UNIVERSITY OF NAIROBI

EFFECTS OF CLIMATE CHANGE ON THE KENYAN CORAL REEF ECO-SYSTEM

BY

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DECLARATION

I affirm that this dissertation is my authentic work. It has not been presented anywhere else for examination or for the award of a degree or publication. In areas where the work of other people has been utilized, proper accreditation has been made and referenced in compliance with the University of Nairobi's guidelines.

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DEDICATION

This dissertation is dedicated to the Lord Almighty and to my family; my husband, Eng. Wesley Magero, my two lovely babies and my parents Mr. and Mrs. Ogali for their steadfast support and encouragement throughout my studies.

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ABSTRACT

The coral reef ecosystem is a natural habitat for many marine organisms that has high economic and tourist significance. Nonetheless, this ecosystem has very low tolerance to the effects of changes brought about by increasing sea surface temperatures and ocean acidification. This study sought to investigate the combined effect of rising sea surface temperatures and ocean acidification on the Kenyan coral reef ecosystem. This was achieved by determining the spatial-temporal variability of sea surface temperatures; evaluating the spatial-temporal variability of ocean acidification over the Kenyan coastline; and simulating the combined effect of sea surface temperature increases and ocean acidification on the coral reef ecosystem.

Historical (2000-2021) data on sea surface temperature (SSTs) was obtained from National Oceanic and Atmospheric Administration (NOAA) and data on dissolved total carbon dioxide (TCO_2) and pH from Global Ocean Data Analysis Project (GLODAP). Future (2022-2081) sea surface temperature and dissolved carbon dioxide data was downloaded from Coupled Model Intercomparison Project (CMIP6) experiment for two Shared Socioeconomic Pathways (SSPs) namely SSP2-4.5 and SSP5-8.5. Statistical, graphical and model simulations analyses were applied in the study to investigate the combined effect of increasing SST and ocean acidification on coral reef ecosystem over the Kenyan coastline.

Results indicate that mean sea surface temperature and dissolved carbon dioxide along the Kenyan coastline varied with seasons and had increased between the years 2000-2021. Trend tests of SSTs and TCO_2 revealed a significant upward trend at 5% level of significance. Rising SSTs led to bleaching in coral reefs along this coastline whereas TCO_2 led to reduced amount of carbonate ion concentration and reduced pH in the sea surface waters which affected the rates of calcification and survival of the coral reefs. The results of the Combined Mortality and Bleaching Output model simulation revealed that bleaching and ocean acidification had negatively affected the coral reef cover resulting in a decline of more than 30% of cover between 2000 and 2021. The results of the simulation also projected that the coral reef cover will continue to decline further in the future short-term (2022-2041), mid-term (2042-2061) and the long-term (2062-2081) under the two climate scenarios. The results indicated that the ecosystem will decline in the long-term by 52% under SSP2-4.5 and 63% under SSP5-8.5 if the trends in SSTs and TCO_2 are maintained.

This study recommends collaborative implementation of climate change policies and practices by national and regional governments, communities and policy makers; enhanced efforts by coastal county governments in Kenya and research organizations to expound on scientific knowledge base while simultaneously implementing sustainable targeted solutions to ensure that the socio-economic benefits of the coral reef ecosystem are sustained.

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LIST OF ACRONYMS AND ABBREVIATIONS

AR5	:	Fifth Assessment Report of the IPCC
AR6	:	Sixth Assessment Report of the IPCC
CMIP6	:	Coupled Model Intercomparison Project cycle 6 experiment
CO_2	:	Carbon dioxide
CO_3^{2-}	:	Carbonate ion
COMBO	:	Coral Mortality and Bleaching Output Model
CORDIO	:	Coastal Oceans Research and Development-Indian Ocean
CRW	:	Coral Reef Watch
GHGs	:	Greenhouse gases
GLODAP	:	Global Ocean Data Analysis Project
H^+	:	Hydrogen ion
H_2CO_3	:	Carbonic acid
HCO_3^-	:	Bicarbonate ion
IPCC	:	Intergovernmental Panel on Climate Change
IUCN	:	International Union for Conservation of Nature
KEMFRI	:	Kenya Marine and Fisheries Research Institute
MK	:	Mann-Kendall
NASA	:	National Aeronautics and Space Administration
NOAA	:	National Oceanic and Atmospheric Administration
OA	:	Ocean Acidification
pH	:	Potential of Hydrogen
SDGs	:	Sustainable Development Goals
SROCC	:	Special Report on Oceans and Cryosphere
SSPs	:	Shared Socio-economic Pathways
SSTs	:	Sea Surface Temperatures
TCO_2	:	Total dissolved carbon dioxide
UN	:	United Nations
UNECA	:	United Nations Economic Commission for Africa
UNEP	:	United Nations Environmental Programme
WIO	:	Western Indian Ocean
WRI	:	World Resources Institute
Ωa	:	Aragonite saturation state

DEFINITION OF TECHNICAL TERMS

Corals: These are underwater structures made up of stacks of calcium carbonate that has been excreted through time by multitudes of polyps (Leal *et al.,* 2017). The polyps vary in size and live in a symbiotic relationship with an algae host referred to as zooxanthellae which gives the coral its color. Corals occur in two types i.e., hard corals (Scleractinia) such as brain and star corals and soft corals (Gorgonians) such as sea fans and sea whips.

Coral reefs: They are made up of both soft and hard corals together with other animals such as crustaceans, fish, sponges, mollusks and sea turtles among others that are all competing for resources such as food, light and space (Keith *et al.*, 2014). The components of the coral reef are dependent and are connected with other organisms, animals and plants. Thus, variations in the plenitude of one species drastically alters the abundance and diversity of the others.

Coral reef ecosystem: This is a type of marine ecosystem that is formed by the coral reefs, the living organisms within the reefs and their abutting marine and terrestrial environment (Kleypas, 2019). Mangrove forests and sea grass beds are an important facet of the coral reef ecosystem.

Mangroves: These are trees that grow along the coastlines of tropical and sub-tropical coasts (Makoye and Kaaya, 2018). Their complex root systems aid in stabilization of shorelines and help to filter out pollutants while producing nutrients. Their roots are submerged in water and act as breeding, nursery and feeding grounds for some marine life.

Sea grasses: These are flowering vegetation which form the link between mangrove habitats and coral reefs (Kleypas, 2019). They shape the food web foundation and provide nutrients; protection and shelter of sea fishes. They also help to filter the water columns, prevent seabed erosion, and release oxygen that is essential for most marine life.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

The coral reef ecosystem is a diversified ecosystem extending from the mid –latitudes and the tropical regions to even higher latitude cold waters (Albright *et al.,* 2016). It serves as a living shelter for marine organisms like invertebrates and fishes who utilize them as nursery grounds (Makoye and Kaaya, 2018), they help to prevent coastal erosion and flooding in more than 100 countries by helping to defend against storms and accounts for 15% of GDP in more than 20 countries (Menéndez *et al.*, 2020). They are also breeding grounds for 50% of marine organisms (UNEP, 2010), they furnish food, medicine and they are building blocks of some islands and are also sites for eco-tourism. Moreover, the ecosystem sustains livelihoods for over 500 million individuals globally. Keith *et al.* (2014) indicates that a healthy coral reef ecosystem supports most marine commercial and subsistence fisheries as well as jobs and businesses created through tourism and recreation.

However, this ecosystem is highly threatened by climate change with climate scenarios showing that 99% of all coral reefs could be lost within this century. Karisa *et al.* (2020) shows that the changing climate is one of the most significant risks to coral reefs, which are disappearing at an alarming rate throughout the world. The impact of climate change is causing massive direct changes to how the ecosystem operates in the normal and indirectly to the life and services that it supports. Among the threats that the ecosystem faces, ocean warming and acidification pose a synergistic challenge with regards to tropical coral reefs and their ecosystems as their survival is hinged on the well-being and production of creatures that build reefs that possess extremely small tolerances for heat and chemicals (Anthony, 2016).

The concentrations of carbon dioxide have increased since the pre-industrial periods (Meyer and Pachauri, 2014) both in the atmosphere and in the oceans on account of consumption of fossil fuels and deforestation (Trnovsky *et al.*, 2016) causing climate change. Vega *et al.* (2020) shows that climate change has posed several threats to the ocean and marine ecosystems, which include among others, rising sea surface temperatures that cause thermal stress leading to coral bleaching, diseases and mortality; sea level rise that leads to increased sedimentation within coral reefs that are found near land; changes in the speed and in the occurrence of tropical storms that lead to stronger, more frequent storms that can cause flooding and destruction of coral reefs. It has also led to changes in precipitation with increased run-off of sediments and land based pollutants and ocean acidification.

On the other hand, global oceans have absorbed extensive quantities of heat as a consequence of elevating amounts of greenhouse gas concentrations in the atmosphere. Stocker (2014) reveals that 93% of excess heat from GHGs emissions had been absorbed by the oceans since the 1970s. This translates to warming of the top layers of most ocean basins in comparison with the pre-industrial times. The Indian Ocean in particular has warmed at a speed of 0.11°C every ten years in contrast to Atlantic at 0.07°C every decade and the Pacific at 0.05°C per decade (Hoegh-Guldberg *et al.*, 2014). This warming is attributed to changes in radiative forcing as a result of increased greenhouse gas concentrations and variations in tropical circulations. This rise is comparable with the average depth of between 0 to 700 m trend of temperature that was observed from 1971 to 2010 (Hoegh-Guldberg *et al.*, 2014; Bindoff *et al.*, 2019). Consequently, carbon dioxide commensurate to roughly 30% of total emissions by human beings of CO_2 into the atmosphere accumulates in oceans (Le Quéré *et al.*, 2010). This causes alterations in ocean carbonate chemistry as is shown in equations 1 and 2 with most of the change being reduced carbonate ion concentrations and increased hydrogen ions (H^+) concentrations leading to a reduction in sea water pH (Lischka *et al.*, 2018).

$$CO_2 + H_2O \longrightarrow H_2CO_3 \tag{1}$$

$$H_2CO_3 \longrightarrow H^+ + HCO_3^- \tag{2}$$

Warming leads to bleaching in coral reefs as a result of high irradiation levels and water temperatures that are above normal (McGowan and Theobald, 2017). In the normal, corals and zooxanthellae, a microscopic algae that dwells in their tissues share a symbiotic relationship (Makoye and Kaaya, 2018). These algae are the corals primary source of food and energy and give them their colour. Warming induces stress on this symbiotic relationship causing the algae to leave the corals tissue (Brown *et al.*, 2019). As a result, the coral loses its major source of food and energy, turns white and gets to an incapacitated position that may lead to its mortality and subsequently, a phase change from a reef where corals predominated to one where algae predominated, followed by a loss of biodiversity (Brown *et al.*, 2019).

Increased hydrogen ions in the sea water causes reduced pH resulting in ocean acidification. This negatively affects the speed of calcification of corals and it escalates the rate of dissolution of $CaCO_3$ affecting reproduction of the coral reef and other marine biodiversity that utilize $CaCO_3$ to build their skeletons and structures (Cyronak *et al.*, 2013; Bindoff *et al.*, 2019). Alterations in temperature besides pH of surface ocean waters extend to a wider scope with implications directly affecting the performance, resource and service provision and survival of marine organisms, particularly the calcifiers such as corals, causes erosion of the reefs and alterations in carbon:

nitrogen ratio of sea water (Brander *et al.*, 2012). The impacts of the changes include: a reduction in the number of calcifying organisms and food web alterations, it affects aquaculture and the supply of human food, it poses the likelihood of coral extinction, loss of habitat and accelerated erosion along the coast.

The combined effect of rising sea surface temperatures (SSTs) and increased CO_2 absorption is therefore extremely detrimental to growth, development and survival of the coral reef ecosystem and it affects the benefits that this ecosystem provides to human populations (Trnovsky *et al.*, 2016). These negative effects have been observed to be on the increase in the post-industrial period after 1950 as compared to the pre-industrial period preceding 1950 because of rapidly increasing emissions of GHGs in the atmosphere.

1.2 Statement of the Problem

Thirty percent of carbon dioxide produced by burning fossil fuels has built up in the oceans since the pre-industrial period causing a lowering of 0.1 units of pH in the top layers of ocean waters (Le Quéré et al. 2010). This is translated to a rise in hydrogen ion [H+] aggregation of up to 26% in seawater (Stocker, 2014). The gradual reduction of pH is anticipated to further lessen between 0.3-0.4 units of pH following the "business as usual" carbon emission scenario, representing 150% increased acidity by the year 2100 (Trnovsky *et al.*, 2016). Increased acidity reduces the quality of sea water with adverse impacts on marine life and marine ecosystems. It poses a dangerous risk to marine life by reducing the ability of some organisms to absorb oxygen and to marine ecosystems like coral reefs by reducing their ability to build their protective shells from molecules (carbonate ions) in sea water thereby losing energy to feed and reproduce. Subsequently, SSTs have escalated by about 1°C throughout the past century and are proceeding averagely at between 1°C and 2°C every 100 years in most tropical areas (Hoegh-Guldberg *et al.*, 2014). High temperatures cause massive coral bleaching which leads to significant disappearance of live corals in different locations globally as they become unable to compete ecologically and die off.

This coupled problem is causing massive direct changes on how the ecosystem operates in the normal and indirectly to the life and services that it supports. The condition is very dire and is more urgent in the tropics, where water temperatures are warmer on average thus pushing corals to their limits. If the present trends in atmospheric CO_2 concentrations continue, this ecosystem will reach, and far exceed, critical thresholds that are associated with their thermal tolerance (above 25.9^0C) and carbonate ion requirements (below 7.8 units of pH). Left unchecked, these stressors will push 90% of coral reefs to threatened status in less than 10 years (by 2030) and nearly all reefs will be threatened and subsequently lost by 2050 (Cornwall *et al.*, 2021). Unhealthy reefs/dead reefs threaten to a very large extent the biodiversity and livelihoods that they abut.

1.3 Hypothesis

1.3.1 Null Hypothesis

Changes in sea surface temperature and ocean acidification will not affect the size of the coral reef ecosystem.

1.3.2 Alternative Hypothesis

Changes in sea surface temperature and ocean acidification will affect the size of the coral reef ecosystem.

1.4 Objective of the study

The principal objective of this research was to investigate the combined effect of sea surface temperature and dissolved carbon dioxide on the Kenyan coral reef ecosystem. The following specific objectives were used to achieve this principal objective;

i. To determine the spatial-temporal variability of sea surface temperature over the Kenyan coastline.
ii. To determine the spatial-temporal variability of dissolved carbon dioxide over the Kenyan coastline.
iii. To simulate the combined effect of sea surface temperature and dissolved carbon dioxide on Kenyan coral reef ecosystem.

1.5 Justification and Significance of the study

1.5.1 Justification of the study

Ocean warming and dissolved carbon dioxide affect the foundation of the entire coral reef ecosystem which is the coral reef. These two variables of climate change affect critical reef biological and ecological processes of growth, reproduction and survival. This is through coral bleaching, ocean acidification, amplification of tropical storms and variations in interactions that are competitive which in turn hinders maturity and population renewal of coral reef colonies (Anthony, 2016). This further translates to a reduction of the vast social and economic benefits that this ecosystem provides to populations who depend on it. The ecosystem harbors the greatest amount of biodiversity than any other global ecosystem and directly supports greater than 500 million individuals globally (Keith *et al.*, 2014), it protects coastlines in more than 100 countries by helping defend against storms and erosion and accounts for 15% of GDP in more than 20 countries (Reid, 2017). Further, it hosts greater than 25% of all marine fish species and provides a wide array of ecosystem services for example subsistence food, protection against flooding and sustenance of the aquaculture and tourism industries (Keith *et al.*, 2014). This study therefore elucidates on how the combined effect of ocean warming and acidification has affected the coral reef ecosystem presently and how these two variables will affect it in the future.

1.5.2 Significance of the study

Changes within the coral reef ecosystem brought about by ocean warming and dissolved carbon dioxide pose a threat to food security in coastal regions, they harm fishing industries and elevate the potential for flooding and erosion in coastal areas that are low-lying by weakening the natural shoreline protection. Unhealthy reefs are a threat to inhabiting organisms and to the livelihoods of people who depend on them (Pandey *et al.*, 2021). They also pose a threat to coastal and marine ecosystems' resilience and adaptation thus weakening the capacity of human beings and natural systems to adapt to the perpetual changes.

This assessment will be useful in the following ways:

1. It will add to the overall agenda of 2030 sustainable development goals (SDGs) in particular the SDG 14 which aims for conservation and utilization of oceans, seas together with oceanic resources in a rational way to promote sustainable development" (Arora and Mishra, 2019). Indicator 14.3.1 of this SDG calls for marine acidity (pH) averages measured at a set of standardized appropriate sampling locations (Arora and Mishra, 2019) This indicator is associated to the SDG Target 14.3 which aims at reducing ocean acidification effects and to deal with them, for example by improved scientific collaboration on all levels.
2. It will contribute to the goals of Africa's blue economy concept that seeks to build an Integrated Coastal Zone Management centered on the ocean ecosystem. It further aims to "promote the conservation of aquatic and marine ecosystems and sustainably use and manage its associated resources" (Childs and Hicks, 2019).
3. It will contribute to realization of the goals of the economic pillar of Kenya's Vision 2030 that is associated with Fisheries development and management in the agricultural sector.
4. It will also be very key towards the achievement of the Big Four Agenda, target 1.0 on Food security in Kenya by providing information on how variations caused by rising temperatures and ocean acidification have affected the location, distribution and abundance of marine fisheries within the ocean. This will be important to farmers and coastal communities who rely on aquaculture for their daily food consumption.
5. It will provide critical scientific information to the coastal county governments, communities and policy makers e.g. Kenya Marine and Fisheries Research Institute, Ministry of Environment and Planning, Agriculture and Fisheries among others to better

formulate policies that ensure reduction of CO_2 emissions in the atmosphere which is directly linked to increased sea surface temperatures affecting the oceans and the country's economy.

1.6 Study Site

Kenya is located along the eastern coast of Africa between Tanzania and Somalia. It has a shoreline that runs close to 1,420 km in length (Wilfred and Remus, 1986) between 1° S and 5° S. The climate and seasonality of this region varies greatly with large scale pressure systems of the western Indian ocean and adjacent land masses (Jacobs *et al.*, 2020).

The coral reef ecosystem along the Kenyan coastline covers an area of approximately 630km^2 representing 0.2% of global coral reef coverage (Lam *et al.* 2019). It is defined by fringing reefs that are narrow in the south and those that are discontinuous and patchy in the north (Karisa *et al.*, 2020) as is shown in Figure 1. Fringing reefs are reefs that grow from near the shoreline around a coastline or an island and are separated by shallow narrow lagoons whereas patch reefs on the other hand are small and isolated reefs that grow from the continental shelf or the bottom of an island. These reefs occur at varying depths that range in a way that low tide is less than 1 m and high tide is over 20 m. Furthermore, some patch reefs are also found in Malindi and Kiunga areas in the north and Shimoni in the south close to the Kenya-Tanzania border.

This site was chosen for this study because of the vulnerability of this ecosystem to bleaching and acidification as a result of changes in sea surface temperatures and dissolved carbon dioxide. These corals have previously suffered severe bleaching episodes in 1998, 2009 and 2016 (Obura *et al.,* 2017) with very narrow recovery periods between the bleaching events. This led to coral mortality in the reefs along this coastline contributing to between 50-80% loss in coral reef coverage. Coupled with the effects of ocean acidification, projections indicate that there will be a devastating loss in the overall coverage of this ecosystem which will affect the amount of coral reef fish catch, coastal protection, erosion and the livelihoods of people.

Figure 1: Location of coral reefs along the Kenya coastline.
Source: UNEP/WCMC (2010). World Atlas of Coral Reefs.

These reefs are the primary marine ecosystem ecologically and economically. However, the sea grass beds plus the mangroves also contribute to the economy of coastal communities. Sea grass beds are typically connected with reefs in lagoons that are shallow between the shore and reef lagoons as well as in the shallow bays and in shallow channels of drowned river beds or creeks (Makoye and Kaaya, 2018). In the northern parts of Kenya however, the influence of cool waters from the Somali upwelling makes the coral reefs to develop poorly because of the reduced optimal growth temperatures and more CO_2 absorption.

CHAPTER TWO

LITERATURE REVIEW

This chapter reviews previous studies on variability of sea surface temperature and dissolved total carbon dioxide on the ocean surface waters. It evaluates the individual effect of bleaching and ocean acidification on the coral reef ecosystem. The interactive outcome of these two variables on the coral reef ecosystem is also reviewed and the conceptual framework used in the study is finally highlighted in the last section.

2.1 Studies on sea surface temperature and its effect on coral reef bleaching

Sea surface temperatures (SSTs) vary across the global oceans from low latitude areas to higher latitude areas (Huang *et al.,* 2017). Near the equator where there is direct overhead sunlight all year round, the surface ocean waters are warmer compared to areas in the polar regions as a result of increased solar irradiation. Moreover, ocean heat within ocean basins is largely driven by anthropogenic forcing through increased greenhouse gas emissions (Johnson *et al.,* 2018). As the oceans take in more heat, sea surface temperatures rise as a result of increased content of heat in the upper layers of the oceans. Lindsey and Dahlman (2020) show that between 1993–2020 the rates of heat-gain, averaged over the surface of the earth were 0.37–0.41 W/M^2 for depths between 0 and 700 m of the ocean, which is considered the surface. These observations were measured using in situ Argo floats at different depths within the range of 0-700 m layer. Garcia-Soto *et al.* (2021) also shows that mean sea surface temperature globally has risen over time from the pre-industrial era with an average warming trend of 0.062±0.013^{0}C every ten years over the period 1900-2019. This rate of warming in the ocean has even accelerated further in the global oceans between 2008-2018 at 0.280±0.068^{0}C, rising more than the long-term mean by 4.5 times (Johnson *et al.,* 2018). Trnovsky *et al.* (2016) shows that intercontinental oceans have absorbed close to 93% of excess heat that comes from the enhanced greenhouse effect as a result of burning fossil fuels. Majority of the warming, about 64% is found in the upper oceans between 0-700 meters.

Regionally, the Indian ocean has warmed up at a faster rate of 0.11^{0}C per decade compared to the Atlantic which has warmed up at a rate of 0.07^{0}C per decade and the Pacific which has warmed up at a rate of 0.05^{0}C accordant with depth average temperature trend (0-700 m) (Hoegh-Guldberg *et al.,* 2014). Roxy *et al.* (2020) linked the observed warming in the Indian Ocean to changes in radiative forcing brought on by higher levels of greenhouse gases and to variations in tropical circulations. Further, the warming was linked to heat transfer originating from Pacific Ocean through the Walker circulation and the Indonesian Through-Flow circulation.

Future projections in temperatures at the ocean's surface in the Indian Ocean basin to the end of this century indicate seasonal and regional variability (Obura *et al.,* 2017). The average of the ensemble CMIP 5 RCP scenarios indicates that the north-western Indian ocean has more warming in comparison to the south-eastern area which has lesser warming. This is because of periodic El Nino events which occur frequently and at higher magnitudes across this region. The warming patterns in both RCP8.5 and RCP4.5 are similar but their magnitudes are different with RCP8.5 projecting a warming rate of 0.35^0C per decade whereas RCP4.5 projects a speed of 0.13^0C in every ten years. According to Roxy *et al.* (2020), projection of climate models show that there will be a rise in SSTs in the Indian ocean by $1.2\text{-}1.6^0$C in the near-term between the years 2040 to 2069 and by $1.6\text{-}2.7^0$C in the far-term (2070-2099) with RCP4.5 (540 ppm CO_2-equivalent). This will translate to more ocean heat content in this basin. Moreover, Cheng *et al.* (2017) indicates that warming in this basin has provided more than 21% of the world's intake of heat by oceans throughout the last two decades.

Persistent increase in sea surface temperatures above a long-term maximum for any region with a change of between $1\text{-}2^0$C causes bleaching in coral reefs, a process by which corals expel the symbiotic algae (zooxanthellae) that lives inside them and turn to white (NOAA, 2017). As a result of bleaching, the corals lose an essential supply of food and energy (Hughes *et al.,* 2017). Persistent warming in the top layers of the ocean leads to a rise in more frequent and more intense bleaching episodes which may precede to coral mortality (Brown *et al.,* 2019). If the affected coral(s) is not severely stressed by bleaching, it can recover. However, if it is severely bleached and algae loss is prolonged, coral disease and death become likely (Obura *et al.,* 2017). Literature also shows that many corals which have previously been affected by intense bleaching may be incapable of recovering in due time because of recurrent bleaching events. Brown *et al.* (2019) show that bleaching events have occurred quite frequently to even give room for complete recovery of coral reef colonies which would thus compromise the ability of reef accretion. According to Sully *et al.* (2019), the patterns of bleaching in corals vary both in time and space with the highest likelihood of bleaching occurring at mid-latitude tropical sites between 15^0N to 20^0S compared to low-latitude sites. Coral reefs in the low latitude sites were found to bleach less because of variations in species composition due to geography and genotype diversity. Genotypes of coral reefs that are less vulnerable to thermal stress are found in the low latitudes and some corals in these area were pre-adapted to thermal stress and were also in the bleaching recovery period (Sully *et al.,* 2019).

Globally, coral bleaching events have affected coral reefs and their ecosystems severely. Obura *et al.* (2017) attributes the wane in global coral reef ecosystem cover to durations of rapid increase in sea surface temperature anomalies and sustained high SST anomalies in most global reefs. The report also indicates that 14% of global coral reefs were lost to bleaching between 2009 and 2019.

In the tropics, warming has severely impacted worldwide marine systems and coral reefs. It has contributed to the loss of marine species and organisms that harbor within the coral reefs to decline in their diversity (Heron *et al.,* 2017) as maximum temperature tolerances are exceeded. Obura *et al.* (2017) shows that within the western part of the Indian Ocean, mass coral reef mortality has been observed over time with major bleaching events in 1998 where coral reef cover declined by 25% from 40% before 1998 to 30% after 1998 and in 2016 where 30% of coral cover showed proof of excessive or extreme bleaching and only 10% having a significant or high mortality (Gudka *et al.,* 2020). Significant loss in average cover of hard coral which forms the basis of the reef ecosystem occurred. The blend of scorching conditions between the years 1998, 2009 and 2016 in SSTs and the in-phase high positive values for both Pacific and Indian Ocean dipoles contributed greatly to the very high bleaching risk along the Kenyan coastline (Obura *et al.,* 2017). The positive phase of the IOD and El Nino Southern Oscillation (ENSO) which occur inter-annually within the warm Indian Ocean caused warmer than normal temperatures at the ocean's surface in the western Indian Ocean relative to the eastern region. IOD SST anomalies were based on Extended Reconstructed Sea Surface Temperature (ERSST) version 5 recorded by World Meteorological Organization (Huang *et al.,* 2017) showed that mean SST anomaly averaged was 1.0^0C, 0.47^0C and 0.86^0C respectively in 1998, 2009 and in 2016 leading to increased sea surface temperatures in the region.

Warming further leads to diseases in reef colonies by increasing the expansion and survival of pathogens, disease transfer, decreased immunity and host susceptibility (Vega *et al.,* 2020). This indicates that for coral reefs that have already been affected by bleaching and reduced rates of accretion, disease exposure poses great risk to their survival and regeneration. This effect is worse on coral reefs that have continually been affected by bleaching because they have very low chances of survival as compared to those that have not been affected (Hoegh-Guldberg *et al.,* 2017).

Along the Kenyan coastline, sea surface temperatures have been observed to vary seasonally being affected with climate variability (Jacobs *et al.,* 2020). Southeasterly winds dominate this coastline from July onwards whereas northeasterly winds dominate it from February onwards (Liao *et al.,* 2017) moderating the temperature of the water. Further, the ocean water temperature is moderated by the global oceanic conveyor belt through thermohaline circulation which distributes heat energy (Huang *et al.,* 2017). Warm water from the tropical areas moves poleward near the surface giving up some of its heat to the atmosphere. As the water loses heat, it becomes a denser substance and it falls to the ocean's depths. The now less dense warmer water moves back toward the tropics and the cycle continues.

These studies have highlighted that sea surface temperatures vary across the globe and within different regions. They have also shown the link between increasing sea surface temperatures and bleaching of coral reefs. This information is however very limited in the western Indian Ocean area where the Kenyan coastline lies. This study addressed this gap by determining how sea surface temperatures have varied along the Kenyan coastline, explaining further how and to what extent they have affected the coral reef ecosystem along this coastline.

2.2 Studies on dissolved carbon dioxide and its effect on ocean acidification

Significant concentrations of anthropogenic CO_2 (approximately 30%) have dissolved into the global oceans (Haigh *et al.,* 2015). This has resulted in reduced carbonate ion concentrations $[CO_3^{2}]$ and increased proton concentrations $[H^+]$ resulting in a decline in pH (Lischka *et al.*, 2018) due to the chemical reaction of CO_2 and water. Trnovsky *et al.* (2016) shows that pH has decreased by 0.1 units since the pre-industrial era representing approximately 30% increase in acidity and a further reduction of 0.3 units has been projected following RCP8.5 at the closing out of the century (Bindoff *et al.*, 2019). The rate of absorption of CO_2 varies among oceans with cold oceans absorbing more CO_2 compared to warm oceans (Lindsey and Dahlman, 2020) due to their higher solubility for CO_2. Thus, the colder the ocean, the more the ocean absorbs CO_2 and vice-versa. This implies that among the three warm ocean basins, the Indian Ocean has the lowest amount of absorbed carbon dioxide as compared to the Pacific and the Atlantic based on their average sea surface temperatures.

Within the tropics like in the western Indian ocean region, model projections reveal that surface water's average pH has dropped over time with projected declines to 7.75 units in the pH scale by the year 2100 following RCP8.5 (Hoegh-Guldberg *et al.*, 2014). Roxy *et al.* (2020) indicates that over the Indian Ocean basin, the pH of the top ocean has fallen by around 0.1 unit (current mean at is at 8.1) in comparison to preceding industrial levels and across the western Indian Ocean where the Kenyan coastline lies it is greater.

The map in Figure 2 and the graph in Figure 3 indicate that the pH of the ocean's surface waters has declined over time in the global oceans and continues to decline as a direct result of dissolved CO_2. The decline is observed to be even greater after the year 2000 as more CO_2 is dissolved in the surface waters.

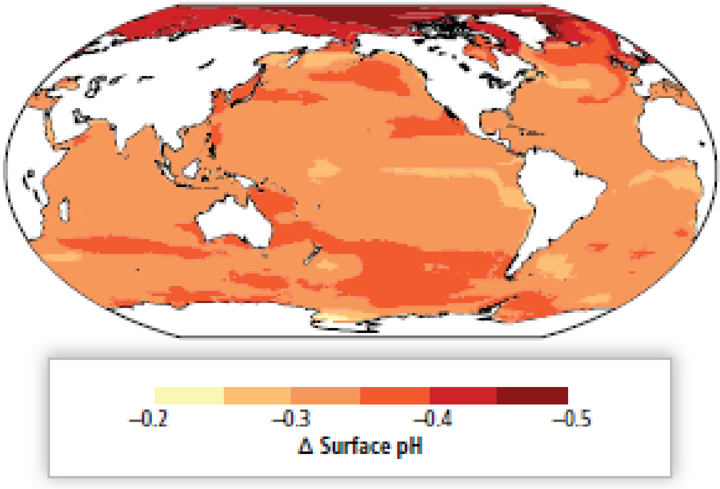

Figure 2: Map of a model simulation showing change in sea surface pH from the 1990s. Source: (Meyer and Pachauri, 2014).

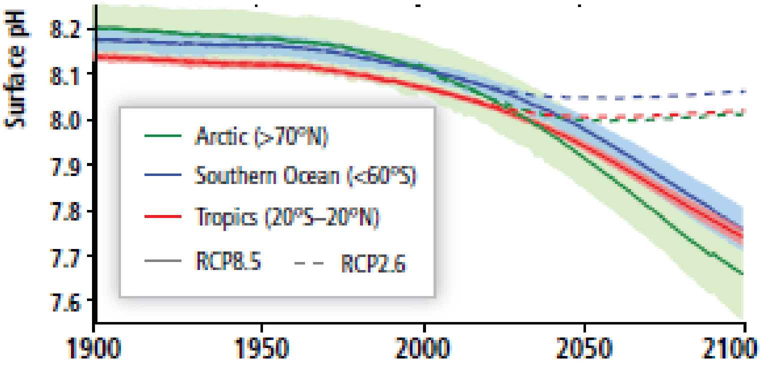

Figure 3: Weighted averages of mean ocean water pH projections over time.

Source: (Hoegh-Guldberg *et al.*, 2014).

Increased CO_2 oxidation in the open waters is projected to decrease concentration of carbonate ions by close to 100 µmol kg/1 in warmer oceans out of the current mean of 250 µmol kg/1 (Meyer and Pachauri, 2014). Currently in the tropical oceans, the entire column of water continues to be under saturated with respect to calcium carbonate, which is a necessity for corals to build their structures. Figure 4 shows how the amount of carbonate ions have decreased and are projected to decrease further to the close of this century with continued ocean's absorption of carbon dioxide by the three ocean basins.

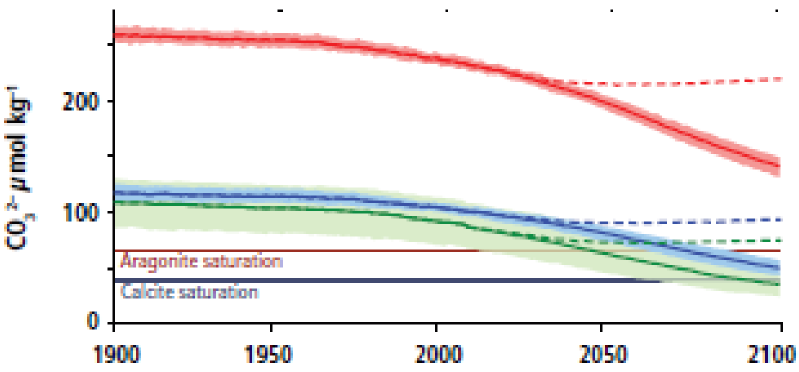

Figure 4: Weighted averages of mean carbonate ion ($CO3^{2-}$) concentration in the ocean surface. Mean is the continuous line and range of models over the Southern Ocean, shown in blue, the Tropical oceans, shown in red, and the Arctic ocean, shown in green.

Source: (Meyer and Pachauri, 2014).

Ocean acidification puts at risk the future of coral reef ecosystems by lowering the concentration of carbonate ions that the ecosystem requires to generate and accumulate calcium carbonate that forms its structures and skeletons.

Globally, according to projections, most corals and coralline algae's rates of calcification will decrease due to ocean acidification in the tropics and in the temperate areas which form reef structures and their sediments (Cornwall *et al.*, 2021). At the same time, acidification will also boost the dissolution of carbonate sediments thereby decreasing accretion (Trnovsky *et al.,* 2016). The delicate balance between calcification (growth) and loss (physical, chemical, and biological erosion) of calcium carbonate within the ocean determines the maintenance ability of reef constructions and to what level can they be sustained (Eyre *et al.,* 2014). The reduction in the concentration of carbonate ions causes an increased carbonate loss together with a decrease in its production. Projections show that the coral reefs with a low capability for reef formation naturally prior to acidification will enter a state of net erosion with acidification (Hoegh-Guldberg *et al.*, 2017) and will not survive. Kleypas, 2019 shows that there are very few coral reefs that can calcify at rates fast enough to counteract biological, physical, and chemical erosion, an absence of living coral cover on most reefs being a contributing factor to these results. Live coral cover supports more types of species of fish per unit area compared to every other marine setting (Obura *et al.,* 2017). Scientific evidence has shown that this decline in carbonate ions due to ocean acidification is significant as it affects how quickly calcareous organisms living in the ocean, for example corals construct their bodies (Bindoff *et al.,* 2019). In the normal, the surface ocean waters are usually supersaturated with the soluble form of $CaCO_3$(aragonite) but with increasing ocean acidification, aragonite saturation state is slowly falling below zero thus the surface waters are becoming under saturated because of reduced carbonate ions posing a risk to calcifying organisms. At this, Zweifler et al. (2021) show that carbonate accretion in coral reefs that are found in warm-water may approach zero or become negative when aragonite falls below 3.0. Trnovsky *et al.* (2016) indicated that thermodynamic potential of calcium carbonate to precipitate or dissolve in sea water is measured by the calcium carbonate saturation state. Precipitation is favoured when $CaCO_3 > 1$ and net dissolution is favoured when CaCO3 < 1 in sea waters. Decreasing pH and aragonite saturation in surface waters also affects the synthesis of $CaCO_3$ mineral, its accumulation, and dissolution within the coral reefs and other marine biodiversity (Cyronak and Eyre, 2016). Development together with growth of coral reef ecosystems highly depends on the net ecosystem calcification (NEC) rates being positive. Reduced pH therefore directly reduces the speed of calcification and escalates the rate of dissolution of $CaCO_3$ thus affecting reproduction of the coral reef and other marine biodiversity who utilize $CaCO_3$ to build their skeletons and structures (Cyronak *et al.,* 2013). This negatively affects the overall NEC leading to a reduction in size of the ecosystem.

Agostini *et al.* (2018) revealed that surface waters in the Indo-pacific region have continually acidified thereby weakening the coral reefs in these regions. Coral reef patterns that are consistent with degradation have been observed along the lines of increasing CO_2 absorption (Smith *et al.*, 2016) and this has then led to reduced amounts of shellfish plus other species of fish and all-inclusive loss in the habitat structure made up of carbonates. Ocean acidification was found to have direct negative influence on corals' early life stages. The larval stage was seen as particularly more susceptible to modifications in carbonate concentration and pH during the development stage of the corals. Acidification induced changes in the development times of larvae, microbial biofilm changes and dispersal distances that serve as settling cues for larvae.

Locally, OA has been observed among other factors to contribute to a decline of fish species whose habitat is the coral reef. Lam *et al.* (2019) indicated that due to ocean acidification, the potential of coral reefs along the Kenyan coastline to provide fisheries and local coral reef related tourism to the communities in this region has gone down. This has impacted negatively to the livelihoods of the local residents who depend on the reef. Reefs in this region are experiencing more stress from decreasing pH and their susceptibility to warming is enhanced further (Agostini *et al.,* 2019).

Ocean acidification along the Kenyan coastline varies with the amount of carbon dioxide that is absorbed by the ocean surface waters. Moreover, the influence of northerly winds induces upwelling in the northern parts of this coastline bringing along with them more concentrations of nutrients from the lower ocean to the surface (Jacobs *et al.,* 2020). Due to the high organic matter present in top layers of the ocean, the waters are rich in increased nutrients together with inorganic carbon concentrations that has dissolved that further contribute to decreased pH and lower calcium carbonate saturation state (Schulz *et al.,* 2019). The coastline also experiences the East African Coastal Current flowing from Tanzania northwards throughout the year and the Somali Current that flows southwards (Karisa *et al.,* 2020).

These studies have accentuated by how much ocean acidification will have an impact on the coral reef ecosystem cover. However, these results have been generalized and in some regions like the western Indian ocean, in particular the Kenyan coastline, information lacks about the consequences of ocean acidification on the coral reef ecosystem along this coastline yet the effects are experienced in most parts. Lam *et al.* (2019) noted that there is not much knowledge and information about acidification in the occidental region of the Indian Ocean. A report by WIOMSA, (2020) equally pointed out that little is understood about monitoring of acidification of the oceans in this area and yet the consequences are felt in every location. These deficiencies were filled in this study by determining the variability across space and time of dissolved carbon dioxide over the Kenyan coral reef ecosystem.

2.3 Studies on combined effect of sea surface temperature and dissolved carbon dioxide on the coral reef ecosystem

Coral reefs have a thermal threshold that occurs at close to 1°C higher than the typical summertime high for any region (Banc-Prandi *et al.,* 2022; Dixon *et al.,* 2022). If this threshold is consistently surpassed over a period of time, coral undergo mass bleaching. Mass coral mortality is anticipated to occur if temperatures rise by more than 2°C higher than the average summer maximum. The concentration of carbonate ions in surface ocean water is the second threshold where coral reefs are no longer able to support their carbonate structures that are distinctive (Feely *et al.,* 2009; Lischka *et al.,* 2018). If these two thresholds are exceeded at the same time therefore, coral reefs will be bleached, they will be unable to reproduce and they will die. Ocean temperature and pH define to a greater extent, the niche within which coral reefs and their associated ecosystem can survive, grow and reproduce.

Previous studies have shown that the interactive consequences of rising sea surface temperatures plus ocean acidification on calcifying aquatic organisms like the coral reefs are greater compared to their individual effects. At the global scale, changes in ocean acidification and warming have dramatically reduced the dispersal, plenitude and continuity the integrated coral reef ecosystem (Gattuso *et al.,* 2013) through direct effects on physiological procedures such photosynthesis, calcium buildup, growth rates, and internal control of pH which lead to disruptions of marine ecosystems and reductions in biodiversity (Dobretsov *et al.*, 2019).

Cornwall *et al.* (2021) stated that under greater carbon dioxide scenarios, the combined consequences of ocean acidification and warming are projected to intensify. In a meta-analysis that was done to estimate total production rates of carbonate in 183 reefs within the three tropical oceanic basins by 2050 and 2100, the study demonstrated that most of the coral reefs were not be able to keep the production of net carbonate positive in the world under RCP4.5 and RCP8.5 as they suffer reduced accretion rates driven by bleaching and ocean acidity. Trnovsky *et al.* (2016) also noted that a combined impact of warming and increased CO_2 affects the metabolism of benthic organisms like the coral reefs negatively as compared to their individual effects. The study found out that during temperature increases only incubations, the relationship between the rate of respiration and gross primary production in coral reefs was strong and significant but when the CO_2 and temperature are coupled in the incubation, the relationships became much weaker and not significant. This weakened relationship was attributed to the presence of increased CO_2 which tampered temperature's impact on benthic metabolism. Further, in a study conducted by Agostini *et al.* (2018) on how high temperatures and carbon dioxide levels affect the metabolism of corals, the results showed that the effect of increased warming on metabolism of corals was stronger as compared to the effect of increased CO_2 and without the combined temperature stress, the effects of acidification were negligible. However, the combination of acidity and greater temperatures resulted in worse consequences on coral reefs because of the amplified diel fluctuations in the environment sorrounding the corals.

Williamson and Guinder, (2021) showed that higher sea surface temperatures and reduced pH will further affect the global marine environment by altering the natural habitat of the coral reef ecosystem and food supply and by changing the ocean chemistry. Marine plants which are primary producers form the level of the food chain below. Warmer acidified waters will lead to a gradual decrease in the quantity of these plants consequently reducing the amount of nutrients that is available for use further along in the food chain. This will have consequences on the functioning of this ecosystem and on the biodiversity that it supports. Ocean warming and acidification are further observed to reduce the quantity of regional and local biodiversity of coral reefs by eliminating delicate species like fisheries whose habitat is the reef and creating changes in the structure of the reefs. Lam *et al.* (2019) projected that plenitude of more receptive corals such as the branching Acropora sp that forms much of the habitat complexity of Indo-Pacific coral reefs is affected severely. In a research conducted by Sun *et al.* (2020) who investigated the impacts of partial carbon dioxide (pCO2) (between 600 and 1,200 atm) and increased sea surface temperatures (between 28.0 and 30.5 C) over the course of 33 days on early evolution and the forms of gene expression in juvenile Acropora sp., the results indicated that juvenile corals of the Acropora sp are extremely sensitive to changes in warming and acidity of the ocean as compared to the adult corals of the same species. This is because it is at this stage that they form their symbiosis establishment to enable them survive and reproduce and alterations in temperature and pH alter this establishment.

The coupled effect of bleaching and acidification is also observed to impact regional reefs found in the Indian ocean by shuffling coral communities. In a two-year simulation study using mesocosms to simulate the impact of warming and acidity of the ocean on coral reef species richness, composition and structure conducted by Timmers *et al.* (2021) showed that elevated warming (+2^{0}C) and reduced pH (-0.2 units) result in shuffling of coral reef community structures and their interactions within the surface waters thereby altering the functioning of the ecosystem. These changes reduce the growth potential and survival of coral reefs thereby changing the competitive hierarchy of corals and microalgae by reducing their ability to maintain and to rapidly colonize the available space following earlier disturbances (Donner and Carilli, 2019).

Basing on research done by Prada *et al.* (2017) which investigated the effects of coupled temperature (16–26 °C) and acidity (pH 8.1–7.4) on Mediterranean coral species' ballooning and mortality, the results showed that increased temperature together with ocean acidity have a significant synergistic impact on the rate of mortality (up to 60%) of coral polyps for both solitary and colonial polyps.This indicated that higher temperatures within the ocean increased the polyps metabolic rates that, in tandem with falling pH levels, lead to fast decline in cellular performance and function within corals. Moreover, the study indicated that prolonged warming will extirpate thermally and pH sensitive coral species before the year 2100 under RCP8.5 while simultaneously slow down the recuperation of some species that can tolerate higher temperatures and acidic levels from acute mass coral bleaching, acidification and death. This is projected to progressively cause dissapearance of coral reefs within tropical areas and a shifting from only having reefs that survive to only the resilient reefs. Similarly, in a study carried out by Buddemeier *et al.* (2008) to estimate the future of coral reef coverage in the eastern Carribean region that had been impacted by massive bleaching in they year 2005, model results projected that coral cover was estimated to decline below 5% by the year 2035 using the depressed values after the 2005 incident as a baseline. To predict the future coral reef cover, the study employed a simulation model, coral mortality and bleaching output model.

Anthony (2016) demonstrated that acidification and warming lowered resilience of coral reefs through increased coral mortality and hampered coral growth using a dynamic community model that was combined with responses to growth and mortality of *Acropora sp* corals and macro algae functions for coral growth by ocean acidity and warming. The study was limited to the coral genus

Acropora because they form the majority of the surface reef structure in the Indo-Pacific region. These species of corals are also highly sensitive to heat stress and acidification of the water. Lam *et al.* (2019) also showed that the two main factors reducing coral resilience, growth rates, and survival are warming and acidity. Bleaching exacerbates and accelerates the decrease of coral calcification, survival, and development because of ocean acidification. Allemand and Orsbon (2019) showed that the most disastrous effects of bleaching episodes on coral reefs are their short-term pulse effects, while ocean acidification's long-term ambient effects weaken the ability of reef ecosystems to withstand such events. Masson-Delmotte *et al.* (2021) indicated with high confidence that, ocean acidity is predicted to compound negative impacts of warming on coral reef species' development, calcification, abundance, and growth at 1.5^0C warming. This will equally exacerbate the resilience of both vulnerable and non-vulnerable coral reefs and put them at risk of deterioration, recovery from disturbances and mortality. Coral reefs may be less able to recuperate from stress due to both acidity and temperature stress (Guillermic et al., 2021).

Meyer and Pachauri, (2014) indicated that more severe variations are expected in the distribution and plenitude of the coral reef ecosystem and its organisms in response to warmer oceans like the Indian ocean and increased acidity owing to the strong connection between living things and their ecosystems and the physical and chemical components of their surroundings. Hoegh-Guldberg *et al. (*2014) revealed that particular small changes in temperature and other variables may give rise to frequently observed significant biological reactions, ranging from straightforward linear trends to more complex non-linear consequences.

Locally, the effect of ocean warming and acidification is observed in the reduced quantity of coral reef fish. Fisheries in the occidental Indian Ocean region mainly depend on coral reefs (Ridgway and Guldberg, 2016) and as thus, any alteration of the functioning of the reef affects them directly. Worm and Lotze, (2021) show that there have been significant changes in species composition of reef fishes following bleaching events and increased acidity in the surface waters which are further attributed linearly to disturbed species diversity and intensity. These two stressors affect physiological processes that influence behaviour of fish. Higher metabolic rates brought about by warming alters activity levels and the use of their habitats whereas the lower capacity to create protective calcified structures in an environment with greater acidity alters their inability to avoid predators (Laubenstein *et al.,* 2018). Further, reduced water quality as a result of increased acidity lowered the ability of fish to absorb oxygen causing them to either migrate or undergo mortality.

These studies have shown that ocean acidification increases the pace at which exposed reef structures and sediments dissolve whereas warming at the surface of oceans is a key environmental factor that regulates how quickly coral grows, but the combined impacts of elevating temperatures at the surface of the sea and ocean acidity are poorly understood. (Trnovsky *et al.,* 2016). Cornwall *et al. (*2021) demonstrated that the coupled effects of mortality and calcification changes and bio erosion rates of specific reef taxa which appear in space across various ocean basins following ocean warming and acidity are not included in global-scale forecasts. Mwachireya *et al. (*2018) also pointed out the need to simulate the impact of ocean acidification and warming plus how populations and ecosystems will respond. This study addressed these gaps by simulating and projecting the combined effects of sea surface temperatures and ocean acidification on the Kenyan coral reef ecosystem.

This study utilized two emission scenario pathways to project the combined effects of sea surface temperatures and dissolved carbon dioxide on the coral reef ecosystem. These are the Shared Socio-economic Pathways (SSPs) intended to enable research on climate change and the analysis of policy. The SSPs include in them the attributes of economic and population growth, education, urbanization and the rate of technological advancement. They differ from earlier climate scenarios i.e., the Representative Concentration Pathways (RCPs) which did not include these attributes. The SSPs however built on RCPs and were designed to be complementary to the RCPs. The RCPs set pathways for GHG emissions and, effectively, the amount of warming that could occur by the close of 2100 whereas the SSPs set the stage on which reductions in emissions will or will not be achieved (van Vuuren *et al.,* 2017).

Two SSPs were chosen for use in this study i.e., SSP2- RCP 4.5 also referred to as SSP2-4.5 and SSP5- RCP 8.5 also referred to as SSP5-8.5. SSP2 which is also referred to as the ‘Middle of the road scenario has significant challenges to mitigation and adaptation’ describes a future that follows a course whereby social, economic, and technical developments don't significantly diverge from those of the past. (Riahi *et al.,* 2017; van Vuuren *et al.,* 2017). Here, income growth and development patterns are uneven. Some countries will make very good progress whereas others will fail to live up to expectations. The national and global institutions work toward but are making sluggish achievement progress in the SDGs. In this scenario also, environmental systems are degrading although they have slight improvements and the consumption of resources and energy is decreasing.

SSP5 on the other hand also referred to as ‘Fossil-fueled Development-Taking the highway’ with low challenges for adaptation and significant challenges for mitigation describes a future in which the world has a lot of belief in free markets, innovation, and human growth capital as the way to achieve sustainable development (Nilsson *et al.*, 2017; Riahi, 2017). Strong investments are also made in institutions, health, and education to improve social and human capital. Simultaneously, there is a leaning for socio-economic development with intense use of fossil fuels and an espousal of lifestyles around energy and resources. These elements fuel rapid global economic expansion and population rise.

SSP2-4.5 was chosen for use in this study because it reflects the situation that is currently present in terms of uneven development patterns along the Kenyan coastline. In some parts of the Kenyan coastline, efforts have been made to prevent the effects of climate change including coral reef replanting, coral gardens conservation and protection whereas in other areas, no efforts are in place. These have brought about non-uniformity in the survival and development of this ecosystem. Moreover, policies formulated by the county institutions in regard to the utilization of the coral reef ecosystem have only been seen to work in some areas along the coastline and not in some. Therefore, SSP2-4.5 provides a definite pathway in analyzing the future of this ecosystem. SSP5-8.5 provides a scenario that looks at an extreme case in which the sustainability of the coral reef ecosystem can be measured against in case no policies or practices are employed to curb the combined effect of rising SSTs and dissolved CO_2.

2.4 Conceptual Framework

Figure 5 shows a conceptual model that was used in this study outlining the functional links between environmental variables and dynamics of the coral reef ecosystem. The arrows represent processes that have either positive (solid arrows) and negative (dashed arrows) effects on growth or survival of coral reefs. The framework shows how the different dynamics of the coral reef ecosystem interact among themselves and how the entire ecosystem is affected by the two environmental variables, ocean warming and ocean acidification individually and synergistically through a model simulation in consideration of two climate pathways. The resultant output of the research is also highlighted.

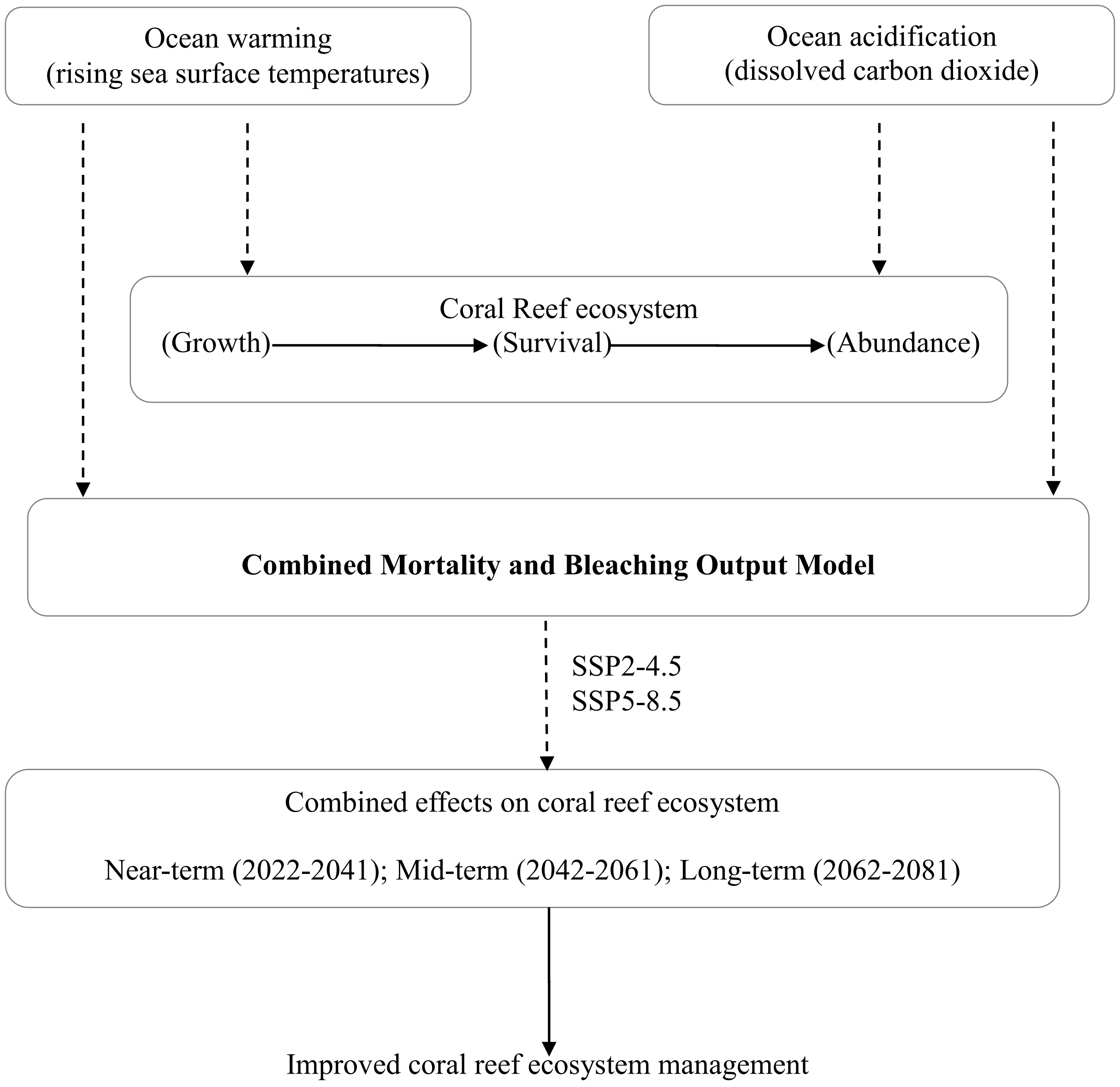

Figure 5: Conceptual Framework

CHAPTER THREE

DATA AND METHODOLOGY

This chapter discusses data that was utilized for this study and the methodology that was applied in order to achieve the objective of the study.

3.1 Data types and Sources

3.1.1 Mean Sea Surface Temperature data

This study utilized mean monthly data on sea surface temperatures for a 31-year span from 1990-2021 as historical sea surface temperature (SST) data. This data was sourced from NOAA, Coral Reef Watch (CRW) program with an area coverage of between 4.04^{o} S - 39.67^{o} E and 2.27^{0} S-40.90^{0}E (latitude and longitude). The SST data from CRW are obtained from different sensors including thermal infrared sensor and microwave sensor that has been deployed on geostationary satellites and polar-orbiting satellites. The attributes of the data are given in Table 1. In situ sea surface temperature from 1,500 buoys (both drifting and moored buoys) covering the global oceans (Kennedy, 2014) were also used in the assemblage of this data to ascertain the accuracy of satellite sea surface temperature by eliminating bias and accumulating data over time (Liu *et al.*, 2014).

The observations of sea surface temperatures used are night-time only ocean temperatures at the surface of the sea that have been adjusted to 0.2 meters depth. This depth represents the skin sea surface area that is as close as possible to the air-sea interface and which can give continuous temperature observations (Akella *et al.,* 2017). Night–time only surface temperature observations were used to reduce the interference of day time heat at and near the sea surface. They have also been used so as to reduce adulteration from solar glare and to take advantage of vertically uniform water temperature at night (Heron *et al.*, 2014).

Table 1: Attributes of sea surface temperature (SST) data used

Type of data	Gridded
Projection	Altitude, Longitude
Spatial resolution	5km x 5km
Temporal resolution	Monthly
Satellite	
Geostationary:	Orbit height: 35,800km Sensor: Imager 2

GOES-W (GOES 15) GOES-E (GOES-13)	**Spectral bands**	**Wavelength λ**	**Resolution(M)**
	Band 1 (MWIR)	3.7-4.0	4000
	Band 2 (TIR)	5.9-7.3	4000
	Band 3 (TIR)	10.2-11.2	4000
	Band 4 (TIR)	12.9-13.6	4000
Polar-Orbiting: Suomi-NPP	Orbit height: 830km Sensor: VIIRS Swath dimensions: 3000km Repeat cycle: 1 day Spatial resolution: 750m Wave bands: 9 visible/ NIR bands plus Day and Night pan band Wave bands: 9 visible/ NIR bands plus Day and Night pan band 8 mid-IR 4 LW IR		

3.1.2 Ocean acidification data

This study focused on two variables that are used to detect ocean acidification within the surface of the ocean that is total dissolved carbon dioxide (TCO$_2$) and changes in sea surface water pH within the ocean. The data used for TCO$_2$ and pH was for the period between 1990-2021, therein considered as historical data. It was accessed from the second version of Global Ocean Data Analysis Project (GLODAP) for world oceans basins that is made up of data for 12 core ocean variables among them total dissolved carbon dioxide and pH data using Data-Interpolating Variational Analysis (DIVA) method of mapping. This data consisted of three components all of which were merged into one dataset namely; the primordial data, the product files corrected of bias (Olsen *et al.*, 2016, and the mapped climatology as described by (Key *et al.*, 2015) together with (Lauvset *et al.*, 2016). Attributes of this data are described in Table 2. Primary data was sourced from 724 cruises consisting of several legs. In some cases, the cruises were blended in regions like the Western Indian ocean. The GLODAPv2 voyage number, EXPOCODE and Alias were used to uniquely identify each cruise and data file.

Table 2: The description of GLODAP version 2 data for seawater pH and total dissolved CO$_2$

Type of data	Calibrated (Bottle data and sensor data)
Projection	Latitude, Longitude

Spatial resolution	1^0 by 1^0
Temporal resolution	Monthly
Scan rate	24 Hz

3.1.3 Coupled Model Intercomparison Project cycle 6 experiment data

Future sea surface temperature and dissolved carbon dioxide data sets used in this study were obtained from Coupled Model Intercomparison Project cycle 6 experiment (CMIP 6) for between 2022 and 2081. This data consisted of runs from 100 distinct climate models from different modelling groups aimed at improving the knowledge of the climate system. The data also gives projections of future weather and uncertainties, providing information for coping with alterations in climate and investigating the predictability of the climate and the capacity of models to forecast it on decadal time scales. (Eyring *et al.*, 2016). Out of all the CMIP 6 models, this study utilized data from the Model for Interdisciplinary Research on Climate (MIROC) version 6 which was able to provide ocean surface temperature and dissolved carbon data values that were based on a detailed global 3D area coverage. Table 3 describes the components of MIROC 6 climate model (Tatebe *et al.,* 2019).

The experiment describes two main classes of CMIP simulations. The first describes archival experiments that envelope the time when present day climate observations exist including how General Circulation Models (GCMs) performed in the past between the years 1850-2005. The second describes future experiments of climate projection that consider the impact of social and economic conditions such as economy and population's impact on greenhouse gas emissions. This impact is seen by combining the mechanisms of shared socio-economic pathway (SSP) and Representative Concentration Pathway (RCP) as is discussed by van Vuuren *et al.* (2017). As a result, climate projections are more reliable and climate policies are better supported. Different future climate forcing paths are shown by the SSP scenarios between the years 2006 and 2100, as well as in some extended trials from 2100 to 2300.

Table 3: Components of MIROC 6 climate model

Projection	360 x 256 longitude-latitude
Horizontal coverage	Global 3D
Horizontal resolution	100km
Temporal coverage	2022-2081
Temporal resolution	Monthly

3.1.4 Coral reef cover data

This data represents the percentage of the area that is occupied by the benthic community which consists of algae (coralline algae, halimeda, micro algae and turf algae), corals (soft and hard corals) and sea grass. These are further categorized in different geographical zones along the Kenyan coastline (North, Central and South). They are also found at different depth levels i.e., shallow communities are found between 0-6m and deep communities are found between 6.5-18m (Karisa *et al.,* 2020). This data also describes the four different types of coral reefs as they occur along the Kenyan coastline namely; fringing reefs, lagoon reefs, patch reefs and channel reefs. It also describes the types of coral reef management state that is unprotected reefs (where extraction is allowed), park reefs (where no extraction is allowed) and reserves (where there is regulated extraction) indicating further whether these reefs are sheltered or exposed.

The four data sets used in this study were found to have different spatial resolutions. These resolutions were re-gridded in order to align them to be of similar resolution before use.

3.2 Methodology

The methodology employed was informed by the specific objectives.

In order to determine the spatial-temporal variability of sea surface temperature and dissolved carbon dioxide over the Kenyan coastline, spatial and temporal variability analysis and trend analysis was employed.

3.2.1 Spatial and Temporal Variability Analysis

Spatial interpolation was employed in this study in order to achieve the spatially distributed maps of sea surface temperature, dissolved carbon dioxide and seawater pH. Spatial interpolation is a method that makes use of the values of well-known geographic sites from close locations to give estimates of other unknown point values (Comber and Zheng, 2019). Kriging interpolation method was applied for use in this study. It is a type of geostatistical interpolation technique which has the ability to produce a prediction surface together with an accuracy of the prediction. The method was employed for use in this study because it considers both the degree of variation and distance when estimating unknown values in an area (Nolan *et al.,* 2021). Further, kriging interpolation assumes that spatial correlation can be utilized to explain variances in a surface by looking at the distance or direction between sample sites. This technique calculates a prediction for an unmeasured place by weighing the nearby measured values using the formula given by equation 3:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{3}$$

where:

$Z(s_i)$ is the value measured at the ith location; λ_i is an unknown weight for the value measured at ith location; s_0 is the prediction location and N is the number of values measured.

Interpolation utilized sea surface temperature and dissolved carbon dioxide data for the period spanning 1990-2021 obtained from NOAA and GLODAP version 2 respectively.

3.2.2 Trend Analysis

Mann-Kendall (MK) test method was utilized in this study to test for the presence of a monotonic increasing or decreasing trends of sea surface temperatures, dissolved carbon dioxide and seawater pH whereas the method of Sen's slope was used to estimate the gradient of the linear trends obtained by the MK test.

3.2.2.1 Mann–Kendall test (MK)

MK trend test is a non-parametric method used in the identification of monotonic trend(s) within data series. It is also employed to check if a time sequence contains an upward or a downward trend (Nguyen *et al.,* 2022). The test is normally applied in the detection of trends in environmental, climate or hydrological data (Gitau *et al.,* 2018). A null hypothesis (Ho) in this test shows lack of a trend in the sequence whereas an alternative hypothesis (Ha) suggests that the series has a trend.

This test was used for analysis in this study because it has three edges. Elementally, it does not require normal distribution of data in the sequence as it is non-parametric. Secondly, it is rank-based and third, it has a limited sensitivity to sudden changes in data that is not uniform (Duy *et al.*, 2022). The test statistic (S) for this method and the mean of S was calculated according to Rauf *et al.*, 2016 and Agarwal *et al.*, 2021.

3.2.2.2 Sen's Slope estimate

This is also a test that is non-parametric and is applied in the recognition of availability of trends inside a data series plus to what extent that trend is. This test computes the slope and intercepts of a time series and typically requires the availability of at least 10 values according to Sen's method (Agarwal *et al.*, 2021). Similarly, a linear model (Beldar *et al.,* 2020) can also be calculated as per equation 5.

$$f(x) = Qx + B \tag{4}$$

where Q is the slope and B is a constant.

Each observation's slope is calculated, and the matching intercept is calculated as the median of all intercepts. Sen's Slope estimator is calculated from N measurements of the slope using the median and according to the method (Alemu and Dioha, 2020).

To determine the statistical significance of the slope obtained by Sen’s estimator results, a comparison of the computed p-value and the significant level, alpha is done. In this case:

If p-value > significant level, then there is no significance in the slope;

If p-value < significant level, then there is a level of significance in the slope.

To simulate the combined effect of sea surface temperature and dissolved carbon dioxide on the Kenyan coral reef ecosystem, model simulation analysis was utilized.

3.2.3 Model Simulation Analysis

This study utilized the Coral Mortality and Bleaching Output (COMBO) Model to evaluate the combined effects of rising SSTs and CO_2 concentrations in sea water on coral reef communities along the Kenyan coastline. The model was used because of its ability to project the effects of alterations in climate from local to regional scale (Buddemeier *et al.*, 2008). It is also user-friendly and analytical in projecting the potential impact of temperature increases and ocean biogeochemistry changes on the coral reef ecosystem. Further, it provides extensive options for input of local data which can be attuned to the conditions of a specific region and adapted for use.

The model utilized:

i. Historical mean monthly and annual sea surface temperature (SST) and dissolved carbon dioxide (TCO_2) data from NOAA/CRW and GLODAP Version 2 respectively over the period 2000-2021.

ii. Future mean monthly and annual sea surface temperature (SST) and dissolved carbon dioxide (TCO_2) data from CMIP6 experiment. These were for two different combined pathways of Shared Socioeconomic Pathway (SSP) and Representative Concentration Pathway (RCP) climate scenarios of the future i.e., SSP2-4.5 and SSP8-4.5.

iii. Baseline coral reef cover data obtained from Karisa *et al.*, 2020.

The COMBO model simulation provided outputs on mortality of coral reefs due to changing conditions of temperature and dissolved carbon dioxide using the quasi-steady state module of the model that assesses responses of coral reefs to changing average conditions. This module was used in this study by including mean monthly and annual SST values and dissolved CO_2 data for the region under study for two different periods i.e., between the year 2000 -2021 and between 2022-2081.

It followed that as SSTs and CO_2 change, long term components of growth and mortality are modified in the simulation according to equation 6 (Buddemeier *et al.*, 2008):

$$\text{Mtemp} = 0.60714 \times \text{SST} - [17.971 + (\text{Tmmm} - 27.1)/100)] \qquad (5)$$

Mtemp refers to temperature induced mortality; 0.60714 is the constant slope; SST represents monthly sea surface temperature; 17.971 is the intercept value; Tmmm is the research area's mean maximum monthly temperature, and 27.1°C is the temperature at which mortality begins to occur on a monthly basis.

The seawater's saturation level with relation to aragonite (Ωa) was calculated as the proportion of dissolved calcium to carbonate ion concentrations in seawater to their product at a balance as shown in equation 7. Thus;

$$([Ca^{2+}] \times [CO3^{2-}]) / [CaCO_3] = \Omega a \qquad (6)$$

Where:
Liquid calcium $[Ca^{2+}]$ is the amount of dissolved calcium ions in seawater, $[CO_3^{2-}]$ is the amount of carbonate ions in seawater, $[CaCO_3]$ is the amount of aragonite (Ωa) that is soluble in seawater, and an is the estimated saturation state.
Therefore, it followed that:

If $\Omega a = 1$, seawater and aragonite are in equilibrium with each other; if $\Omega a > 1$, with regards to aragonite, the seawater is supersaturated. and if $\Omega a < 1$, seawater is not sufficiently saturated with aragonite.

Sensitivity of coral reef growth to variations in aragonite saturation state is interpreted as a decrease in growth rate per unit compared to the maximum growth rate at Ωa=3.0, which is assumed in the simulation (Cyronak and Eyre, 2016).

The baseline for simulations in the model was between 2000-2021, a period of 22 years. Three timelines were considered for future projections in the simulations namely 2022-2041 (Near-Term); 2042-2061 (Mid-Term) and 2062-2081 (Long-Term). Near-term refers to the period from present to the middle of the century (Bindoff *et al.,* 2019) whereas Mid-term and Long-term describe the period from mid-century to the end. These are in line with the Go Blue initiative by UN-HABITAT whose focus is to unlock the potential of sea-land opportunities in the urban areas of the six coastal county governments in Kenya for sustained, inclusive and sustainable economic growth. They also correlate with the Kenya National Adaptation Plan (Government of Kenya, 2016) which aims at improving climate resilience in order to fulfill Vision 2030 and beyond and also align with model projections utilized universally by climate groups to look at how changes in climate variables affect the future of climate.

Before using it in this research, the COMBO model was calibrated to determine the optimum SST and aragonite saturation rate that could yield the maximum growth rate of the coral reef cover over the Kenyan coastline. The graph in Figure 6 shows that as SSTs increase beyond the optimum value, the relative growth rate of coral reefs and its ecosystem is reduced. This growth continues to decline and can go up to zero when temperatures exceed the maximum threshold of survival and development of reefs. Figure 7 indicates that as the state of aragonite saturation increases, relative growth rate of coral reefs also increases concurrently. This therefore shows that, an increase in SST beyond the optimum value and reduction in aragonite saturation state below the optimum value affect the relative growth rate negatively. These outcomes are consistent with those of Worm and Lotze, (2021) which showed that rising SSTs hinder the biological functioning of coral reefs that translates to their growth and development. Hoegh-Guldberg *et al.* (2017) also show that when Ωa falls below 1.0, surface ocean waters become under saturated with respect to aragonite hence accretion and growth of calcifying organisms like coral reefs becomes impossible.

The results of the simulation express the growth response of coral reefs and their surrounding ecosystem as a function of the maximum response. Thus, maximum growth occurred at $SST=25.9^0C$ (the threshold beyond which bleaching occurs) and at aragonite saturation state (Ωa) $=3.0$.

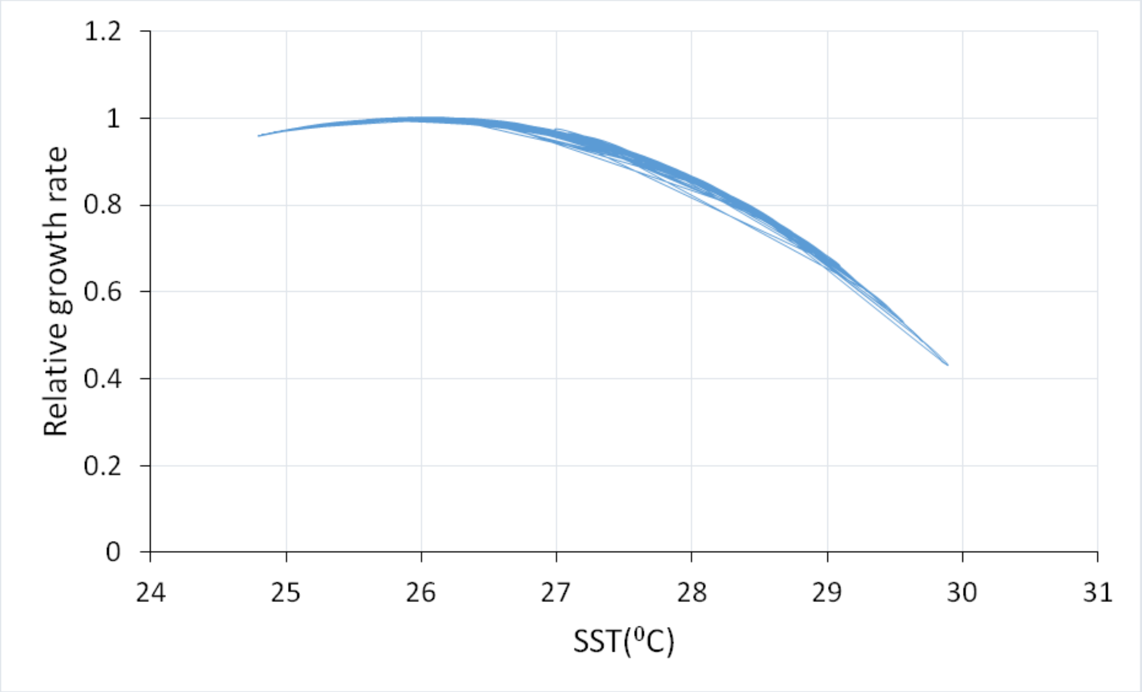

Figure 6: Model simulation curve for relative coral growth rate verses SSTs over the Kenyan coastline between 2000 and 2021.

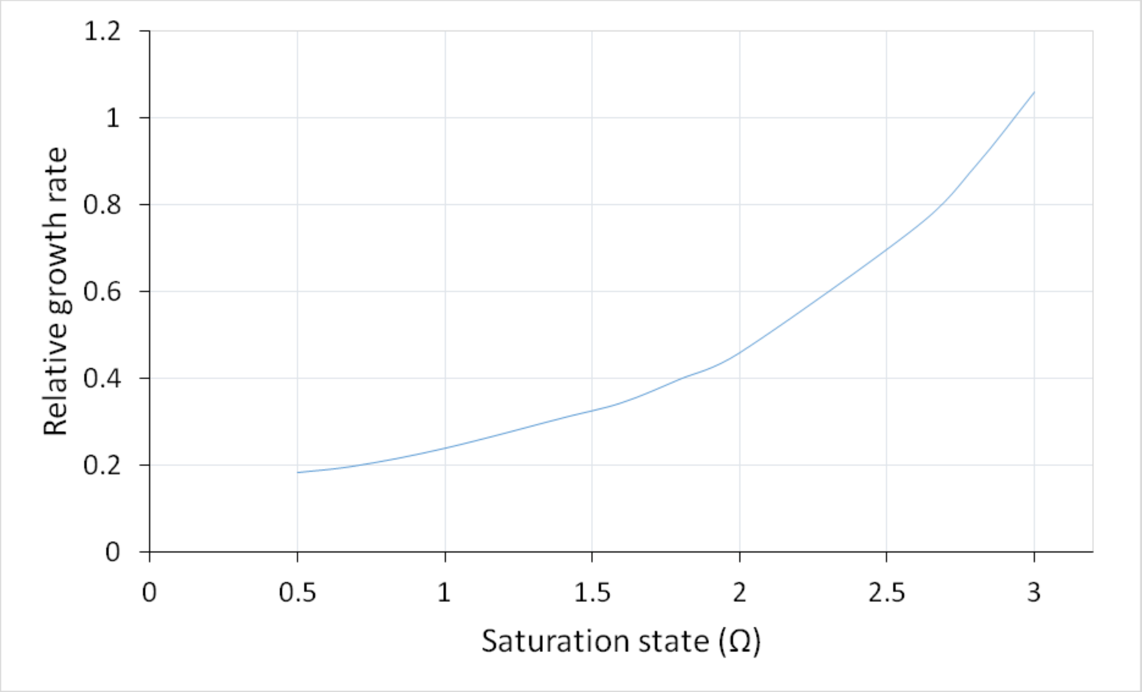

Figure 7: Model simulation curve for relative coral growth rate verses aragonite saturation state over the Kenyan coastline between 2000 and 2021.

CHAPTER FOUR

RESULTS AND DISCUSSION

In this chapter, the results obtained when the various methods outlined in section 3.2 were applied to the datasets highlighted in section 3.1 are presented and discussed.

4.1 Results for spatial-temporal variability of sea surface temperatures over Kenyan coastline

4.1.1 Spatial variation of sea surface temperatures

The spatial variation of mean SSTs was calculated on a monthly basis from January to December between 1990 and 2021. The mean sea surface temperature was observed to vary considerably between months, seasons and across different geographical locations along the Kenyan coastline. The results indicated a notable zonation of SSTs along this coastline from the northern area to southern area as SSTs were observed to increase gradually from the south towards the north as is shown in Figure 8. These variations were attributed to changes in latitude across the coastline and patterns of ocean currents which flow across this coastline.

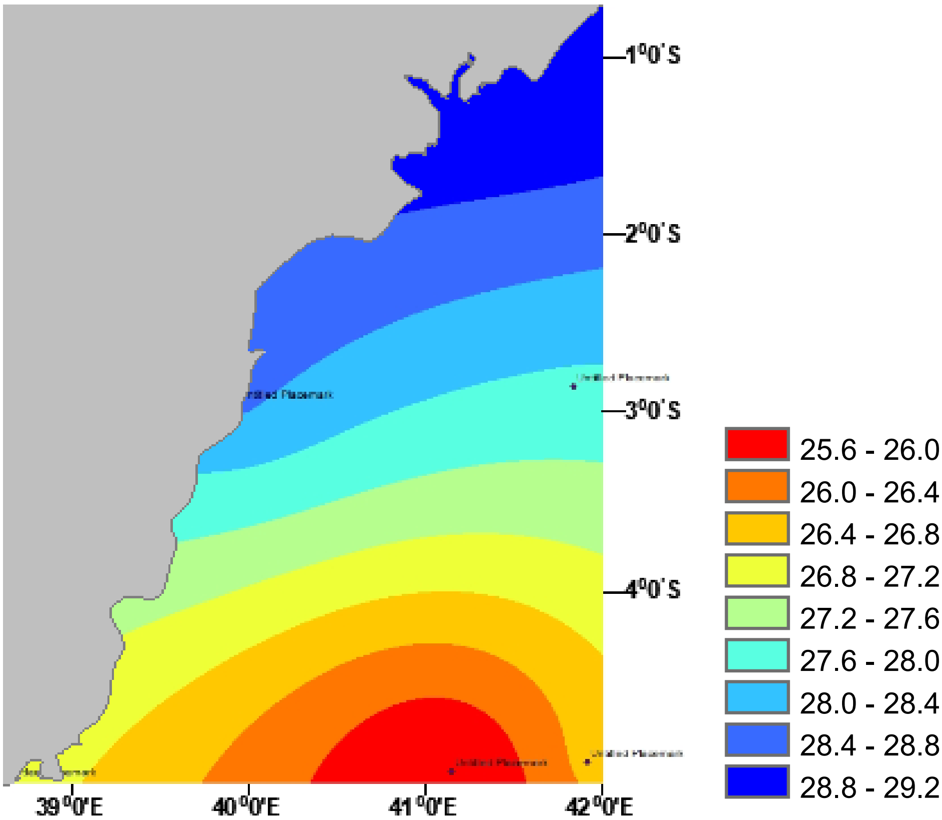

Figure 8: Spatial distribution of mean sea surface temperatures (^{0}C) over the Kenyan coastline for the period 1990-2021.

4.1.2 Temporal variation of sea surface temperatures

Monthly mean SSTs calculated between 1990 and 2021 showed that SSTs along the entire Kenyan coastline increase gradually from January to April, then decrease from May to September and increase again from October to December as is shown in Figure 9. This indicated two seasonal variations in sea surface temperatures along this coastline, when SSTs are high and when SSTs are low.

The calculated standard deviation also showed that SSTs in the colder season with a standard deviation of less than 0.4^0C are adjacent to the mean as compared to SSTs in the warmer season with a standard deviation of 0.5^0C or more. This implied that in the warmer season, sea surface temperatures varied over a wider range and deviated further because of more than normal heat that has been absorbed by the surface ocean waters.

In the warmer season, maximum monthly SSTs ranged from 29.9^0C in April to 27.5^0C in October whereas in the colder season, maximum SSTs ranged from 27.3^0C in June to 26.1 in August. Minimum monthly SSTs for the warm season ranged from 28.3^0C in April to 25.6^0C in October while in the colder season, minimum SSTs ranged from 27.3^0C in May to 24.4^0C in August.

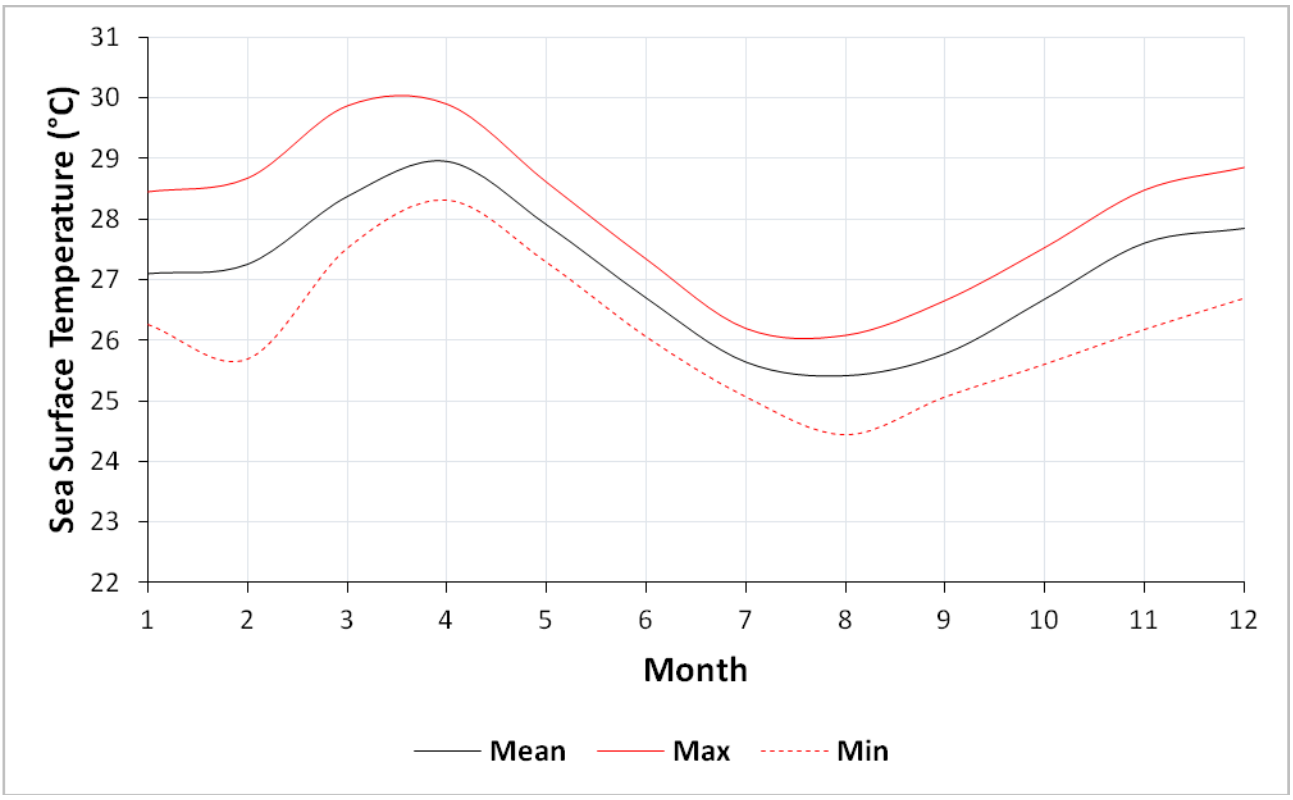

Figure 9: Mean, Maximum and Minimum sea surface temperatures (^{0}C) over the Kenyan coastline for the period 1990-2021.

4.1.3 Trend test results for sea surface temperatures

Trend analysis for the Kenyan coastline was done with data on sea surface temperatures for 31 years, from 1990 to 2021. The results of the trend analysis of sea surface temperature over the Kenyan coastline are shown in Figure 10 and Table 4.

SSTs over the Kenyan coastline showed an increasing trend over the entire coastline. Figure 10 represents annual sea surface temperatures with maximum SST recorded being 27.9^0C and minimum recorded SST being 26.6^0C. The test statistic (S) value for average SSTs obtained by the MK test was 27.1^0C as stated in Table 4 which represents the mean SST for this coastline. The trend results also show that SSTs have averagely changed over time with periods of more than normal SSTs experienced across this coastline at different times. The gradual change in temperatures has led to the rise in water temperatures.

The increasing trend of SSTs show that the surface ocean waters have continually absorbed more heat from the atmosphere over time leading to the rise of sea surface temperature. The rise in temperature leads to bleaching of coral reefs as their thermal limits become exceeded. The thermal threshold for the coral reefs along the Kenyan coastline is 25.9^0C as shown by Dixon *et al.* (2022) beyond which bleaching occurs causing the corals to lose their source of food and energy by expelling algae (Hughes *et al.*, 2017). This phenomenon translates to more negative effects on marine life and species which utilize the coral reefs in various ways (Makoye and Kaaya, 2018).

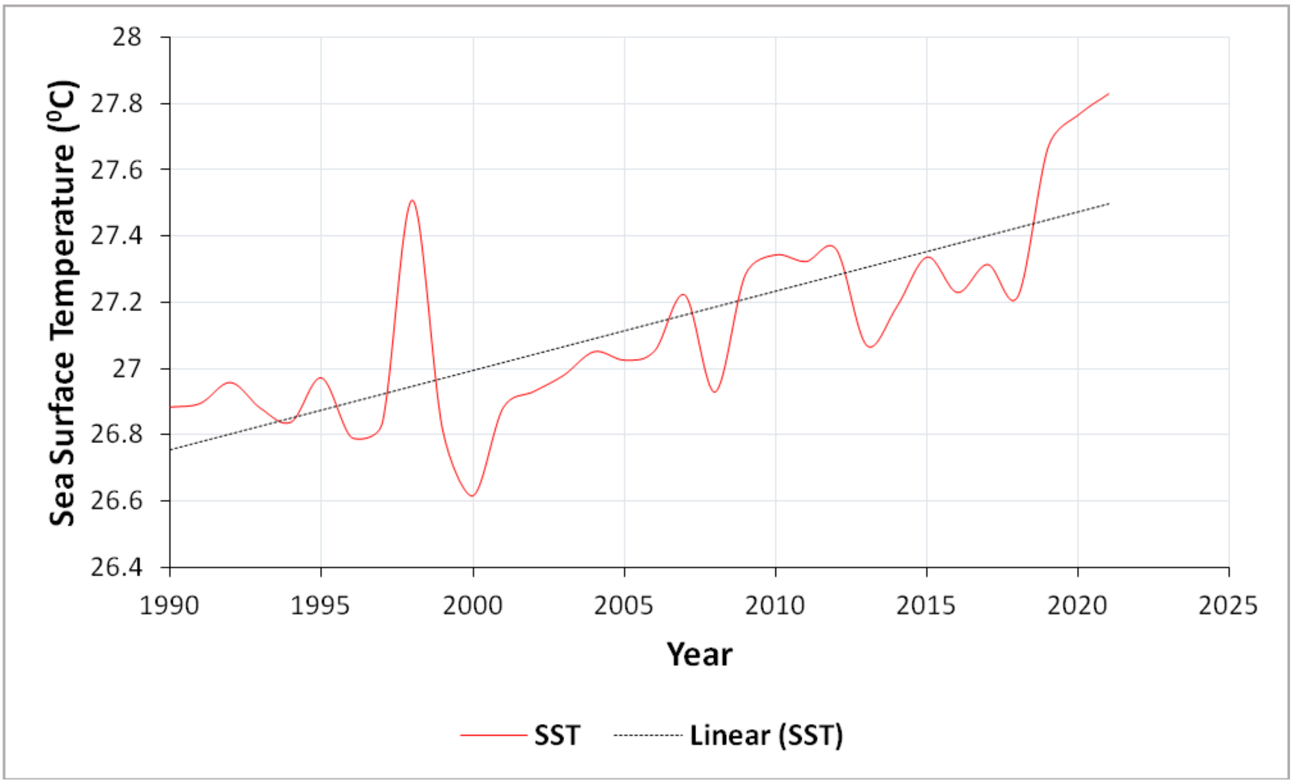

Figure 10: Time series of observed mean annual sea surface temperatures (^{0}C) over the Kenyan coastline between 1990-2021.

Moreover, the positive Sen's slope results, Q= 0.022 shown in Figure 11 and Table 4 indicated an increasing slope of 0.022^{0}C per year over the Kenyan coastline in the period 1990-2021. The slope was found to be significant at a level of significance of 5% because the obtained p-value was lower than the alpha significant level 0.050. This positive Sen's value agreed with positive values for the MK statistic. These results imply further that the temperature of the sea has risen significantly in the preceding years and if the trend in the emissions of GHGs will continue as they are or even increase over time in the future, then SSTs will continue to escalate.

These results agree with those of Hoegh-Guldberg *et al.* (2014) and Johnson *et al.* (2018) who found out that the speed of warming in the oceans had increased significantly in the global oceans at 0.280±0.068^{0}C higher than the long term mean between 2008 and 2018 and that the Indian ocean had warmed up faster than the other two tropical oceans, the Atlantic and the Pacific. The results also concur with the findings of a study done by Vu Duy, 2022 on analysis of sea surface temperature trends using mann-kendall test in Hai Pong whose results confirmed an increase in annual SST at a rate of 0.02^{0}C every year from 1995 to 2020.

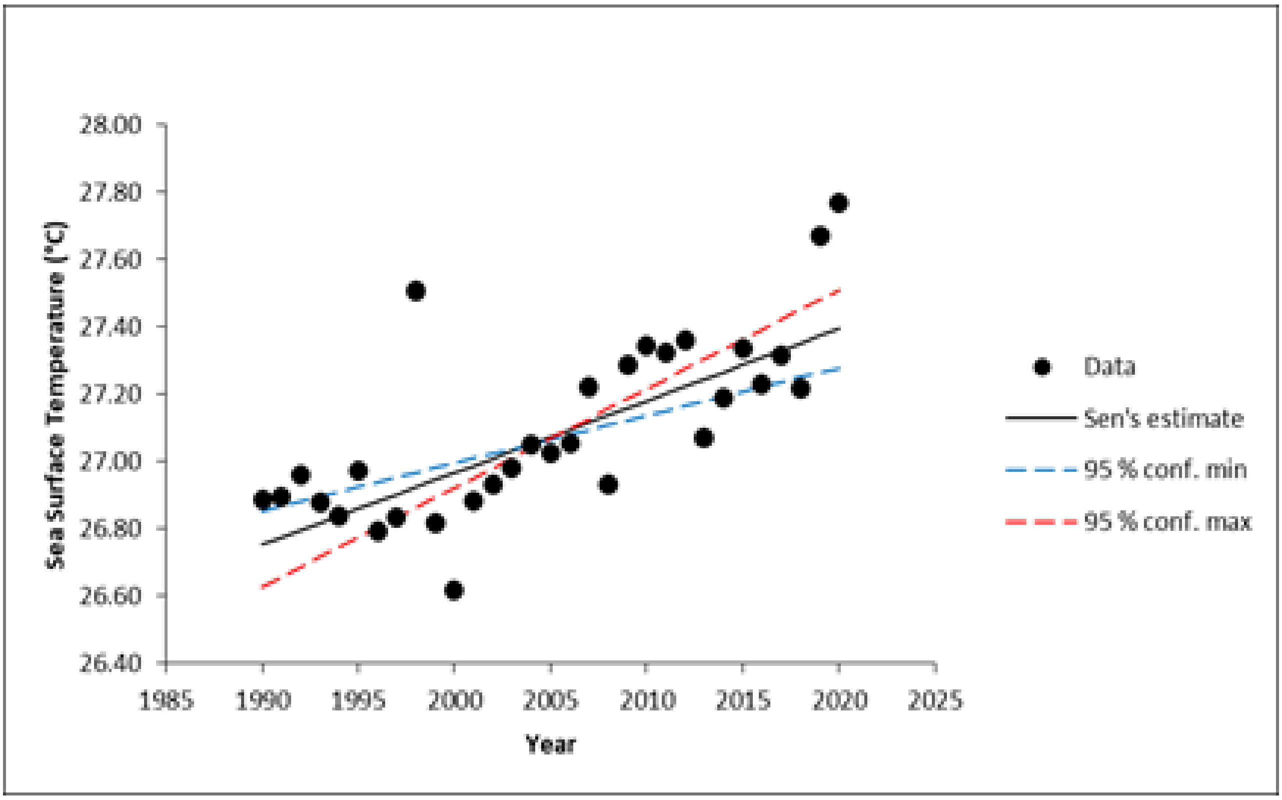

Figure 11: Sen's slope of mean annual sea surface temperatures (^{0}C) over the Kenyan coastline between 1990-2021.

Table 4: Trend test results of mean annual sea surface temperatures (^{0}C) using MK test over the Kenyan coastline.

Variable	**SST(^{0}C)**
Test statistic (S)	27.110
P value (two-tailed)	<0.0001
Alpha	0.050
Sen's slope Q	0.022
Trend	Increasing

4.2 Results for spatial-temporal variability of absorbed carbon dioxide over Kenyan coastline

4.2.1 Spatial variation of total absorbed carbon dioxide and pH

The spatial variation of mean total dissolved carbon dioxide was calculated between 1990 and 2021. The mean values of TCO_2 varied considerably across the entire Kenyan coastline with a significant regional variation between the northern part and the southern part. The results also indicated that the waters in the northern part of this coastline were more concentrated with carbon dioxide as compared to those in the southern part as shown in Figure 12.

The spatial variation observed in annual mean of pH along the Kenyan coastline showed a narrow range in the southern part of the coastline and a wider range in the northern part. Figure 13 shows the spatial distribution of pH within the surface waters of the Kenyan coastline. Moreover, the results indicated that the northern region was more susceptible to reduced levels of pH compared with the southern area. This can be linked to the observation made in the spatial distribution of CO_2 high amounts of carbon dioxide dissolving in the northern waters. This implies that the waters in the north are more acidic compared to the southern waters. This is attributed to the impacts of the cold Somali current which flows downwards towards Lamu region in the northern part making the waters cooler thus highly absorbent of CO_2. The influence of the Northerly winds which bring about upwelling and results in high organic matter present in the upper layers of ocean contributing further to decreased pH levels.

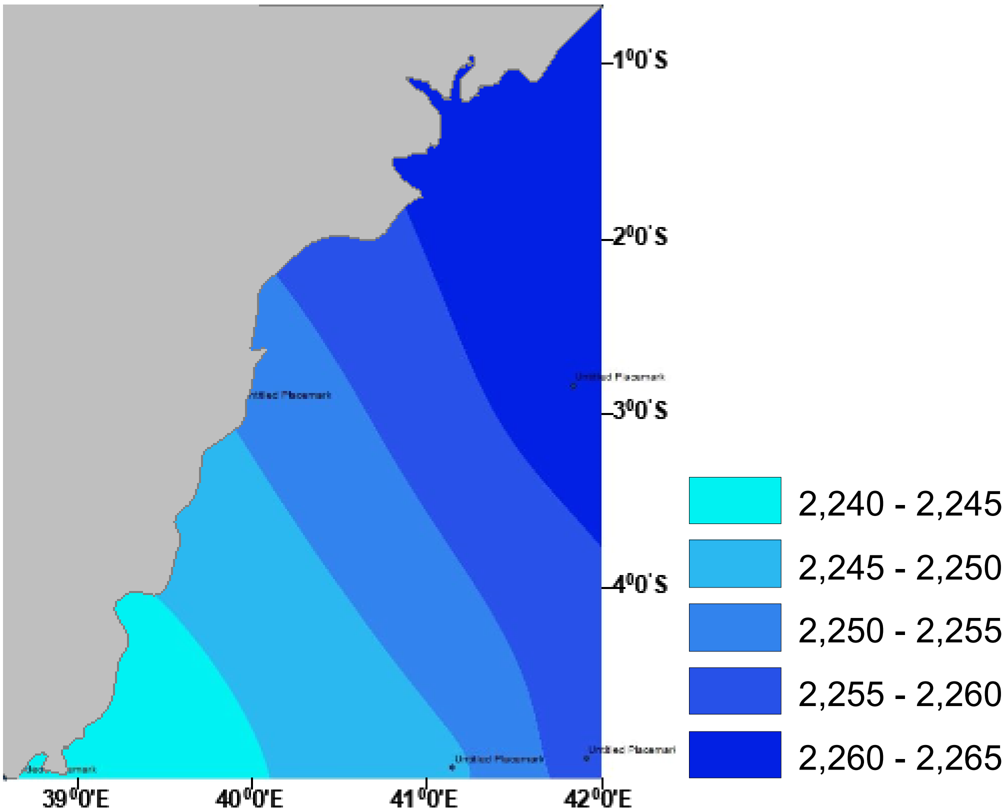

Figure 12: Spatial distribution of mean dissolved carbon dioxide (umol/kg) over the Kenyan coastline for the period 1990-2021.

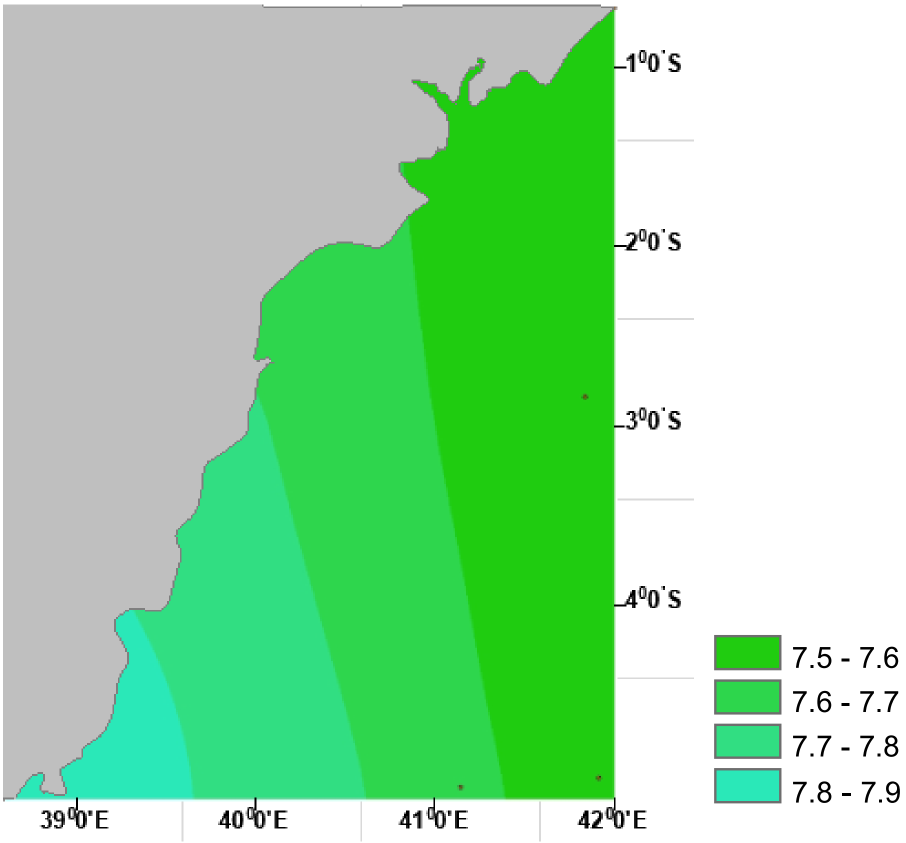

Figure 13: Spatial distribution of mean pH over the Kenyan coastline for the period 1990-2021.

4.2.2 Temporal variation of total absorbed carbon dioxide and pH

Annual mean TCO_2 calculated between 1990 and 2021 showed that TCO_2 along the entire Kenyan coastline had increased between 1990 and 2021 as is shown in Table 5, Figures 12 and 13. Moreover, annual mean pH calculated for the same time period indicated that the pH of the surface waters along this coastline had declined over time. The maximum annual TCO_2 was found to be 2284.8 umol/kg corresponding to a minimum pH value of 6.8 units of pH that was observed within the same timeline. Further, the minimum annual TCO_2 was found to be 2218.4 umol/kg which corresponded to the maximum observed pH value of 8.48. This correspondence was made because, the more the water absorbs carbon dioxide, the less the pH of the water becomes and vice versa. The calculated standard deviation of both TCO_2 and pH implied a strong relationship and variation between the two variables such that when one increases (TCO_2) the other one decreases (pH) and subsequently, when one decreases (TCO_2) the other one increases (pH).

Table 5: Statistical information on total absorbed carbon dioxide (umol/kg) and pH for the period 1990-2021 along the Kenyan coastline.

	Maximum	**Minimum**	**Mean**	**Std deviation**
TCO_2	2284.8	2218.4	2337.35	17.9812
pH	8.48	6.8	8.02	0.424315

4.2.3 Trend test results for total dissolved carbon dioxide

The trend analysis for total dissolved carbon dioxide (TCO_2) was calculated with 31 years of data between 1990 and 2021. The trend results of TCO_2 over the Kenyan coastline are as shown in Figure 14 and Table 6.

It was noted that TCO_2 over the entire Kenyan coastline showed an increasing trend. Figure 14 shows the annual total dissolved carbon dioxide with maximum observed TCO_2 being 2284.8 umol/kg and minimum observed TCO_2 being 2218.4 umol/kg. The test statistic (S) value for average TCO_2 obtained by MK test was 2265.175 umol/kg as shown in Table 6 which represents the mean TCO_2 for this coastline for the period 1990-2021.

The increasing trend of TCO_2 revealed that the content of carbon dioxide which dissolved in oceans has spiraled over time leading to an increase in surface ocean water acidity and reduced levels of pH. This has contributed to reduced amounts of $CaCO_3$ that is available for coral reefs to be able to reproduce, form and maintain their structures. These results are consistent with studies done by Cornwall *et al.* (2021) on declining production of calcium carbonate under ocean acidity and warming who found out that acidification in oceans reduced rates of calcification in corals and coralline algae within tropical areas and in temperate areas that formed reef structures and their sediments. The outcomes also concur with results of Lischka *et al.* (2018) and Bindoff *et al.* (2019) who found out that increased CO_2 absorption by surface ocean waters causes alterations in ocean carbonate chemistry and that reduced carbonate ions are significant biologically because they affect the speeds at which calcareous aquatic species such as corals create their structures.

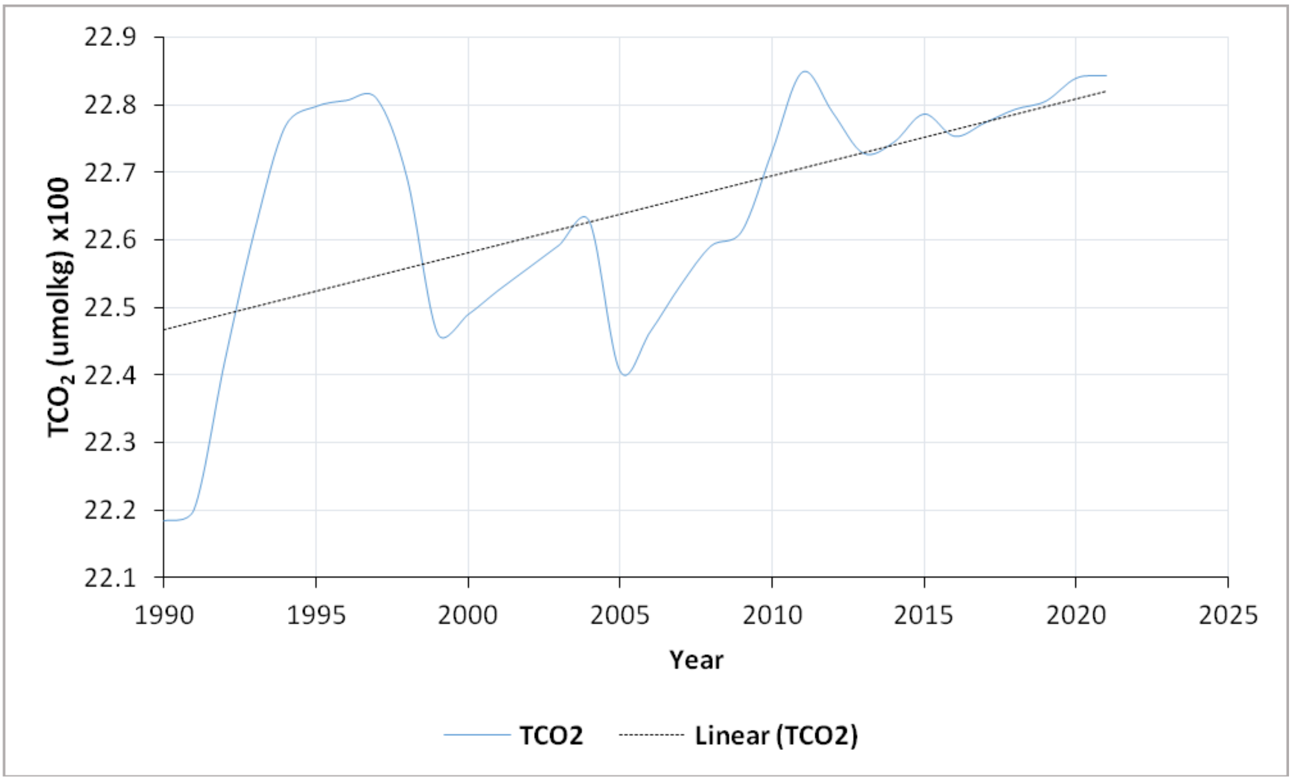

Figure 14: Time series of observed mean annual total absorbed carbon dioxide (umol/kg) over the Kenyan coastline between 1990-2021.

Additionally, the positive Sen's slope results of Q= 1.283 shown Figure 15 and Table 6 indicated an increasing slope of 1.283 umol/kg per year over the Kenyan coastline for the period 1990 to 2021. The slope was found to be significant at 5% significant level as the measured p-value was lesser than the alpha significance value 0.050. This positive Sen's value endorsed the MK statistic's positive values. These results further implied that significant amounts of carbon dioxide have continued to dissolve into the top waters of the ocean and that if the trend is continued, then more carbon dioxide will dissolve in the waters making them more acidic. These findings agreed with those of Haigh *et al.* (2015) who found out that approximately 30% of all atmospheric concentrations of carbon dioxide had disslove into the global oceans leading to ocean acidification.

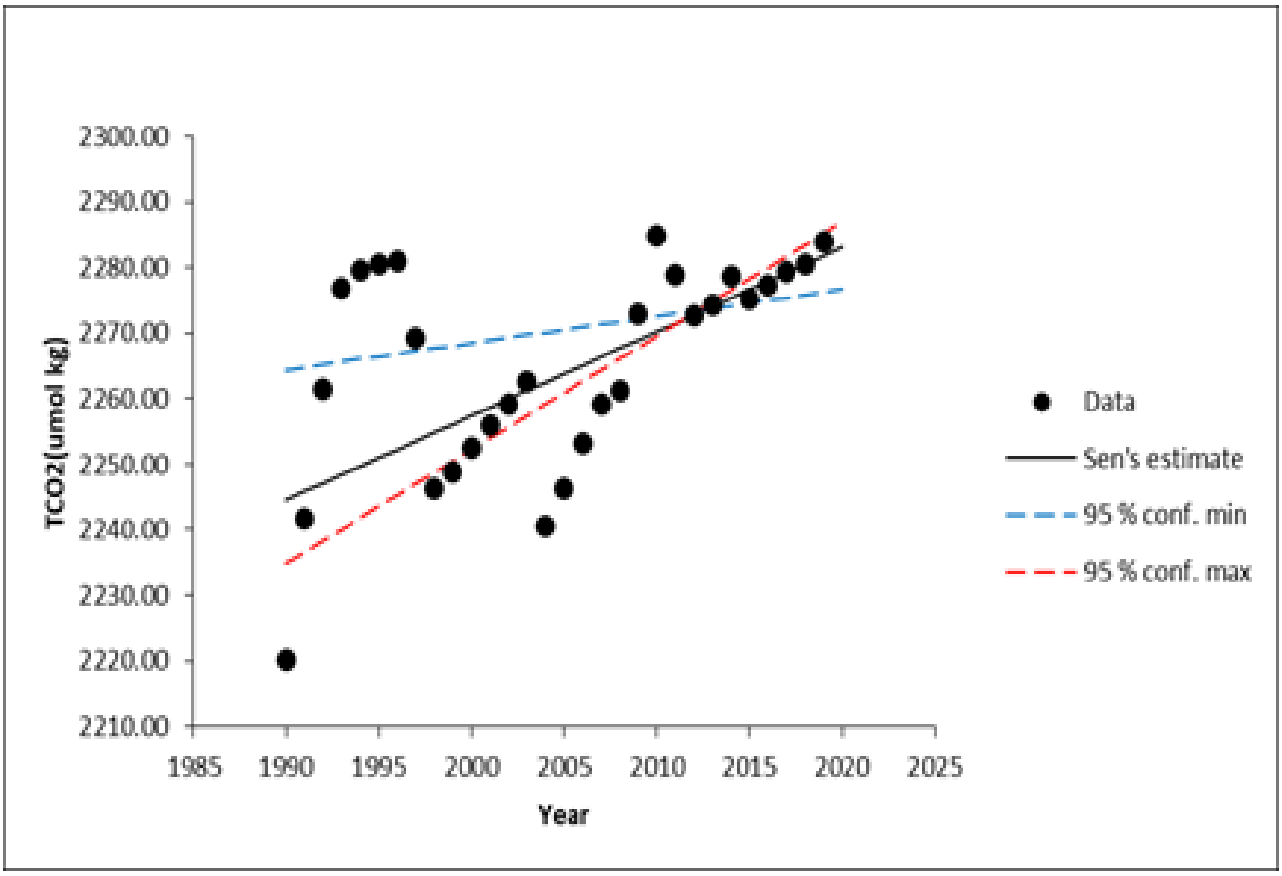

Figure 15: Sen's slope of mean annual total absorbed carbon dioxide (umol/kg) over the Kenyan coastline between 1990-2021.

Table 6: Trend test results of mean annual total absorbed carbon dioxide (umol/kg) using MK test over the Kenyan coastline.

Variable	**TCO_2**
Test statistic(S)	2265.175
P value(two-tailed)	0.003
Alpha	0.050
Sen's slope Q	1.283
Trend	Increasing

4.2.4 Trend test results for ocean surface water pH

The results of the MK trend test for mean annual pH over the Kenyan coastline in the period 1990 to 2021 are shown in Figure 16 and Table 7. It was established that pH over the Kenyan coastline showed a decreasing trend over the entire coastline. In Figure 16, the maximum recorded pH was 8.48 units of pH and the minimum recorded was 6.8 units of pH. The test statistic (S) value of mean pH was found to be -7.7 units of pH as indicated in Table 7 representing the mean pH for this coastline for the period 1990-2021. The negative mean value indicated a decreasing trend in pH over this coastline. Figure 16 also showed that after the year 2020, the levels of water acidity along the shoreline of Kenya dropped below the 7.0 units of pH reference line separating alkalinity from acidity. These results concur with previous studies done by Trnovsky *et al.* (2016) that found out that compared to pre-industrial times, pH of the surface ocean waters has reduced by 0.1 units which represented 30% increase in the acidity. Further, the results also concur with Roxy *et al.* (2020) that revealed that over the Indian Ocean, of the surface ocean declined by about 0.1-unit in comparison to pre-industrial levels, which is greater over the western Indian ocean region.

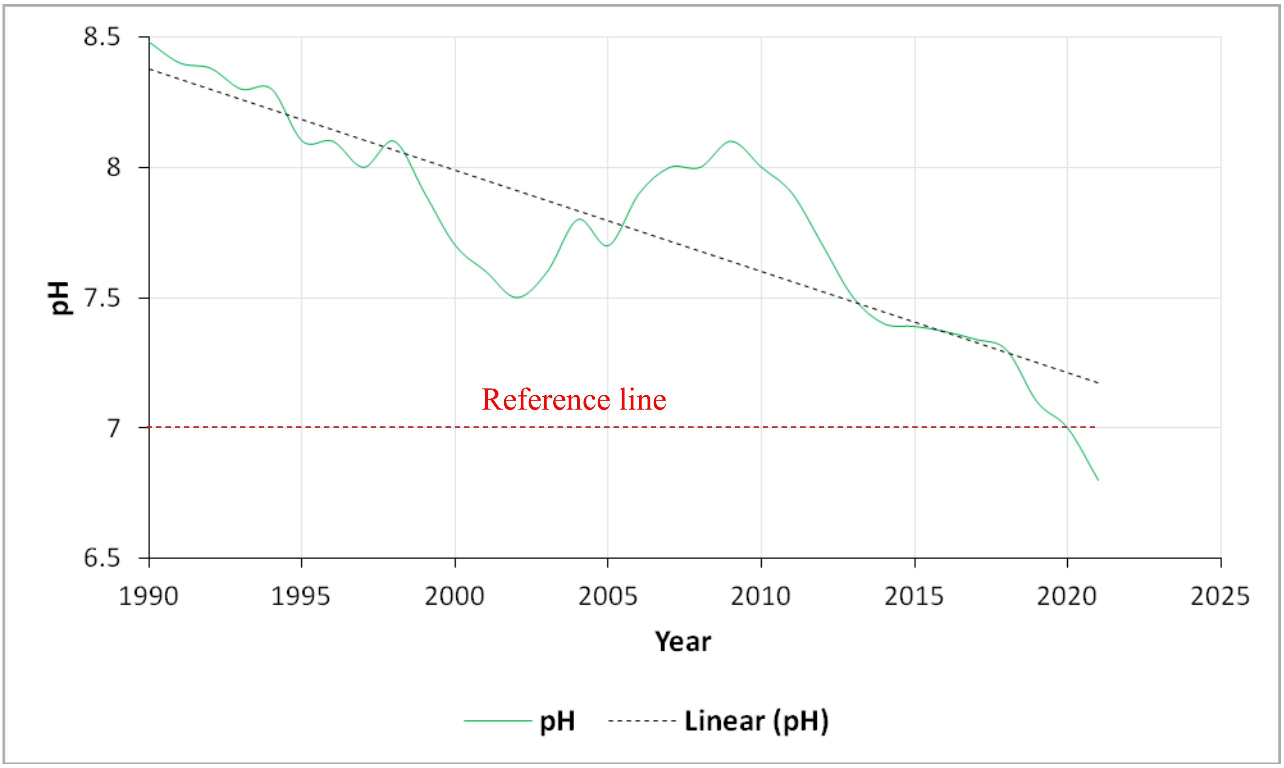

Figure 16: Time series of observed mean annual pH of sea surface waters along the Kenyan coastline between 1990-2021.

Moreover, the negative Sen's slope Q= -3.93 shown Figure 17 and Table 7 indicated a downward slope which was found to be significant at 5% significance level because the p-value was lesser as compared to the alpha significance level 0.050. This negative Sen's value concurs with the negative result of the MK statistic. This can be attributed to increased absorption of CO_2 by the surface waters which forms carbonic acid that is further broken down into H^+ and CO_3^{2-} ions. The growth in the number of H^+ lowers the water pH. This result is in concurrence with Kleypas, (2019) that also found out that increased CO_2 absorption by warm oceans will lead to the concentration of hydrogen ions rising in the sea waters thus causing the oceans to become more acidic. The results are also consistent with model results of Hoegh-Guldberg *et al.,* 2014 which had projected a greater decline of pH in the surface ocean waters after the year 2014 with RCP2.6 and RCP8.5.

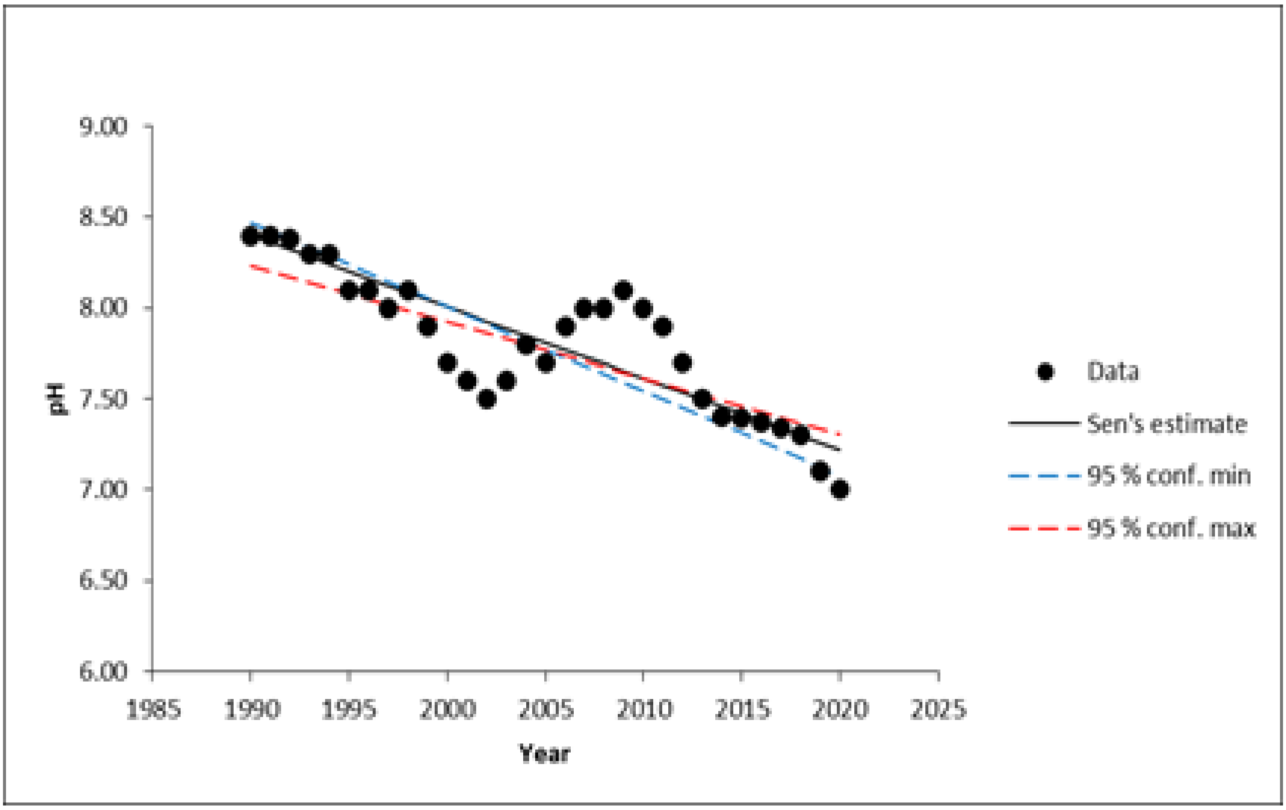

Figure 17: Sen's slope of mean annual pH over the Kenyan coastline between 1990-2021.

Table 7: Trend test results of mean annual pH using MK test over the Kenyan coastline.

Variable	**pH**
Test statistic (S)	-7.7
P value (two-tailed)	0.017
Alpha	0.050
Sen's slope Q	-3.93
Trend	Decreasing

4.3 Results for combined effects of SSTs and absorbed CO_2 using the Combined Mortality and Bleaching Output model simulation

4.3.1 COMBO Model Validation

The COMBO model was verified through comparison of model values of mean monthly SSTs and TCO_2 for the Kenyan coastline in the period 2000-2021 to satellite-based values obtained from Operational Sea Surface Temperature and Ice Analysis Product (OSTIA) (Good *et al.*, 2020) and from Global Ocean Health Multi-observations product (Le Traon *et al.,* 2019) obtained from Copernicus Marine Service.

To compare the baseline simulations and actual observations, correlation analysis method was employed (Makowski *et al.,* 2020). This method calculates the level of change in one variable due to the change in the other variable. A high correlation indicates that the two variables have a strong relationship whereas a low correlation indicates a weak relationship between the two variables. Further, a positive correlation occurs when an increase in one variable leads to an increase in the other variable while a negative correlation occurs when an increase in one leads to a decrease in the other and vice-versa. At this, mean annual model values from COMBO were plotted versus satellite-based observations as shown in Figure 18 and Figure 19. The COMBO values showed great concurrence in respect to the variety and range of temperature observations and dissolved carbon dioxide.

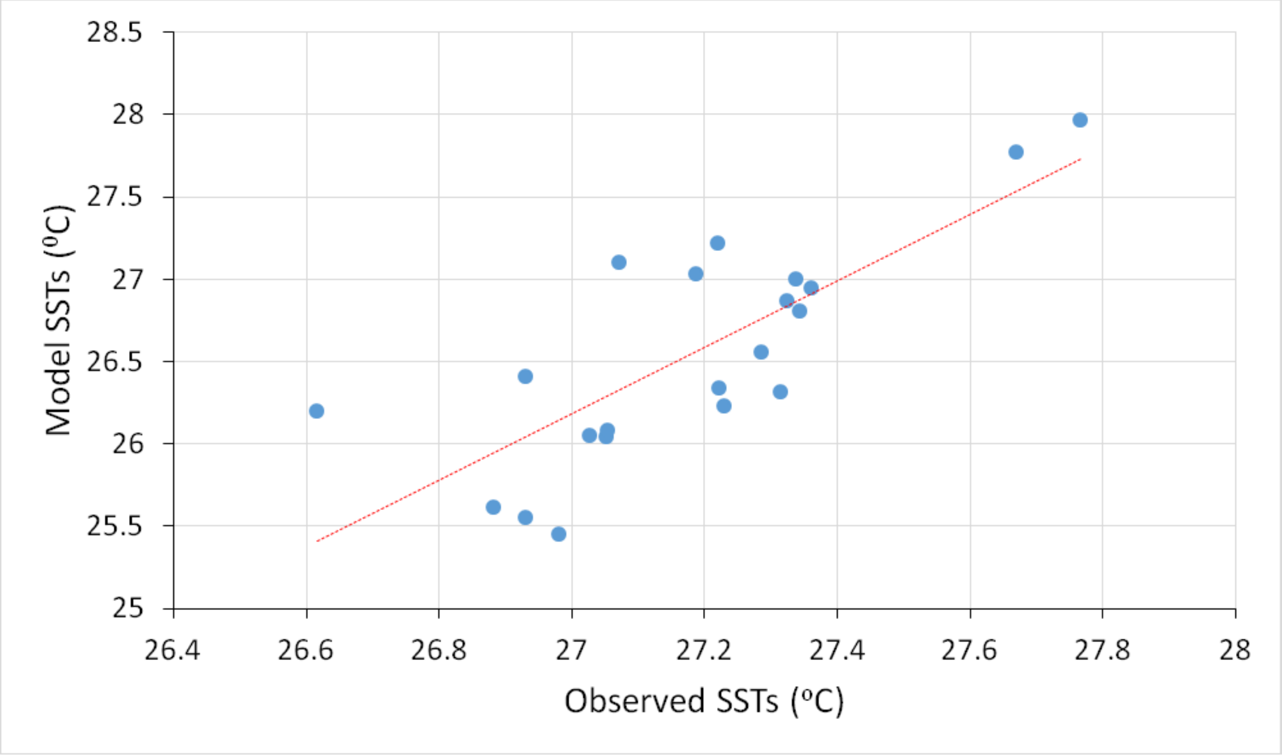

Figure 18: Scatter plot of observed SSTs and model SSTs.

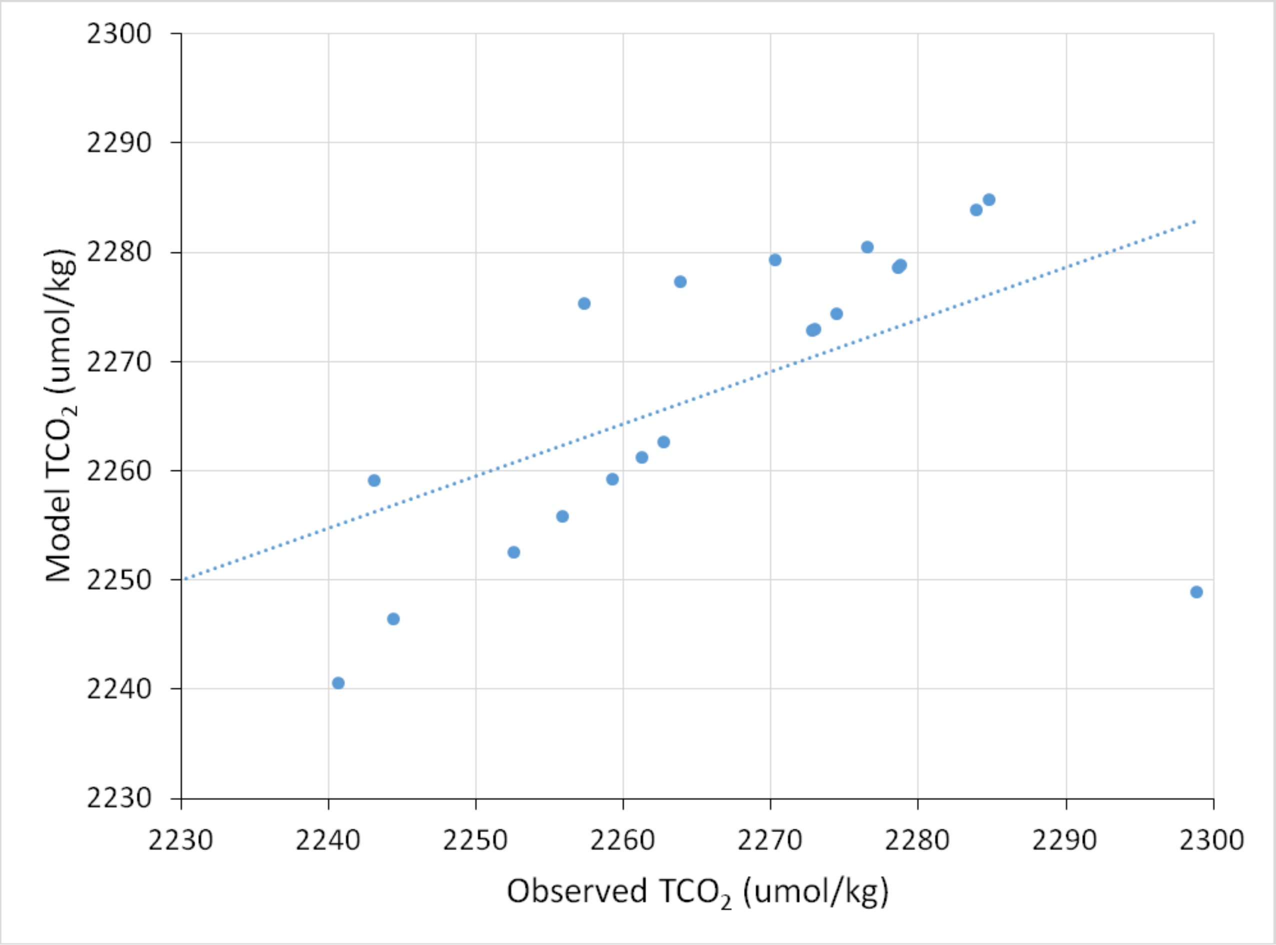

Figure 19: Scatter plot of observed TCO$_2$ and model TCO$_2$.

4.3.2 Analysis of coral reefs response to increasing sea surface temperatures

The results of the model simulation showing the response of the coral reef cover to sea surface temperature variations are shown in Figure 20. The model simulation results indicated that rising sea surface temperatures beyond the optimum value significantly affected the coral reef cover negatively between the year 2000 and 2021. As a result, there was a reduction of 3.2% of coral reef cover along the Kenyan coastline as shown in Table 8. The decline in reef cover was attributed to coral reef bleaching which is a direct consequence of increase in sea surface temperature. Bleaching weakens the structure of coral reefs and makes them susceptible to diseases and eventual mortality.

These results were found to be consistent with literature that showed that ocean warming is occurring more quickly from 1993 to 2017 representing an increase in heat uptake of at least two times (Bindoff *et al.*, 2019). They also corroborate with findings of prior studies done by Osborne *et al.* (2017) who attributed the decline in global coral reef ecosystem cover to periods of rapid increase in sea surface temperature anomalies and sustained high SST anomalies in most global reefs and to the slow rates of coral recovery in the Indo-pacific region following earlier bleaching episodes. Obura *et al.* (2017) equally indicated that there had been a substantial drop in average hard coral cover which formed the basis of the reef ecosystem in the western region of the Indian ocean because of persistently higher temperatures at the surface of the sea that consequently caused bleaching of coral reefs in this region leading to an increase in the amount of dead corals and a decrease in the amount of live corals.

The simulation results in Figure 20 further projected that in the future, coral reef cover is expected to decrease in its percentage size if temperatures continue to increase. The COMBO model projections reveal that in the near-term period between 2022-2041, more coral reef cover loss is expected of up to 6% and 11% following SSP2-4.5 and SSP SSP5-8.5 respectively as outlined in Table 8. This suggests a devastating future for the coral reefs along this coastline together with their ecosystems. The decline is also seen to prolong into the mid-term and in the long-term with sustained increases in sea surface temperatures.

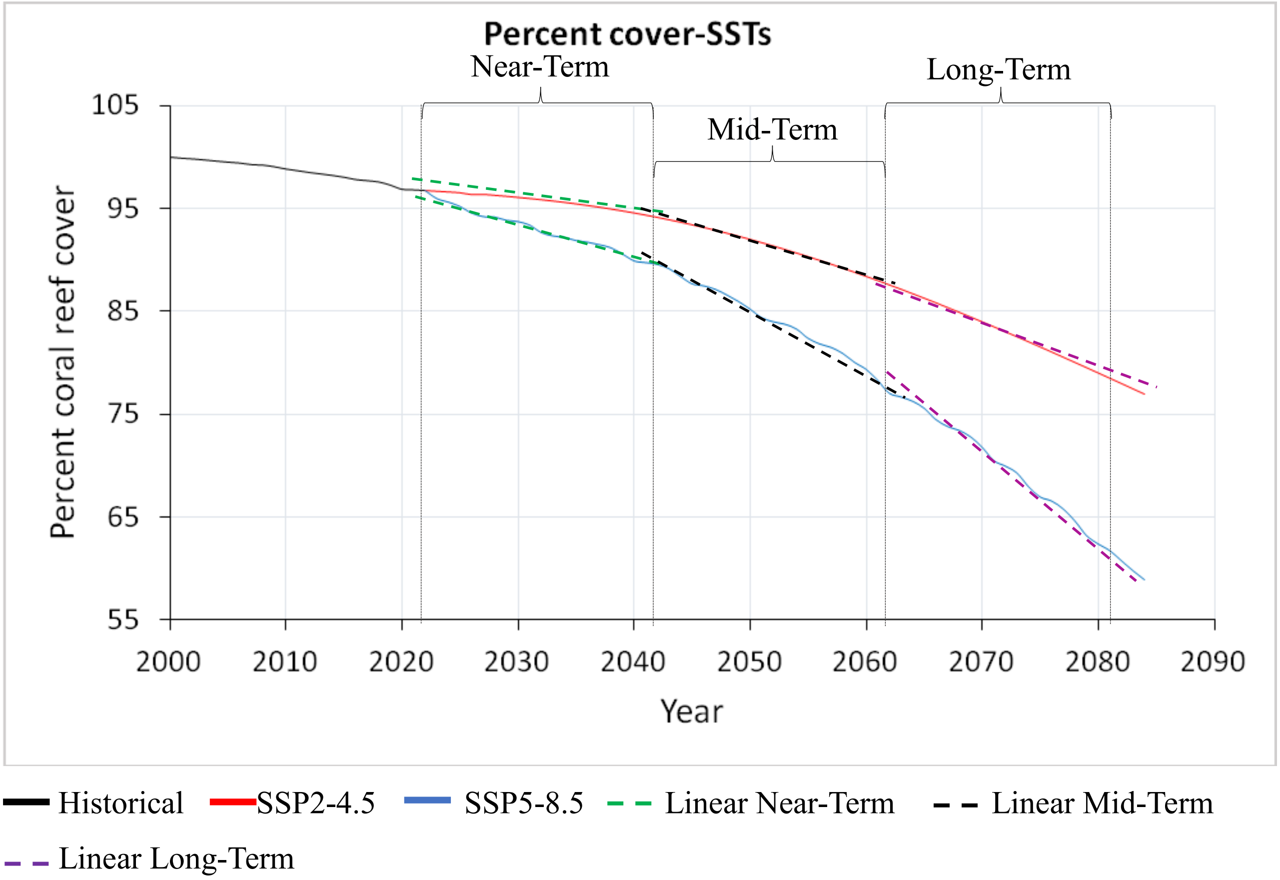

Figure 20: Model simulation of historical (2000-2021) and projected (2022-2081) responses in percentage coverage of coral reefs along the Kenyan coastline to the rising SSTs under two climate scenarios SSP2-4.5 and SSP5-8.5 in the Near-Term, Mid-Term and Long-Term.

Table 8: Percentage of coral reef cover change attributed to Sea Surface Temperature (SSTs).

	Percentage change in cover	
Historical	-3.2	
	SSP2-4.5	**SSP5-8.5**
Near-Term	-6.0	-11
Mid -Term	-13	-22
Long -Term	-22	-38

4.3.3 Analysis of coral reefs response to absorbed carbon dioxide.

The model simulation results in Figure 21 revealed that dissolved carbon dioxide in the ocean affected coral reef cover negatively historically between the years 2000-2021. This has led to a reduction of 3.5% of coral reef cover along the Kenyan coastline as indicated in Table 9. This loss was attributed to decreased sea surface water pH and a decline in the number of carbonate ions following ocean acidification which the corals required to build their structures and skeletons.

These outcomes concurred with outcomes of previous studies by Cornwall *et al.* (2021) that established that ocean acidification was projected to reduce the rates of calcification of most corals in the tropics which form reef structures and sediments. Trnovsky *et al.* (2016) also showed that ocean acidification would reduce the rates of accretion of coral reefs by increasing the dissolution of carbonate sediments in the ocean.

Moreover, the simulation results in Figure 21 projected that there would be more coral reef cover loss due to continued ocean dissolving of carbon dioxide in future. The projections showed that there would be a decline in coral cover of up to 11% as shown in Table 9 in the near-term (2022-2041) following SSP2-4.5 and up to 15% following SSP5-8.5. The loss would escalate into the mid-term (2042-2061) and the long-term (2062-2081) as the surface waters would become more acidic. This was observed to be detrimental to the coral reef ecosystem because it would interfere with the ability of the coral reefs to maintain the rate of their biological, physical, and chemical deterioration brought about by acidification through calcifying.

These results agreed with findings of research by Cyronak *et al.* (2013) that showed reduced pH of surface ocean waters directly reduces the speed of calcification in coral reefs and escalates the rate of dissolution of $CaCO_3$ thereby affecting reproduction of the coral reef and other marine biodiversity who utilize $CaCO_3$ to build their skeletons and structures. Lam *et al.* (2019) also showed that coral reefs along the Kenyan coastline region experience more stress from decreasing pH levels which increases further their increased sensitivity to heat and other stresses. As a consequence of this, their net calcification rates were curtailed as they became unable to reproduce and to form their anatomies thus reduced in size, shrunk and were not able to develop into maturity levels as a result.

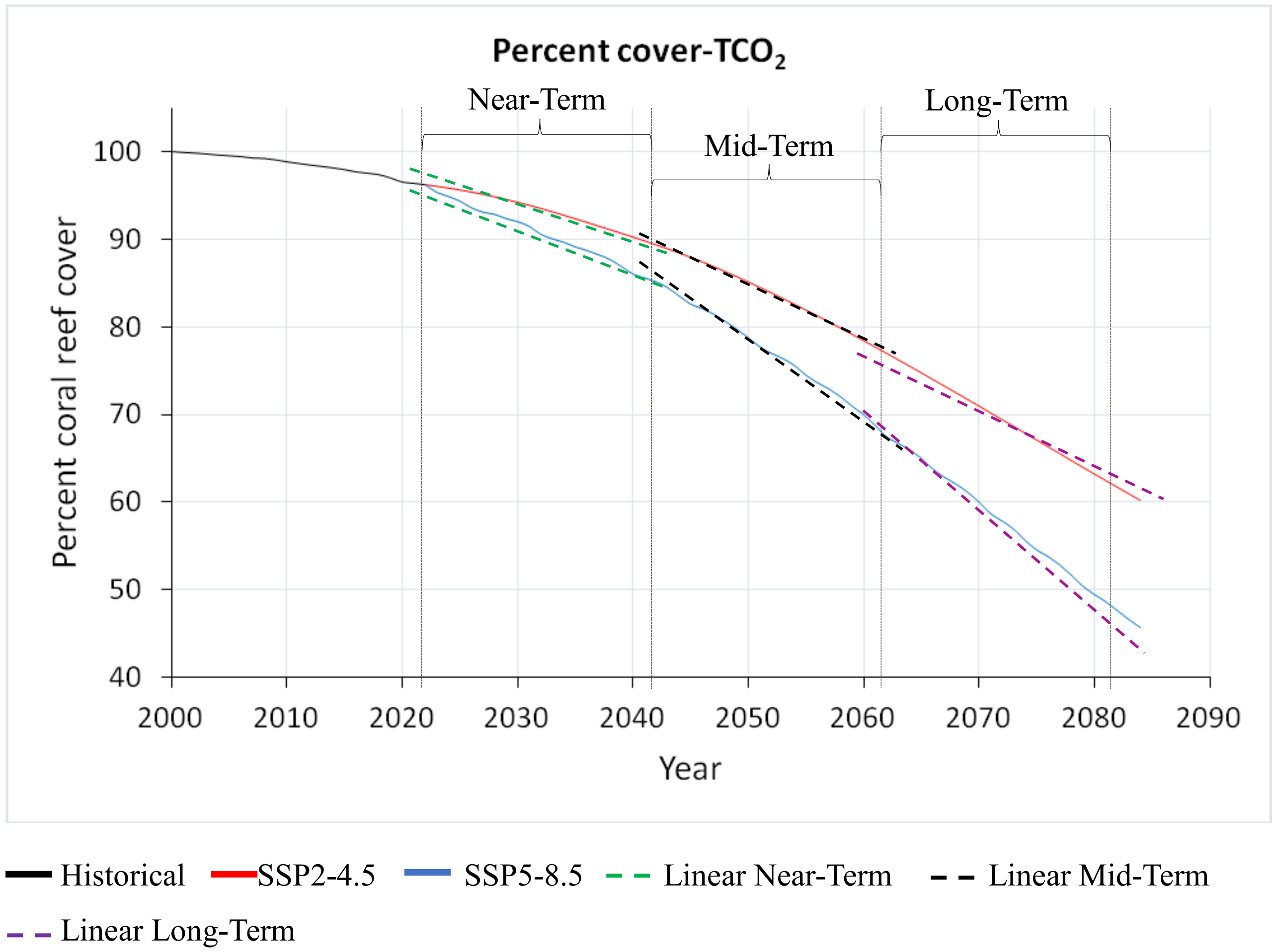

Figure 21: Model simulation of historical (2000-2021) and projected (2022-2081) responses in percentage coverage of coral reefs along the Kenyan coastline to dissolved CO_2 under two climate scenarios SSP2-4.5 and SSP5-8.5 in the Near-Term, Mid-Term and Long-Term.

Table 9: Percentage coral reef cover change attributed to dissolved CO_2 in seawater

	Percentage change in cover	
Historical	-3.5	
	SSP2-4.5	**SSP5-8.5**
Near-Term	-11	-15
Mid -Term	-23	-32
Long -Term	-38	-53

4.3.4 Analysis of the combined effects of sea surface temperature and absorbed carbon dioxide in ocean waters in future.

Results of the model simulation showing the coral reefs cover reaction to the combined effect of sea surface temperature and ocean acidification are shown in Figure 22. The results indicated that there would be a decline in the percentage of coral reef cover between the years 2022 and 2081 due to the combined effect of rising SSTs and continued absorption of CO_2 in the surface ocean waters along the Kenyan coastline. The projections indicated that there would be a cumulative loss in coral reef cover of up to 15% as is shown in Table 10 in the near-term with SSP2-4.5 and up to 18% with SSP5-8.5. This reduction in cover is projected to increase further into the mid-term (2042-2061) and in the long-term (2062-2081) following SSP2-4.5 and SSP5-8.5 as indicated in Table 10 because the surface waters would become warmer and more acidic as had been seen earlier in section 4.1 and section 4.2 of this study. This loss represents over ten times the amount of historical coral reef cover loss between the years 2000 and 2021 by virtue of the action of sea surface temperature and ocean acidification independently. The increased cumulative loss was attributed to exceeded thresholds of temperature and carbonate ion concentration for this coastline which brought about the coupled problem of bleaching and ocean acidification on the coral reefs with the eventual resultant effect being the risk of mortality.

These compare to results of previous studies by Gattuso *et al.,* 2013 who established that on the global scale, changes in warming and ocean acidification dramatically reduced the dispersal, plenitude and survival of the entire coral reef ecosystems by interfering with the corals reefs physiological processes that build and sustain them. Godbold *et al.* (2017) equally showed that changes in temperature and carbonate chemistry within the surface waters are projected to have considerable negative effects on coral reefs and on marine biodiversity and that many coral reef populations won't be able to support a positive rate of net carbon production under RCP4.5 and RCP8.5 because they will suffer reduced accretion rates driven by bleaching and ocean acidification. Further, the results of this study concur with those of a study done by Prada *et al.* (2017) who found out that ocean warming and acidification have a strong synergistic relationship on the mortality of coral polyps. These two stressors increase the metabolism of the polyps leading to abrupt collapse of their cellular processes and performance hence affecting their development and plenitude.

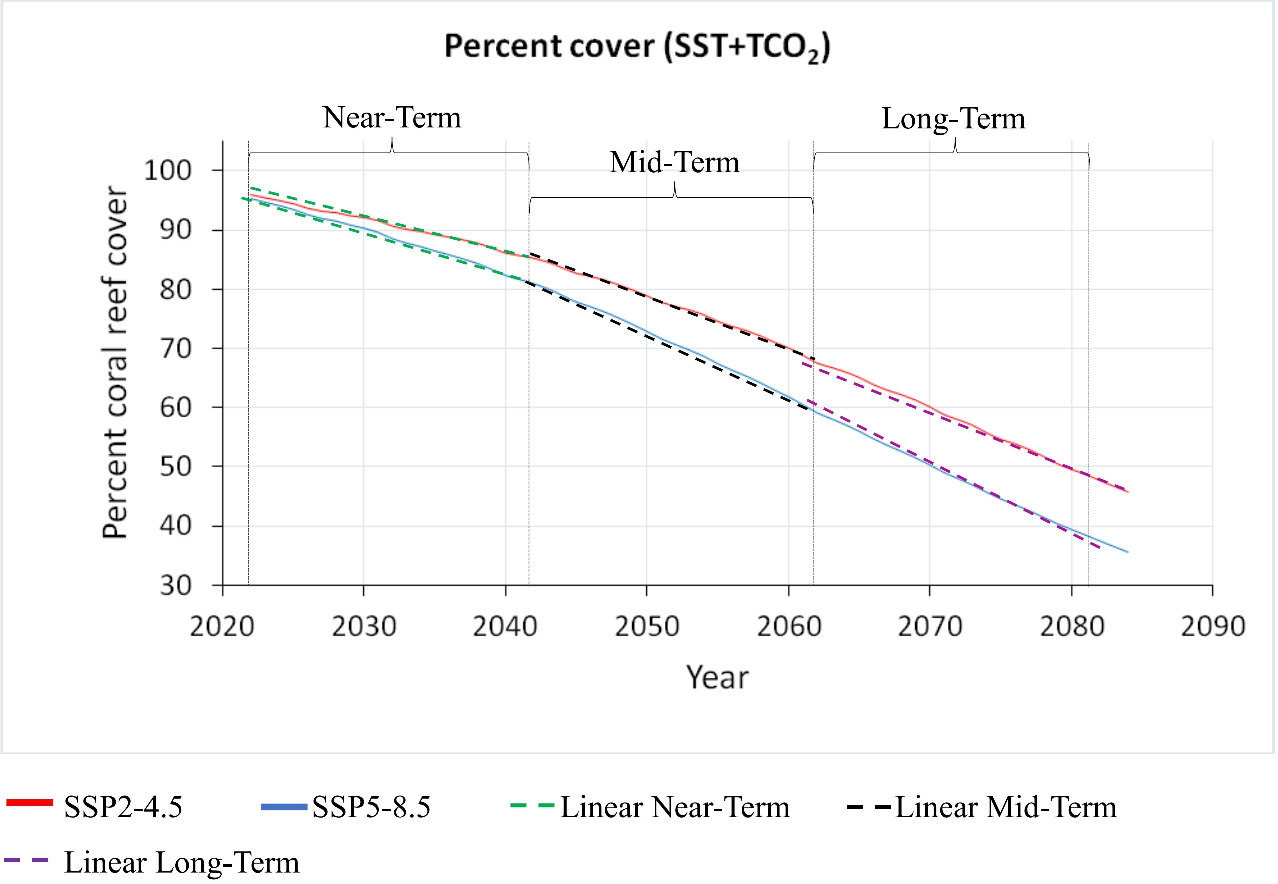

Figure 22: Model simulation of projected future (2022-2081) responses in percentage coverage of coral reefs along the Kenyan coastline to SSTs and dissolved CO_2 under two climate scenarios SSP2-4.5 and SSP5-8.5 in the Near-Term, Mid-Term and Long-Term.

Table 10: Percentage coral reef cover change attributed to the combined effects of both rising SSTs and dissolved CO_2 in seawater

	Percentage change in cover	
	SSP2-4.5	**SSP5-8.5**
Near-Term	-15	-18
Mid -Term	-31	-39
Long -Term	-52	-63

These results indicate that rising SSTs and increasing ocean acidification will have massive impact on the coral reef ecosystem along the Kenyan coastline. The ocean surface waters are expected to be significantly warmer as evidenced by analysis and corroborated by other studies (Cheng *et al.*, 2017; Roxy *et al.*, 2020) indicating a devastating future for this coral reef ecosystem. More CO_2 is also anticipated to dissolve in ocean waters (Trnovsky *et al.*, 2016; Lischka *et al.*, 2018) and as thus, the resultant impact to the coral reef ecosystem cannot be ignored. The reef cover decline will greatly diminish the services that the ecosystem provides to the society which include among others; provision of habitat to marine organisms who utilize them as nursery grounds (Makoye and Kaaya, 2018), prevention of coastal erosion and flooding, defense of the main lands against storms (Menéndez *et al.*, 2020), provision of breeding grounds for 50% of marine organisms (UNEP, 2010), provision of food, medicine and livelihoods for over 500 million people in the world (Keith *et al.*, 2014), they are sites for ecotourism and they lay foundations for some islands globally.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

This study aimed to ascertain the effects of climate change on the coral reef ecosystem along the Kenyan coastline. In particular, it looked into two indicators; sea surface temperatures and ocean acidification and how their combined effect would affect the coral reef ecosystem. The study hypothesized that sea surface temperatures will continue to rise as oceans absorb excess heat from the atmosphere because of increasing GHG concentrations. Similarly, the concentration of carbon dioxide in sea waters will continue to rise thereby lowering the sea water pH and leading to ocean acidification as oceans absorb more of the excess CO_2 in the atmosphere.

5.1 Conclusion

The results of this study have shown that sea surface temperatures along the Kenyan coastline vary with changes in climate variability. The significant increasing trend of sea surface temperatures along this coastline between the year 1990 and 2021 indicated that the surface ocean waters have continued to absorb more heat from the atmosphere and increase in their mean heat content. Because of the elevated water temperatures, bleaching in coral reefs along this coastline has become inevitable subsequently leading to their loss and mortality. From these results, the study projects that sea surface temperatures along this coastline will continue to escalate and its effect on the coral reef ecosystem will continue if the trend in GHGs persist.

The findings of this study have also shown that the amount of carbon dioxide which dissolves in oceans varies with the amount of the GHG in the atmosphere. The trend of absorbed carbon dioxide versus time over the Kenyan coastline showed an increasing trend that was significant which implied that that surface waters of the ocean have continually absorbed more carbon dioxide from the atmosphere. The significant downward trend of pH along this coastline further indicated that the waters have become more acidic because of the absorption of CO_2. This has led to reduced rates of calcification in the coral reefs found along this coastline, subsequently affecting the overall size of the reefs. Out of these results, the study projects that if the current trends in emission of CO_2 are sustained, more carbon dioxide will be dissolved in the oceans thereby reducing the pH further which will in turn impede reproduction and sustenance of the coral reefs and their ecosystems.

The results of the COMBO model simulation used in this study also revealed that rising SSTs and dissolved CO_2 in the ocean has negatively affected the coral reef cover along the Kenyan coastline historically over the study period. The loss has been attributed to coral bleaching which is a direct consequence of increase in sea surface water temperature, reduced surface water pH and a depletion in the number of carbonate ions because of ocean acidification that the corals require to build their structures. The results of the simulation also projected that the coral reef cover will keep deteriorating greatly in the subsequent short-term (2022-2041), mid-term (2042-2061) and in the long-term (2062-2081) under SSP2-4.5 and SSP5-8.5 climate scenarios.

The results of the combined effect of rising sea surface temperature and ocean acidification on the coral reef ecosystem along the Kenyan coastline was observed to be very damaging and will lead to the mortality and even near extinction of this ecosystem by the year 2081.

5.2 Recommendations

In light of the findings of this study, the study recommends the following:

It recommends collaborative implementation of policies and practices by national and regional governments, research institutions and policy makers that will reduce the amount of GHG emissions in the atmosphere which further leads to increased sea surface temperatures.

The study also recommends urgent action(s) to concurrently address ocean acidification at global and regional scales through mitigation of carbon dioxide and at the local scale through building coral reef ecosystem resilience to the effects of acidification. It calls for enhanced efforts by the six coastal county governments in Kenya, the community, research organizations to expound on scientific knowledge base while simultaneously implementing targeted and sustainable solutions.

It further calls on the six coastal county governments in Kenya to recognize the input of the scientific society as regards the synergistic effects of ocean bleaching and acidification on the future of the coral reef ecosystem and to chart a course toward sustainable ocean economy. This will ensure that the coral reef ecosystem contributes to the socio-economic development of coastal, regional and global populations.

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