01	0.11	0.05	0.17	0.10	0.97	0.00
	Inundation	-0.54	-0.07	-0.15	0.82	0.02	-0.03	0.03	0.00
	LDI	0.04	0.03	0.21	0.11	-0.57	0.79	-0.01	0.00
	Land-use	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
	VCI	0.02	-0.07	-0.06	-0.02	-0.80	-0.56	0.20	0.00
	SLA	-0.62	-0.23	-0.49	-0.51	-0.06	0.20	0.13	0.00
	Slope	-0.02	0.92	-0.38	-0.01	-0.06	0.03	0.05	0.00
	Contribution ratio	**0.42**	**0.27**	**0.15**	**0.06**	**0.04**	**0.04**	**0.01**	**0.00**
Madagascar	**Factor loadings**								
	Climate (future)	0.05	0.18	-0.06	0.03	-0.18	0.01	0.15	0.95
	Gravity of Market	0.03	0.11	-0.08	0.01	0.12	0.02	-0.97	0.15
	Inundation	-0.06	-0.32	0.57	-0.37	-0.54	-0.33	-0.16	0.04
	LDI	-0.02	0.05	-0.13	0.20	-0.69	0.66	-0.08	-0.15
	Landuse	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
	VCI	-0.12	0.14	0.17	-0.74	0.28	0.55	0.04	0.06
	SLA	-0.26	-0.80	0.09	0.25	0.26	0.31	-0.04	0.21
	Slope	0.92	-0.13	0.29	0.08	0.11	0.19	0.01	0.01

Table A2. Statistical exposure indices for the variables considered and the final vulnerability estimates, summarised by sectors

		CLIMATE HISTORICAL		CLIMATE FUTURE		GRAVITY OF MARKETS		LANDUSE		LDI & EROSION		VCI		SLA		INUNDATION		SLOPE		VULNERABILITY INDEX	
		X	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**
Kenya	Lamu	0.9	0.0	1.0	0.0	0.1	0.0	0.0	0.2	0.8	0.0	0.5	0.6	0.1	0.0	0.8	0.1	0.5	0.2	0.3	0.1
	Kipini	0.9	0.0	0.9	0.0	0.2	0.1	0.0	0.2	0.6	0.0	0.6	0.6	0.1	0.0	0.8	0.1	0.5	0.2	0.3	0.1
	Mida Creek	0.8	0.0	0.9	0.0	0.3	0.0	0.0	0.1	0.7	0.1	0.3	0.6	0.1	0.0	0.7	0.1	0.4	0.2	0.3	0.1
	Kilifi	0.8	0.0	0.8	0.0	0.5	0.1	0.1	0.3	0.6	0.1	0.7	0.6	0.1	0.0	0.4	0.7	1.0	0.8	0.3	0.1
	Mombasa	0.8	0.0	0.8	0.0	0.5	0.1	0.0	0.2	0.7	0.0	0.8	0.5	0.1	0.0	0.7	0.2	0.4	0.3	0.2	0.1
	Southern	0.8	0.0	0.8	0.0	0.3	0.1	0.0	0.2	0.8	0.1	0.4	0.5	0.1	0.0	0.7	0.1	0.5	0.2	0.4	0.1
Tanzania	Pemba	0.8	0.0	0.9	0.0	0.2	0.1	0.1	0.3	0.7	0.1	0.6	0.1	0.1	0.0	0.6	0.2	0.5	0.3	0.3	0.1
	Mkinga	0.7	0.0	0.7	0.0	0.2	0.0	0.0	0.2	0.7	0.1	0.6	0.1	0.2	0.0	0.4	0.1	0.6	0.3	0.4	0.1
	Tanga	0.7	0.0	0.7	0.0	0.3	0.1	0.1	0.2	0.8	0.1	0.6	0.1	0.1	0.0	0.1	0.1	0.4	0.2	0.4	0.1
	Unguja	0.8	0.0	0.8	0.0	0.3	0.0	0.0	0.2	0.7	0.0	0.6	0.1	0.0	0.0	0.3	0.1	0.5	0.2	0.4	0.1
	Pangani	0.7	0.0	0.8	0.0	0.3	0.0	0.0	0.1	0.8	0.0	0.5	0.1	0.0	0.0	0.2	0.1	0.5	0.2	0.3	0.1
	Bagamoyo	0.8	0.0	0.7	0.0	0.3	0.1	0.1	0.3	0.8	0.0	0.6	0.1	0.1	0.0	0.2	0.2	0.5	0.2	0.3	0.1
	Dar-es-Salaam	0.8	0.0	0.8	0.0	0.1	0.0	0.0	0.1	0.9	0.0	0.6	0.1	0.1	0.0	0.3	0.1	0.5	0.2	0.4	0.1
	Mkuranga	0.8	0.0	0.8	0.0	0.1	0.0	0.0	0.1	0.9	0.1	0.6	0.1	0.1	0.0	0.3	0.1	0.5	0.2	0.3	0.1
	Rufiji	0.7	0.0	0.8	0.0	0.1	0.0	0.0	0.1	0.5	0.1	0.6	0.1	0.0	0.0	0.0	0.1	0.5	0.2	0.5	0.1
	Mafia Island	0.8	0.0	0.9	0.0	0.0	0.0	0.0	0.2	0.9	0.0	0.6	0.1	0.0	0.0	0.1	0.3	0.6	0.4	0.4	0.1
	Kilwa	0.7	0.0	0.9	0.0	0.1	0.0	0.0	0.2	0.7	0.0	0.6	0.1	0.2	0.0	0.0	0.1	0.5	0.2	0.4	0.2
	Lindi	0.8	0.0	0.9	0.0	0.2	0.1	0.1	0.2	0.9	0.0	0.7	0.1	0.2	0.0	0.4	0.2	0.6	0.3	0.5	0.1
	Mtwara	0.7	0.0	0.9	0.0	0.2	0.1	0.0	0.2	0.9	0.1	0.6	0.1	0.1	0.0	0.5	0.1	0.5	0.2	0.4	0.1

		CLIMATE HISTORICAL		CLIMATE FUTURE		GRAVITY OF MARKETS		LANDUSE		LDI & EROSION		VCI		SLA		INUNDATION		SLOPE		VULNERABILITY INDEX	
		X	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**
Mozambique	North	0.8	0.0	0.9	0.0	0.1	0.1	0.0	0.2	0.9	0.0	0.7	0.1	0.1	0.0	0.3	0.1	0.5	0.3	0.5	0.1
	Rovuma	0.9	0.0	0.9	0.0	0.1	0.0	0.1	0.2	0.7	0.1	0.7	0.1	0.1	0.0	0.3	0.1	0.4	0.2	0.4	0.1
	Pemba	0.8	0.0	0.9	0.0	0.2	0.1	0.0	0.1	0.7	0.0	0.6	0.1	0.1	0.0	0.3	0.1	0.4	0.2	0.5	0.1
	Nacala	0.7	0.0	0.9	0.0	0.2	0.1	0.0	0.2	0.9	0.0	0.6	0.1	0.3	0.1	0.4	0.1	0.4	0.2	0.4	0.1
	Moz Island	0.5	0.0	0.7	0.1	0.1	0.0	0.0	0.1	0.6	0.1	0.6	0.1	0.7	0.0	0.6	0.1	0.5	0.2	0.6	0.1
	Angoche	0.7	0.0	0.9	0.0	0.2	0.1	0.0	0.2	0.8	0.0	0.6	0.1	0.6	0.1	0.5	0.1	0.4	0.2	0.5	0.1
	Central	0.4	0.0	0.5	0.1	0.0	0.0	0.0	0.2	0.9	0.0	0.6	0.1	0.4	0.1	0.7	0.1	0.4	0.2	0.6	0.1
	Bons Sinais	0.4	0.0	0.4	0.0	0.1	0.1	0.0	0.1	0.8	0.0	0.6	0.1	0.7	0.0	0.7	0.1	0.5	0.2	0.6	0.1
	Zambezi Delta	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.1	0.7	0.1	0.6	0.1	0.6	0.0	0.8	0.1	0.5	0.2	0.7	0.1
	Buzi-Savane	0.3	0.0	0.3	0.0	0.1	0.1	0.1	0.2	0.7	0.3	0.7	0.1	0.3	0.0	0.8	0.1	0.5	0.3	0.6	0.1
	Bazaruto	0.4	0.0	0.6	0.0	0.1	0.0	0.0	0.1	0.6	0.0	0.6	0.1	0.5	0.0	0.7	0.1	0.4	0.2	0.7	0.1
	Pomene	0.4	0.0	0.6	0.0	0.1	0.0	0.0	0.1	0.9	0.0	0.6	0.1	0.4	0.0	0.8	0.1	0.5	0.2	0.6	0.1
	Inhambane	0.4	0.0	0.5	0.0	0.3	0.1	0.0	0.1	0.6	0.1	0.6	0.1	0.3	0.0	0.7	0.1	0.4	0.2	0.6	0.1
	Limpopo	0.2	0.0	0.0	0.0	0.1	0.0	0.1	0.3	0.5	0.1	0.5	0.1	0.5	0.0	0.8	0.1	0.6	0.3	0.6	0.2
	Maputo Bay	0.2	0.0	0.2	0.0	0.2	0.1	0.0	0.2	0.6	0.1	0.7	0.1	0.5	0.0	0.6	0.1	0.5	0.2	0.6	0.1
Madagascar	North	0.8	0.1	1.0	0.0	0.1	0.1	0.0	0.2	0.5	0.1	0.6	0.1	0.5	0.1	0.5	0.1	0.5	0.2	0.5	0.0
	North-west	0.7	0.0	1.0	0.0	0.0	0.0	0.0	0.2	0.6	0.1	0.6	0.1	0.6	0.0	0.6	0.1	0.5	0.2	0.5	0.0
	West	0.7	0.1	0.9	0.0	0.0	0.0	0.1	0.3	0.5	0.1	0.6	0.1	0.8	0.1	0.7	0.1	0.5	0.3	0.5	0.0
	South-west	0.6	0.0	0.8	0.1	0.0	0.1	0.1	0.2	0.9	0.0	0.6	0.1	1.0	0.0	0.7	0.1	0.5	0.2	0.5	0.0

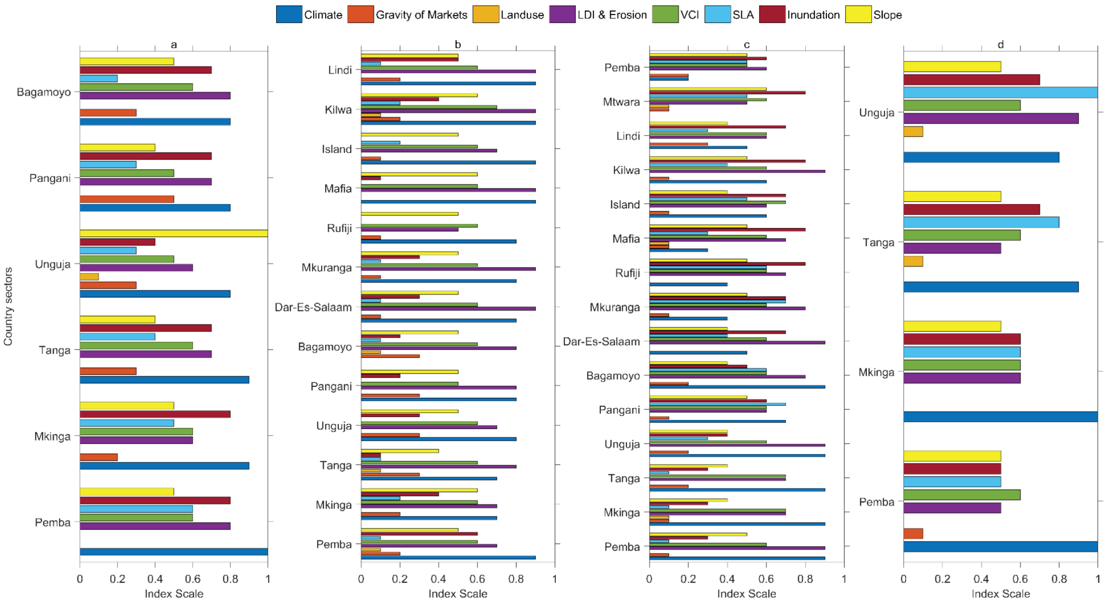

Figure A2. Exposure indices for the different variables for a) the Kenya sectors, b) the Tanzania sectors, c) the Mozambique sectors and d) the Madagascar sectors.

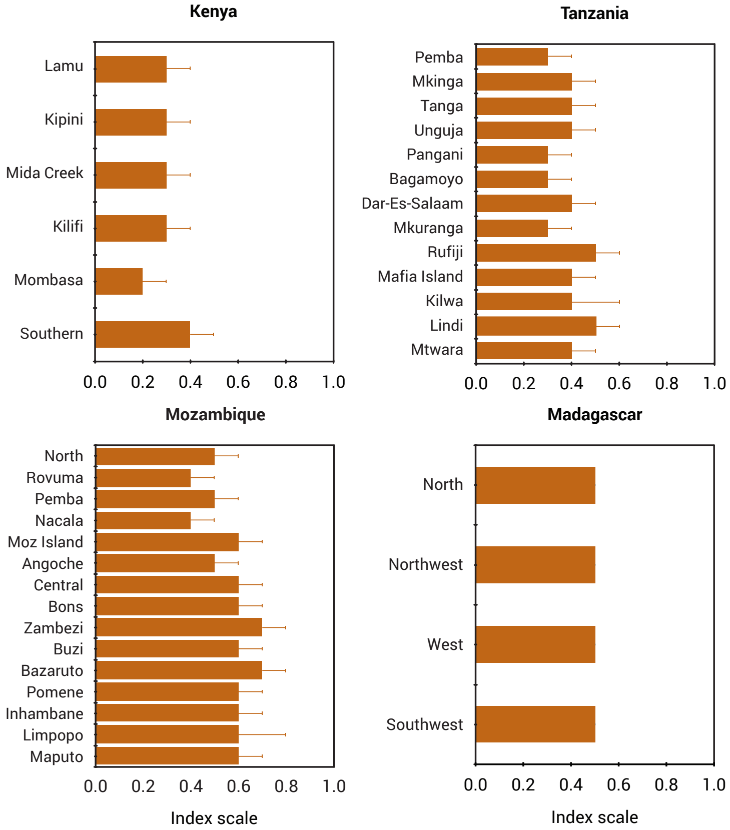

Figure A3. Vulnerability indices for different countries by sector.

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Case study 2.
Exposure of coral reefs to Environmental Change and the Implications for Management

Coral reefs are the world's most diverse marine ecosystems and are critical for the livelihoods of millions of people who depend on them. Despite this, the health of many coral reefs has declined for decades due to elevated temperatures causing frequent bleaching events and mortality. The fourth Intergovernmental Panel on Climate Change (IPCC) assessment states "Corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of about 1–3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless there is thermal adaptation or acclimatization by corals." The IPCC listed the following changes as pertinent to coral reefs:

- Rising sea surface temperatures;
- Increasing concentrations of CO2 in seawater;
- Sea level rise;
- Possible shifting of ocean currents;
- Associated rises in UV concentrations; and
- Increases in hurricanes and cyclonic storms.

Coral reefs exposed to elevated SST exceeding the summer maximum by more than 1°C for 4 weeks results in coral bleaching. The third global coral bleaching event, which started in 2014 extended well into 2017, was the longest coral bleaching event on record. The length of the event means corals in some parts of the world had no time to recover in 2014 or 2015 during the cool/winter season, prior to experiencing bleaching the following year. With widespread and severe coral bleaching events already becoming more common, and the challenge for reef management in deciding where to target actions to reduce anthropogenic stress, this case study summarizes and elaborate some of the methods used to assess coral reef exposure to elevated SST. 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).

Step 1: establishing context

Activity 1: Objectives of the vulnerability assessment

The objective of this vulnerability assessment case study is to demonstrate how to evaluate the exposure of coral reef to sea surface temperatures by applying established methods on how coral reefs in the region are impacted by environmental stress.

Activity 2: Desktop searches

After setting-up the objectives for coral reef assessment, we carried out literature to gather information on important climate indicators to coral reefs. Spatial and temporal predictions of coral bleaching under varying environmental conditions could therefore provide valuable information to support local management of coral reefs.

Activity 3: Setting boundary

The case study focused on the WIO region where coral bleaching has been observed since 1982 with the frequency and severity of bleaching projected to increase under global warming.

Step 2: Gather relevant data

Useful data and information were collected from different sources after conducting literature review. We used the global Coral Reef

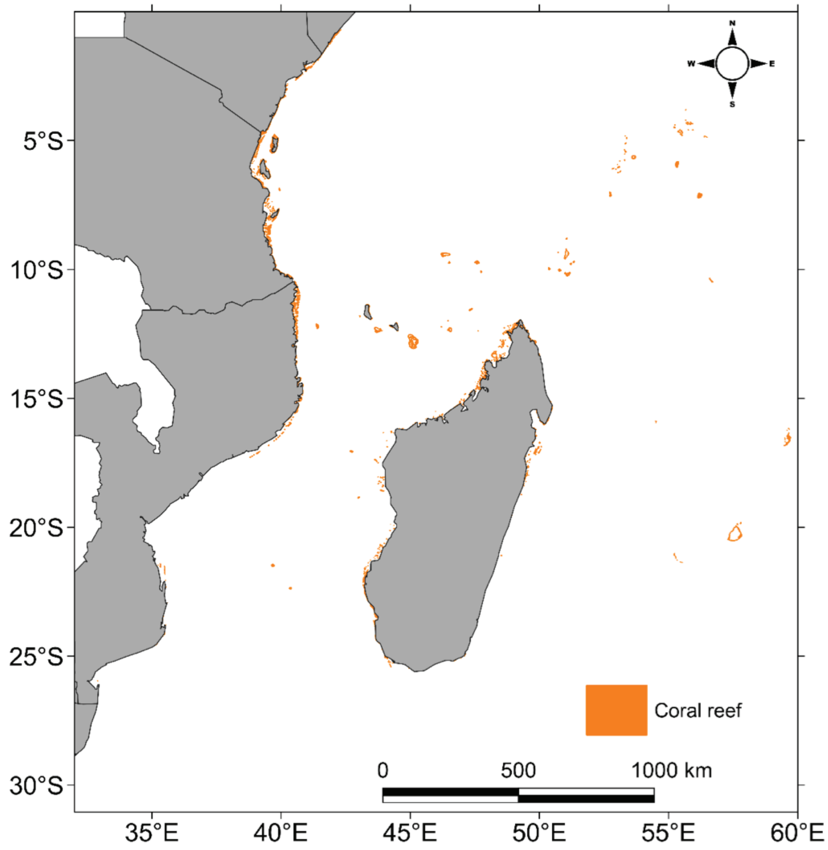

Figure A1. Coral reef distribution in the western Indian Ocean. Data source: UNEP-WCMC.

Temperature Anomaly Database (CoRTAD Version 6) from the National Oceanic and Atmospheric Administration (www.nodc.noaa.gov/sog/cortad/) to calculate thermals indices and assess coral bleaching prevalence. All CoRTAD variables were weekly data provided on a grid cell basis, of ~4 km resolution, from 1982 to 2017.

To assess exposure of coral reefs to future thermal stress, we used monthly simulated SST data for the Relative Concentration Pathway experiments (RCP 4.5 and RCP8.5) conducted for the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Moss *et al.*, 2010). The CMIP5 data are archived and are made freely available by the Program for Climate Model 102 Diagnosis and Inter-comparison (PCMDI) at http://pcmdi3.llnl.gov/esgcet/home.htm.

Step 3: Evaluating exposure dimension

To evaluate coral reef exposure to environmental stress, several thermal indices were calculated

Activity 1: Trends (SST rates of change)

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

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

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

Activity 2: Calculating sea surface temperature climatology (long-term average conditions)

Evaluating areas at risk of bleaching, used 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 (Liu *et al*., 2014; Liu *et al*., 2003).

Activity 3: Calculating 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 the anomaly is:

$$\text{SST\_anomaly} = \text{SST} - \text{climatology} \qquad (2)$$

Activity 4: Estimating 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; Strong *et al*., 2004) has been widely used to predict coral bleaching. Glynn and D'Croz, (1990)a major reef-building coral in the tropical eastern Pacific, resulted in loss of zooxanthellae, histopathological abnormalities, and mortality similar to that observed during the severe 1982–83 El Niño-Southern Oscillation (ENSO 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:

$$\boldsymbol{DHW}=\frac{1}{7}\sum_{i=1}^{84}\boldsymbol{HS}_i\ \boldsymbol{ifHS}_i \geq 1^{\circ}\mathrm{C} \qquad (3)$$

Activity 5: Estimating future bleaching scenarios

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 was 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*., 2014; Van Hooidonk *et al*., 2016) over a four-month rolling window (Donner, 2009) using the formulae below:

$$\boldsymbol{DHW}=\sum_{i=1}^{12}\boldsymbol{HS}_i\ \boldsymbol{ifHS}_i \geq 1^{\circ}\mathrm{C} \qquad (4)$$

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 *et al.*, 2005; Van Hooidonk *et al.*, 2016).

Activity 6: Estimating stress frequency

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

Results

Annual SST trend

Annual averaged reef SSTs warmed an average of 0.14°C/decade during the study period with nearly 85% (1961 pixels) showing a positive trend above 0.1°C/decade while 3% of reef locations showed 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 warm 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.

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

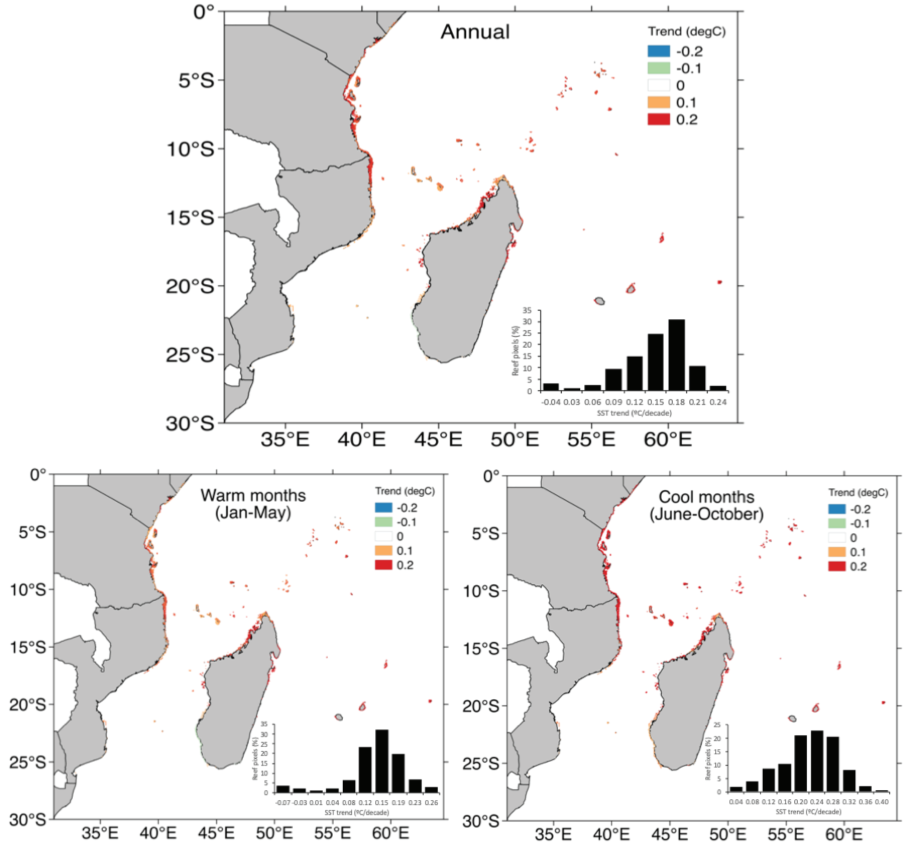

Figure A2. Trends in annual sea temperature at reef scale calculated from NOAA coral reef SST (1985-2017) for warm months (Jan-May) and cool months (June-October). The trend values are in °C/decade and the histograms show the distribution of SST trend in the region.

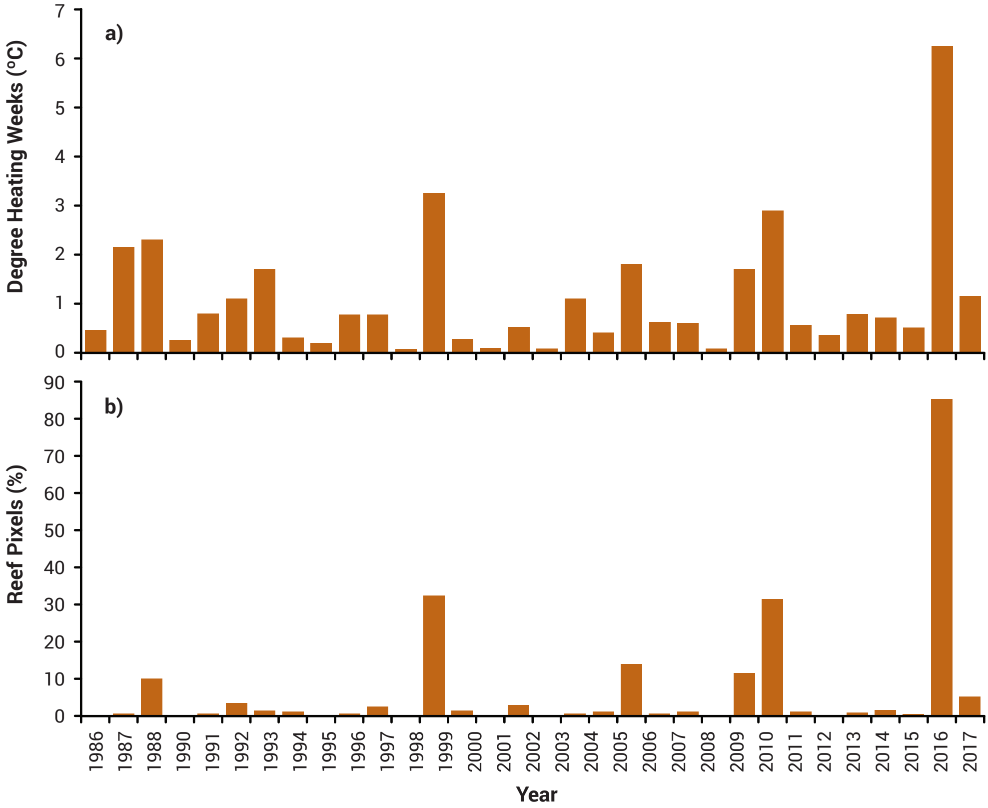

Figure A3. a) Histogram of accumulated heat stress defined as Degree Heating Weeks from 1986-2017, (b) frequency of bleaching level thermal stress defined as DHW ≥ 4 °C-weeks showing the average percentage of reef pixels affected by bleaching-level thermal stress.

Future bleaching scenarios

Coral reef futures vary greatly among countries in the WIO for the two RCPs. Coral reef climate losers and winners occur in almost all countries in the region; however, some countries have more climate winners than others. For example, majority of coral reefs in East Africa 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.

Conclusion

In summary, the analysis of thermal history and projections at regional coral reef locations revealed warming at almost all reefs in recent decades; summertime temperature increased through the record at the great majority of reefs. Results from 1987–2017 show that warming of coral reef waters was distinctly higher than that reported for ocean waters in general with ~90% of reef pixels warmed through this period. Faster warming in cooler seasons (June-October) than in warmer seasons (January-May) mean that coral reefs have less of a reprieve from warm-season stress, which can enhance disease outbreaks. In contrast, reefs experiencing more rapid warming of their warm seasons may experience increased bleaching and infectious disease.

Under RCP8.5, severe bleaching is projected to occur within this century for most coral reefs in the WIO region. Therefore, a combination of greenhouse gas emission and improved coral reef management will be required to avoid the degradation of coral reef ecosystem from frequent mass coral bleaching events.

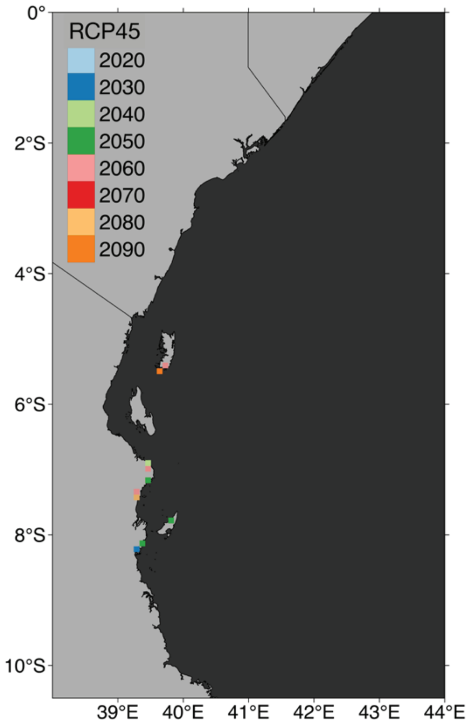

Figure A4. East Africa: Statistically downscaled projections of the timing of the onset of severe bleaching conditions defined as exceedance of DHM > 2 under RCP4.5 and RCP8.5

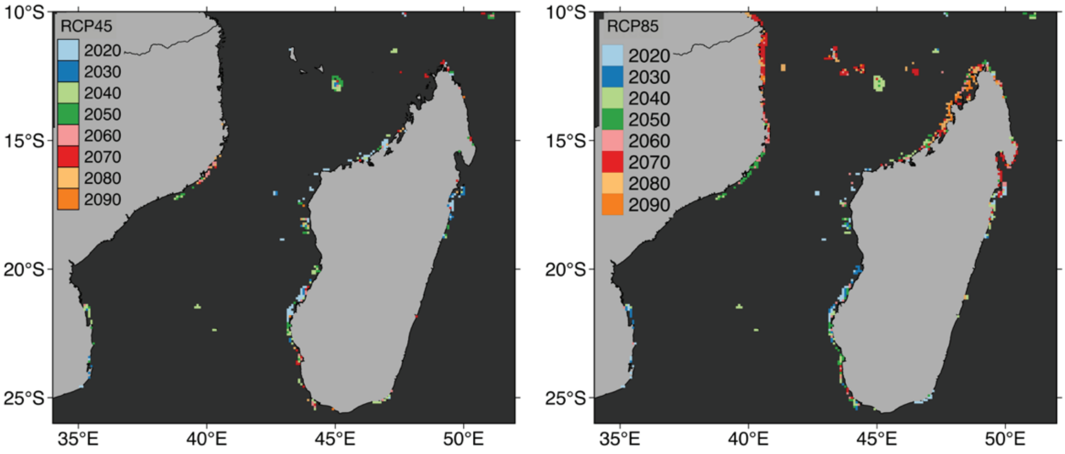

Figure A5. Mozambique, Comoros, and Madagascar: Statistically downscaled projections of the timing of the onset of severe bleaching conditions defined as exceedance of DHM > 2 under RCP4.5 and RCP8.5

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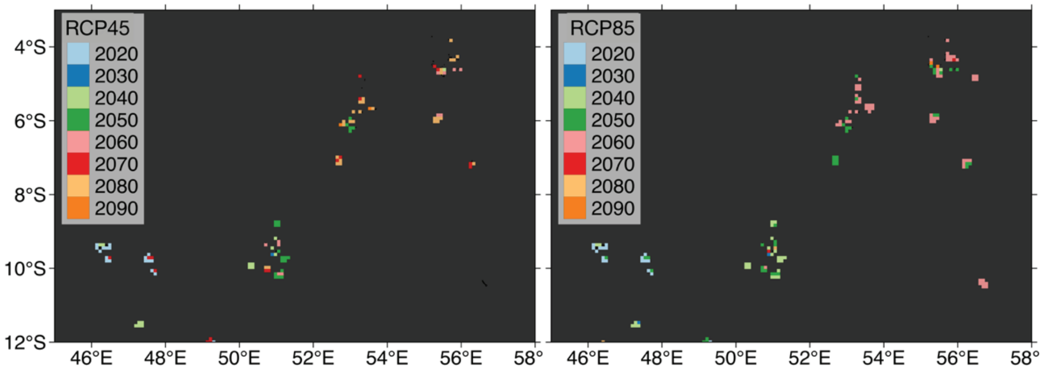

Figure A6. Seychelles: Statistically downscaled projections of the timing of the onset of severe bleaching conditions defined as exceedance of DHM > 2 under RCP4.5 and RCP8.5

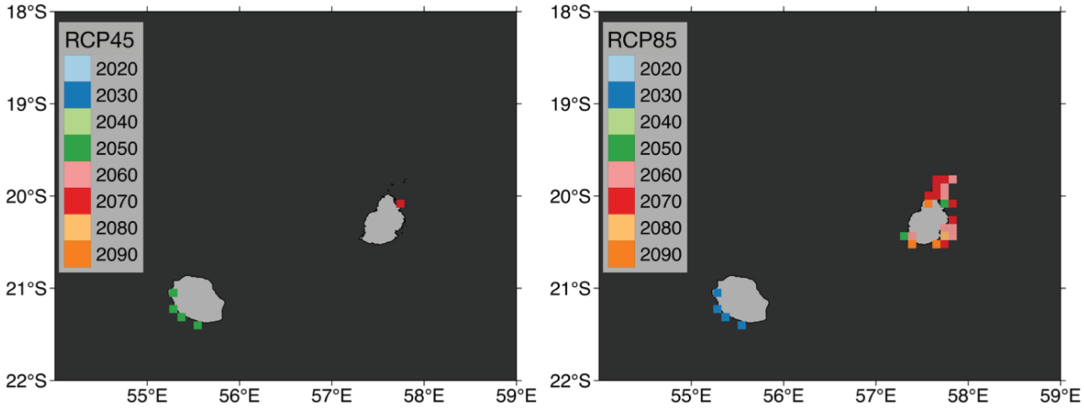

Figure A7. Mauritius: Statistically downscaled projections of the timing of the onset of severe bleaching conditions defined as exceedance of DHM > 2 under RCP4.5 and RCP8.5

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The Nairobi Convention through the GEF-funded project, Implementation of the Strategic Action Programme for the protection of the Western Indian Ocean from land-based sources and activities (WIOSAP), in collaboration with WIOMSA, are facilitating the production of a series of regional Guidelines. The first three volumes are on Seagrass Ecosystem Restoration, Mangrove Ecosystem Restoration and Assessment of Environmental Flows in the WIO Region.

The participating countries in the WIOSAP include Comoros, Madagascar, Mauritius, Seychelles, Mozambique, Kenya, Tanzania, France (not a beneficiary of GEF funds), Somalia and South Africa. The Goal of the WIOSAP is to: 'Improve and maintain the environmental health of the region's coastal and marine ecosystems through improved management of land-based stresses'. The specific objective of the WIOSAP is 'To reduce impacts from land-based sources and activities and sustainably manage critical coastal-riverine ecosystems through the implementation of the WIOSAP priorities with the support of partnerships at national and regional levels.'