REPORT ON OCEAN ACIDIFICATION MONITORING IN THE WESTERN INDIAN OCEAN REGION
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SUMMARY

Carbon dioxide (CO$_2$) emissions from human activities are largely absorbed by the ocean, accounting for about one-third of the total emissions over the past 200 years from the combustion of fossil fuels, the production of cement, and changes in land use (Sabine et al., 2004). The uptake of CO$_2$ by the ocean benefits society by moderating the rate of climate change but also causes unprecedented changes to ocean chemistry, decreasing the pH of the water and leading to a suite of chemical changes collectively known as ocean acidification. Like climate change, ocean acidification is a growing global problem that will intensify with continued CO$_2$ emissions and has the potential to change marine ecosystems and affect benefits to society.

The chemistry of the ocean is changing at an unprecedented rate and magnitude due to anthropogenic carbon dioxide emissions; the rate of change exceeds that which has occurred for at least the past hundreds of thousands of years. Unless anthropogenic CO$_2$ emissions are substantially curbed, or atmospheric CO$_2$ is controlled by some other means, the average pH of the ocean will continue to fall. Ocean acidification has demonstrated impacts on many marine organisms. While the ultimate consequences are still unknown, there is a risk of ecosystem change that may threaten coral reefs, fisheries, protected species, and other natural resources of value to society.

Since the start of the Industrial Revolution, the average pH of ocean surface waters has decreased by about 0.1 units, from about 8.2 to 8.1. Model predictions show an additional 0.2–0.3 drop in pH by the end of the century, even under optimistic scenarios. Perhaps more important is that the rate of this change exceeds any known change in ocean chemistry for at least 800,000 years. The major changes in ocean chemistry caused by increasing atmospheric CO$_2$ are well understood and can be precisely calculated, despite some uncertainty resulting from biological feedback processes.

However, the direct biological effects of ocean acidification are less certain and will vary among organisms, with some coping well and others not at all. The long-term consequences of ocean acidification for marine biota are unknown, but changes in many ecosystems and the services they provide to society appear likely based on current understanding.

In response to these concerns, WIOMSA launched ocean acidification projects in six countries: Kenya, Mauritius, Mozambique, Seychelles, South Africa and Tanzania, with the support of the Swedish International Development Cooperation Agency and institutional partners in the WIO region. The research provides a baseline that will foster the development of an integrated science strategy for ocean acidification monitoring, research and impact assessment. It presents a review of the current state of knowledge on ocean acidification in the WIO region and identifies the gaps in information required to improve understanding and address the consequences of ocean acidification.

The report consists of seven chapters. Chapter 1 introduces the subject of ocean acidification and chapters 2 to 7 summarize the results of ocean acidification monitoring in the six countries that participated in the four-year monitoring project. Lessons learned and recommendations are presented for each country.
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### ABBREVIATIONS

<table>
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<tr>
<td>OA</td>
<td>Ocean acidification</td>
</tr>
<tr>
<td>WIO</td>
<td>Western Indian Ocean</td>
</tr>
<tr>
<td>WIO</td>
<td>Western Indian Ocean Marine Science Association</td>
</tr>
<tr>
<td>TAFIRI</td>
<td>Tanzania Fisheries Research Institute</td>
</tr>
<tr>
<td>KMFRI</td>
<td>Kenya Marine and Fisheries Research Institute</td>
</tr>
<tr>
<td>ORI</td>
<td>Oceanographic Research Institute</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>H⁺</td>
<td>Hydrogen ion</td>
</tr>
<tr>
<td>CO₃²⁻</td>
<td>Carbonate ion</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>Bicarbonate</td>
</tr>
<tr>
<td>DIC</td>
<td>Dissolved inorganic carbon</td>
</tr>
<tr>
<td>TA</td>
<td>Total alkalinity</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>PCO₂</td>
<td>Partial pressure of carbon dioxide</td>
</tr>
<tr>
<td>GHGs</td>
<td>Greenhouse gases</td>
</tr>
<tr>
<td>DOC</td>
<td>Dissolved organic carbon</td>
</tr>
<tr>
<td>DOM</td>
<td>Dissolved organic matter</td>
</tr>
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1.1. INTRODUCTION

The oceans have absorbed a significant portion of all anthropogenic carbon dioxide (CO$_2$) emissions (approximately a third of the CO$_2$ emitted from fossil fuel emissions, cement production and deforestation; and in doing so have tempered the rise in atmospheric CO$_2$ levels and avoided some CO$_2$-related climate warming. In addition to playing a pivotal role in moderating climate, oceanic uptake of CO$_2$ is causing important changes in ocean chemistry and biology. Carbon dioxide dissolved in water acts as an acid, decreasing its pH and fostering a series of chemical changes. The entire process is known as ocean acidification. Because it is another consequence of anthropogenic CO$_2$ emissions, ocean acidification has been dubbed “the other CO$_2$ problem”, and the “sleeper issue” of global change. Ocean acidification, like climate change, is a growing problem that is linked to the rate and amount of CO$_2$ emissions and is expected to affect ecosystems and society on a global scale.

Unlike the uncertainties regarding the extent of CO$_2$-induced climate change, the principal changes in seawater chemistry that result from an increase in CO$_2$ concentration can be measured or calculated precisely. Importantly, these chemical changes are also practically irreversible on a time scale of centuries due to the inherently slow turnover of biogeochemical cycles in the oceans. The mean pH of the ocean’s surface has decreased by about 0.1 unit (from approximately 8.2 to 8.1) since the beginning of the industrial revolution, representing a rate of change exceeding any known to have occurred for at least hundreds of thousands of years. Model projections indicate that if emissions continue on their current trajectory (i.e., business-as-usual scenarios), pH may drop by another 0.3 units by the end of the century. Even under optimistic scenarios (i.e., SRES scenario B14), mean ocean surface pH is expected to drop below 7.9.

The scientific research on the biological effects of acidification is still in its infancy and there is much uncertainty regarding its ultimate effects on marine ecosystems. However, marine organisms will be affected by the chemical changes in their environment brought about by ocean acidification; the question is how and how much. Several biological processes are already known to be sensitive to the foreseeable changes in seawater chemistry. A prime example is the impairment in the ability of some organisms to maintain skeletons or protective structures made of calcium carbonate resulting from even a modest degree of acidification, although the underlying mechanisms responsible for this effect are not well understood. Effects on the physiology of individual organisms can be amplified through food web and other interactions, ultimately affecting entire ecosystems. Organisms forming oceanic ecosystems have evolved over millennia to an aqueous environment of remarkably constant composition. There is reason to be concerned about how they will acclimate or adapt to the changes resulting from ocean acidification – changes that are occurring very rapidly on geochemical and evolutionary timescales.

1.2. CONTEXT FOR DECISION-MAKING

It may seem that ocean acidification is a concern for the future. But ocean acidification is occurring now, and the urgent need for decision support is already quite evident. Recently, studies have reported failures in marine reproduction caused by ocean acidification, despite the fact that the evidence linking the failures to acidification is largely anecdotal. On the other hand, there is quite convincing evidence that coral reefs will be affected by acidification, but coral reef managers, who are just now beginning to develop adaptation plans to deal with climate change, have limited information on how to address acidification as well. These two examples highlight
the urgent need for information on the consequences of acidification, and also how affected groups can adapt to these changes.

Like climate change, ocean acidification potentially affects governments, private organizations, and individuals – many of whom have insufficient information to consider fully the options for adaptation, mitigation, or policy-development concerning the potentially far-reaching consequences of ocean acidification. While human activities have caused changes in the chemistry of the ocean in the past, none of those changes have been as fundamental, as widespread, and as long-lasting as those caused by ocean acidification. The resulting biological and ecological effects may not be as rapid and dramatic as those caused by other human activities (such as fishing and coastal pollution) but they will steadily increase over many years to come. Such long and gradual changes in ocean chemistry and biology – possibly punctuated by sudden ecological disruptions – undermines the foundation of existing empirical knowledge based on long-term studies of marine systems. Like climate change, ocean acidification renders experience an undependable guide to decision making in the future.

To deal effectively with ocean acidification, decision makers will require new and different kinds of information and will need to develop new ways of thinking. For some, ocean acidification will be one more reason to reduce greenhouse gas emissions; for others, the priority will be on coping with the ecological effects. But in all circumstances, more information to clarify, inform, and support choices will be needed. As is the case for climate change, decision support for ocean acidification will include organized efforts to produce, disseminate, and facilitate the use of data and information in order to improve the quality and efficacy of (climate-related) decisions. The fundamental issue for ocean acidification decision support is the quality and timing of relevant information. Although the ongoing changes in ocean chemistry are well understood, the biological consequences are just now being elucidated.

The problem is complicated because acidification is only one of a collection of stressful changes occurring in the world’s oceans. It is also fundamentally difficult to understand how biological effects will cascade through food webs, and modify the structure and function of marine ecosystems. It may never be possible to predict with precision how and when acidification will affect a particular ecosystem. Ultimately, the information needed is related to social and economic impacts and pertains to “human dimensions” as has been noted in previous reports. It is not only important to identify what user groups will be affected and when, but also to understand how resilient these groups are to the consequences of acidification and how capable they are of adapting to the changing circumstances.

To begin addressing these social problems, the report identifies high priority research and monitoring needs in order to answer the questions of what to measure and why. It also addresses the problem of ocean acidification by identifying elements of an effective regional strategy to help federal agencies provide the information needed by resource managers facing the impacts of ocean acidification in the marine environment.
1.3. OCEAN ACIDIFICATION ON SEAWATER’S CHEMISTRY

As atmospheric CO$_2$ increases and dissolves into the ocean, it modifies the chemistry of seawater. The principal weak acids and bases that can exchange hydrogen ion in seawater and are thus responsible for controlling its pH are inorganic carbon species and, to a lesser extent, borate. Inorganic carbon dissolved in the ocean occurs in three principal forms: dissolved carbon dioxide (CO$_2$ aq), bicarbonate ion (HCO$_3^-$), and carbonate ion (CO$_3^{2-}$). CO$_2$ dissolved in seawater acts as an acid and provides hydrogen ions (H$^+$) to any added base to form bicarbonate:

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^-$$  \hfill (1)

CO$_3^{2-}$ acts as a base and takes up H$^+$ from any added acid to also form bicarbonate:

$$H^+ + CO_3^{2-} \rightarrow HCO_3^-$$  \hfill (2)

Borate [B(OH)$_4^-$] also acts as a base to take up H$^+$ from any acid to form boric acid [B(OH)$_3$]:

$$H^+ + B(OH)_4^- \rightarrow B(OH)_3 + H_2O$$  \hfill (3)

As equation 1 and 2 illustrates, bicarbonate can act as an acid or a base (i.e., donate or accept hydrogen ions) depending on conditions. Under present-day conditions, these reactions buffer the pH of surface seawater at a slightly basic value of about 8.1 (above the neutral value around 7.0). At this pH, the total dissolved inorganic carbon (DIC = 2 mM) consists of approximately 1% CO$_2$, 90% HCO$_3^-$, and 9% CO$_3^{2-}$ (Figure 1.1). The total boric acid concentration ([B(OH)$_4^-$]) is about 1/5 that of DIC. As discussed, increases in CO$_2$ will increase the H$^+$ concentration, thus decreasing pH; the opposite occurs when CO$_2$ decreases. We note that isotope fractionation between B(OH)$_3$ and B(OH)$_4^-$ is used for estimating past pH values.

![Figure 1.1: Typical concentrations of the major weak acids and weak bases in seawater as a function of pH. This conceptual diagram was redrawn from Dickson (2001)](image-url)
1.4. ANTHROPOGENIC CARBON DIOXIDE EMISSIONS AND OCEAN ACIDIFICATION

The exchange of CO$_2$ at the air-water interface is relatively fast, taking place on a time scale of months to a year so that, on average, the concentration of CO$_2$ in surface seawater remains approximately at equilibrium with that of the atmosphere. As the concentration of atmospheric CO$_2$ gas increases year after year, some of it dissolves into the ocean such that about a third of the total CO$_2$ added to the atmosphere from anthropogenic sources – including fossil fuel emissions, cement production and deforestation – over the past 150 years is now dissolved in the oceans (Sabine et al., 2004; Khatiwala, et al., 2009).

The increase in dissolved CO$_2$ concentration decreases the pH and shifts the equilibrium of inorganic carbon species in seawater, resulting in an increase in CO$_2$ and HCO$_3^-$ concentrations and a decrease in CO$_3^{2-}$ concentration (Figure 1.2). For example, under present conditions in the mid North Pacific, for every 100 molecules of CO$_2$ dissolved from the atmosphere, about 7 remain as CO$_2$, 15 react with B(OH)$_4^-$, and 78 react with CO$_3^{2-}$, resulting in an increase of HCO$_3^-$ by 171 molecules. The buffering capacity of seawater – the ability to resist changes in acid-base chemistry upon addition of an acid such as CO$_2$ – depends on the concentration of bases, principally CO$_3^{2-}$ and B(OH)$_4^-$, to neutralize the acid (Figure 1.2). Upon acidification of the oceans, the buffering capacity of seawater will decrease along with pH. Also, ocean water masses that are presently already high in CO$_2$ for any reason are less buffered against further increases in CO$_2$ than those with lower CO$_2$.

![Figure 1.2: Conceptual diagram showing the effect of increasing CO$_2$ concentration on acid-base species in seawater](image-url)
CHAPTER TWO
KENYA’S PROFILE

SUMMARY
Artisanal fisheries of the Western Indian Ocean region provide a vital source of protein and income for coastal communities. Coral-associated and pelagic fish are the dominant catch. With decreasing pH in seawater, which most affects corals, the artisanal fishery is threatened. This research provides baseline information on ocean acidification in the coastal waters of Kenya. The chapter presents changes in the pCO$_2$, pH, DIC and TA of coastal lagoons in Kenya.
2.1. BACKGROUND AND RATIONALE

Ocean acidification, a decrease in the pH of seawater brought about by the rising anthropogenic carbon dioxide (CO₂) emissions, has been occurring globally for at least the past 20 years (Caldeira and Wickett, 2003). The oceans play an important role in the global carbon cycle, acting as a “carbon sink” by taking up about one third of CO₂ from the atmosphere and transporting it around the globe (Le Quéré et al., 2013). When CO₂ enters seawater, it increases dissolved CO₂ concentrations while also combining with water to form carbonic acid, which mostly dissociates into bicarbonate and hydrogen ions. The hydrogen ions (H⁺) produced in this process lower the pH of the seawater. They also react with carbonate ions that are additionally present in seawater to form more bicarbonate ions, reducing the concentration of carbonate ions (See Figure 1.2).

This in turn decreases the saturation state of seawater with respect to calcium carbonate minerals (aragonite and calcite) used by organisms in building shells and skeletons (Le Quéré et al., 2013; James et al., 2020). According to Cornwall and Hurd (2015) and Gaylord et al. (2015), calcifying species in particular seem to be the “losers” in the case of a more acidic ocean and exhibit a range of negative responses, especially when acidification is combined with other stressors, which poses significant challenges to these already threatened tropical marine ecosystems.

The improvement and security of livelihoods, the support of local and national economies, the provision of food and nutrition, and other important functions all depend on Kenya’s coastal and marine ecosystems. Generally, fisheries are likely to be impacted by ocean acidification directly (due to biological and physiological changes) or indirectly (due to changes in habitat and prey availability). A better understanding of the interactions between the effects of ocean acidification and other stresses, will make it easier to pinpoint the roles they play in influencing the dynamics of marine ecosystems thus informing the various management strategies of marine resources.

Figure 2.1: Critical habitats found along the coastal waters of Kenya
The project aimed to develop national capability and capacity to monitor, quantify, and track ocean acidification and its effects in Kenya’s coastal waters. Specific objectives were to:

i. Develop an ocean carbonate chemistry observatory program for improved understanding and forecasting of the effects of ocean acidification;

ii. Determine the responses of organisms and ecosystems to ocean acidification;

iii. Model and predict biogeochemical and ecological responses to ocean acidification;

iv. Assess the impact of ocean acidification on socioeconomic activities and governance of ocean resources; and

v. Develop a dissemination strategy for educational and public outreach.
2.2. SAMPLING

Surface water samples were collected from selected locations (in coral, seagrass and mangrove ecosystems) using a Niskin bottle (Figure 2.2). In-situ physicochemical parameters such as pH and temperature were measured using a pH sensor (Orion™ ROSS Ultra™ pH/ATC Triode™, Thermo Scientific model), while salinity was measured using a YSI Sensor meter (Professional Plus (Pro Plus) Multi-parameter, Xylem Inc, model) (Figure 2.2). The pre-cleaned sampling containers were rinsed twice with the sampled water and then filled with samples collected using the Niskin bottle. The samples were transported to the laboratory in a cool box at low temperatures.

Figure 2.2: Map showing the sampling sites in Kwale, Kilifi and Mombasa Counties in Kenya
2.3. FINDINGS

2.3.1. Carbonate chemistry trends in coral reefs

The mean±standard deviation of the surface-water temperatures in the sampled locations in coral reef in 2020 and 2021 were 28.1±1.1°C and 27.9±0.4°C, respectively. Salinity ranged between 32.5–33.3 and 32.1–32.2 PSU in 2020 and 2021, respectively. Kilifi, Mombasa, and Kwale Counties had a mean pH of 7.97, 7.98, and 7.94 in 2020, and a mean pH of 8.01, 8.03, and 7.99 in 2021, respectively. The pCO$_2$ ranged between 431–525 and 396–435 µatm in 2020 and 2021, respectively. The pCO$_2$ showed a strong negative correlation with the calcite (Ωcalc) and aragonite (Ωarag) saturation states (Figure 2.3). This is because Ωarag is the primary mineral form of CaCO$_3$ that forms the structure of corals (Hubbard et al., 2016). The decline in pH reduces the seawater Ωcalc and Ωarag saturation which can lead to lower rates of reef calcification since aragonite is the mineral form of calcium carbonate (CaCO$_3$) deposited by corals (Kleypas et al., 2011; McLeod et al., 2013). The concentration of dissolved inorganic carbon (DIC) and total alkalinity (TA) on coral reefs ranged between 1805–1871 µmol/Kg and 2060–2132 µmol/Kg in 2020 and 2021, respectively.

![Figure 2.3](image_url)

**Figure 2.3:** Concentration of a) pH, b) pCO$_2$, and c) correlation of pH and pCO$_2$ in coral reefs along the coastal waters of Kilifi, Mombasa and Kwale Counties for 2020 and 2021

2.3.2. Carbonate chemistry trends in seagrass beds

The mean surface seawater temperature in seagrass beds in 2020 and 2021 ranged between 27.4–28.8 and 27.0–28.0°C, respectively, whereas salinity showed a mean±SD of 33.0±0.3 and 32.3±0.2 PSU in 2020 and 2021, respectively. The mean concentration of DIC and TA in 2020 ranged between 1878–1917 and 2124–2143 µmol/Kg, whereas in 2021 DIC and TA ranged between 1823–1865 and 2084–2124 µmol/Kg. Biogeochemical processes such as photosynthesis, respiration, carbonate precipitation, and dissolution tend to demonstrate predictable relationships in TA and DIC (Challener et al., 2016). There was no difference in the mean pH in 2020 and 2021 (pH 7.93), whereas pCO$_2$ levels in 2020 and 2021 were 526±0.2 and 471±0.2 µatm, respectively. A strong negative correlation was observed between pCO$_2$ and pH$_T$ (Figure 2.4), suggesting that as photosynthesis occurs, CO$_2$ is removed from the water column and pCO$_2$ decreases, whereas respiration results in an opposite trend. Calcite (Ωcalc) and aragonite (Ωarag) were in the range of 4.01–4.52 and 2.73–3.02, respectively, and inversely related to the pH$_T$. 

![Figure 2.4](image_url)
2.3.3. Carbonate chemistry trends in mangroves

High DIC and TA values in water samples from mangrove ecosystems could have been caused by organic matter respiration within the water column, CO₂ exchange with the atmosphere, or the contribution from pore waters richer in inorganic carbon (Koné and Borges, 2008). In addition, external sources such as riverine and ocean-derived carbon inputs may also play a role. The mean pCO₂ levels in 2020 and 2021 were 890 and 593 µatm, respectively (Table 2.1). High pCO₂ concentrations in the surface water column of mangrove forests were higher compared to the seagrass bed and coral reefs, and this could be due to the influx of pore water rich in pCO₂ due to respiration in the mangrove sediment.

Table 2.1: Seawater carbonate chemistry in mangroves

<table>
<thead>
<tr>
<th>Carbonate species</th>
<th>Kwale 2020</th>
<th>Kwale 2021</th>
<th>Mombasa 2020</th>
<th>Mombasa 2021</th>
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<tr>
<td>pH₇ (total scale)</td>
<td>7.79</td>
<td>7.81</td>
<td>7.7</td>
<td>7.96</td>
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<tr>
<td>pCO₂ (µatm)</td>
<td>841</td>
<td>718</td>
<td>939</td>
<td>468</td>
</tr>
<tr>
<td>Omega Ca (Ωcalc)</td>
<td>3.5</td>
<td>3.5</td>
<td>2.8</td>
<td>4.5</td>
</tr>
<tr>
<td>Omega Ar (Ωarag)</td>
<td>2.3</td>
<td>2.3</td>
<td>1.9</td>
<td>3</td>
</tr>
<tr>
<td>DIC (µmol/Kg)</td>
<td>1979</td>
<td>1926</td>
<td>1953</td>
<td>1867</td>
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<td>Sal (PSU)</td>
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<td>33.1</td>
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<td>TA Conc (µmol/Kg)</td>
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<td>2116</td>
<td>2092</td>
<td>2121</td>
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<tr>
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<td>29.8</td>
<td>30.7</td>
<td>28.8</td>
</tr>
</tbody>
</table>
2.4. RELEVANCE OF THE FINDINGS

2.4.1. National process

The findings of the project have been key in documenting the impacts of ocean acidification on calcifying organisms. We anticipate that this will have a greater impact on the government’s commitment to the Nationally Determined Contributions in accordance with the Paris Agreement.

2.4.2. Regional contribution

i. The project has been key in generating data in fulfillment of the vision of the Nairobi Convention.

ii. The project has hosted regional training on strengthening regional capacity for ocean acidification experiments, from inception to results, sponsored by WIOMSA and IAEA

2.4.3. Global contribution

The project has contributed towards addressing:

i. Sustainable Development Goal (SDG) Target 14.3: Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels; and

ii. The Honolulu Strategy, which aims to lessen the negative effects of marine litter on the environment, people, and the economy.
LESSONS LEARNED

i. Quality control and assurance are important components of carbonate chemistry studies but certified reference material is costly. Institutional partnerships are key to addressing the cost challenge;

ii. Ocean acidification research has not been promoted as well as research on, e.g. pollutants and more awareness of its importance is required;

iii. Chemical analysis is costly in the long run compared to autonomous sensors, thus the focus should shift to incorporate the sensors alongside chemical analysis.

COUNTRY SPECIFIC RECOMMENDATIONS

i. There is a need to extend the extent of monitoring to cover Lamu, Tana River and Garissa counties;

ii. More resources are required from the government to finance regular monitoring activities, at least once a month.

WIO-REGION RECOMMENDATION

i. Capacity building on multi-stressors;

ii. Procurement of in-situ sensors;

iii. Promote further collaboration between the north and the south and between the less and the more advanced laboratories;

iv. Explore possibilities of partners that are willing to support the acquisition of CRMs.

DATA MANAGEMENT

The project has developed metadata for each activity implemented. The metadata will be hosted on the KMFRI database and will be available for the general public. All the project data will be open access and will be available on request to directorkmfri@gmail.com accompanied by details of the metadata, justification of why data are needed and commitment to acknowledge KMFRI and WIOMSA in any product generated from the data.
CHAPTER THREE
TANZANIA’S PROFILE

SUMMARY

This chapter provides an overview of the spatial and diel variability of carbonate chemistry in Tanzanian coastal waters, and parameters and processes that drive it. It also sheds light on the impact of seagrass cover loss due to anthropogenic disturbances on the ability of seagrasses to mitigate ocean acidification on short time scales, as well as the potential of mangroves to do so. Furthermore, the report provides recommendations that can be used to assist policymakers in Tanzania and the wider WIO region to achieve SDG 14.3 indicators.
3.1. BACKGROUND AND RATIONALE

Atmospheric CO$_{2}$ concentrations are increasing globally because of human activities such as the burning of fossil fuels, cement production, and land-use change, reaching historical levels of 421.57 parts per million in 2022. The ocean has absorbed roughly 48 percent of all CO$_{2}$ emissions since the beginning of the industrial revolution (Sabine et al., 2004) and continues to absorb approximately 30 percent of CO$_{2}$ emitted annually (Le Quéré et al., 2013). This leads to a steady decrease in the pH and saturation state of carbonate minerals (aragonite and calcite), as well as changes in carbonate chemistry (carbon dioxide partial pressure (pCO$_{2}$), dissolved inorganic carbon (DIC), and TA, a phenomenon known as ocean acidification (OA) (Feely et al., 2009; Doney et al. 2009). The average pH of the ocean’s surface, for example, has dropped from a historically steady value of 8.2 to 8.1 today, amounting to a 30 percent rise in acidity (Feely et al., 2009; Doney et al. 2009; Orr, 2011). As a result, some areas of the ocean are under-saturated with calcium carbonate (Doney 2020; Waldbusser and Salisbury 2014).

Under the worst-case scenario of business-as-usual CO$_{2}$ emissions, the concentration of CO$_{2}$ in the atmosphere is projected to reach ~900 parts per million by 2100, resulting in a 150 percent increase in acidity (Feely et al., 2009; Orr, 2011). On the other hand, projecting pH in coastal waters having seagrass meadows, mangroves, and coral reefs has proven difficult because it is controlled by a complex set of factors such as community metabolism (a balance between photosynthesis of vegetation cover and community respiration), eutrophication, inputs from underground freshwater discharge and rivers, and climatic factors (such as temperature and dissolved oxygen), some of which are localized in nature (Hofmann et al., 2011). A growing body of evidence shows that ocean acidification can have dramatic consequences for marine species and ecosystems (Doney et al., 2020; Dupont and Pörtner, 2013; Kroeker et al., 2013), threatening the diversity, productivity, and overall health of the marine environment and the ecosystem services it provides, such as food security, coastal protection, and economic development (Denman et al., 2011).

Tanzania’s coastal waters host extended coral reefs, seagrass meadows, and mangroves, and their biogeochemical (e.g., sulfate reduction and denitrification) and physiological (photosynthesis, respiration, and calcification) processes can influence seawater carbonate chemistry in different ways (Sippo et al., 2016; Liu et al., 2021). Photosynthetic activity in plants consumes CO$_{2}$, which, in turn, raises the pH of a system (Semesi et al., 2009). Community respiration produces CO$_{2}$, which raises pCO$_{2}$ and, in turn, lowers the pH of a system (Semesi et al., 2009). The calcification process in coral reefs and other calcifying organisms consumes carbonate ions (CO$_{3}^{2-}$) and produces CO$_{2}$, raising pCO$_{2}$ and lowering pH and TA in the system (Semesi et al., 2009). Tanzania’s coastal waters may also receive freshwater from rivers (Mtoni et al., 2013), which are high in TA due to the dissolution of limestone, calcium silicate, and feldspar minerals and have a low pH, which can influence carbonate chemistry.

Tidal movement also occurs in coastal waters (George et al., 2018), which may affect physicochemical parameters (temperature, salinity, and tidal height) that drive the pH, pCO$_{2}$, DIC, and TA of a system. The coastal waters are also subject to frequent upwelling periods (Painter et al., 2021), which may bring subsurface waters with high pCO$_{2}$ and low pH, exacerbating ocean acidification (Waldbusser and Salisbury, 2014). The socioeconomic structure of the seascape can also accelerate ocean acidification by changing the physical and chemical properties that drive pH, pCO$_{2}$, and DIC of water because of pollution, overexploitation, and habitat destruction (Lam et al., 2019). In general, ocean acidification will most likely have a significant impact on mariculture (Doney, 2020; Barton et al., 2012), tourism (Brander et al., 2009), and
fisheries (Le Quesne & Pinnegar, 2012) development in the Tanzanian coastal waters. Ocean acidification is also likely to amplify the effects of other global stressors (such as rising temperatures and deoxygenation) on marine species and ecosystems that are occurring concurrently (Bijma et al., 2013). Measurements of ocean acidification at the local scale within Tanzanian coastal waters are therefore urgently needed to translate how large-scale projected changes will manifest within Tanzania and the wider WIO, as well as to inform local adaptation and resilience planning to achieve the Sustainable Development Goal 14.3 indicator.

This report provides an overview of the spatial and diel variability of carbonate chemistry in Tanzanian coastal waters, as well as the parameters and processes that drive it. It also sheds light on the impact of seagrass cover loss due to anthropogenic disturbances on the ability of seagrasses to mitigate ocean acidification on short time scales, as well as the potential of mangroves to do so. Furthermore, the report provides recommendations that can be used to assist policymakers in Tanzania and the wider WIO region to achieve SDG 14.3 indicators.

3.2. LINKAGE TO REGIONAL AND GLOBAL PROCESSES

Changes in seawater chemistry in Tanzanian coastal waters can be linked to regional and global processes in a variety of ways. First, coastal upwelling events that bring water from the deeper ocean with low oxygen, high CO$_2$, low pH, and low aragonite saturation state ($\Omega_{\text{Ar}}$) to the surface (Sembas et al., 2019) can amplify ocean acidification and its effects on coastal ecosystems (Waldbusser and Salisbury, 2014). Second, the region’s predominant monsoon wind stress can amplify upwelling events (Painter, 2021; Sembas et al., 2019), bringing water from the deeper ocean with low oxygen, high CO$_2$, low pH, and low $\Omega_{\text{Ca}}$ near the coast (Waldbusser and Salisbury, 2014; Barton et al., 2012), enhancing ocean acidification and its effects on coastal ecosystems. Third, changes in atmospheric CO$_2$ growth rate, ocean uptake of CO$_2$, and El Niño-Southern Oscillation (ENSO) events can all cause interannual variability in ocean acidification in Tanzania. Because of increased upwelling during ENSO, ocean acidification appears to accelerate, adding spatial complexity to ocean carbonate chemistry. Fourth, the East African Coastal Current (EACC), which mixes continental shelf and deeper offshore waters, can also influence ocean acidification in Tanzania. As a result, the Pemba Channel serves as an important conduit for bringing deeper ocean waters with high-CO$_2$ waters, low oxygen, low pH, and low $\Omega_{\text{Ar}}$ closer to the coast. The shifting monsoon winds cause the latitudinal range of the EACC to expand and contract, as well as the EACC to accelerate and decelerate (Painter et al., 2021), with implications for ocean acidification in the country and the larger WIO region. Ocean warming will result in an increased organic metabolism (respiration and photosynthesis) in coastal habitats (George et al, 2019), influencing seawater chemistry.
3.3. SAMPLING

The study was carried out along the coasts of Dar es Salaam, Bagamoyo, and Rufiji in Tanzania (Figure 3.1). These study sites share similar coastal features, like the presence of coral reefs, seagrass meadows, and mangroves, and are subject to varying degrees of anthropogenic disturbances. The Dar es Salaam site is close to Dar es Salaam City and is considered to experience a high degree of anthropogenic disturbance. The Bagamoyo site is located more than 50 km from Dar es Salaam City and is considered to experience medium anthropogenic disturbance. The Rufiji site is located more than 200 km from Dar es Salaam City and is considered to experience low anthropogenic disturbance. However, the potential anthropogenic stressors...
(such as pollution) originating from the Rufiji River catchment, as well as the solubility of alkalinity sources in the catchment, which can cause alkalinity in these areas to rise quickly, are of interest for monitoring ocean acidification in the country. All of the sites are affected by predominant northeast and southeast monsoon winds and the EACC.

### 3.3.1. Determination of pH, temperature, salinity and tidal height

The pH was measured using the ST20 OHAUS pH meter, calibrated (three-point calibration) with a buffer provided by the device manufacturer. The Seabird SBE19plusProfilerCTD was used to measure temperature and salinity. On each sampling date, tidal height data were obtained from the tide chart calendar at https://www.tide-forecast.com/locations/Dar-Es-Salaam-Tanzania/tides/latest.

### 3.3.2. Determination of total alkalinity

TA was determined by adding the carbonate alkalinity obtained from color endpoint titration to borate alkalinity, which was estimated from in situ pH, salinity, and temperature as described in Parsons et al. (1984) and Strickland et al. (1968). Borate and carbonate alkalinity together contribute to more than 99% of seawater's total alkalinity (Middelburg et al. 2019; Zeebe and Wolf-Gladrow, 2001).

### 3.3.3. Estimation of dissolved inorganic carbon, partial pressure of carbon dioxide and aragonite saturation state

The CO$_2$ system calculator was used to compute the remaining carbonate chemistry parameters DIC and pCO$_2$ using a pair of pH-TA variables as input, along with salinity and temperature data as described by Pelletier et al. (2007). The relationship between salinity normalized DIC and TA was used to determine key processes driving dissolved inorganic carbon and total alkalinity as described by Chou et al. (2021). The buffering capacity of seawater was determined using the Revelle factor and the DIC/TA ratios. The DIC/TA was calculated using the DIC/TA ratio, while the Revelle factor was calculated using the CO$_2$ system calculator as described by Pelletier et al. (2007).
The carbonate chemistry parameters of seawater (pH, pCO$_2$, TA, and DIC) varied among mangrove, seagrass, and coral reef habitats (Figure 3.3). The highest and lowest pH values were found in seagrass and mangrove habitats, respectively. The highest levels of DIC, pCO$_2$, and TA were found in mangrove habitats. The carbonate chemistry parameters of seawater in habitats are influenced by the time of day and tidal height (Figure 3.3). The pH of seagrass, mangrove, and coral reef habitats is higher during the day than at night (Figure 3.3). pH rises with tidal height in mangrove and coral reef habitats but falls in seagrass habitats. The tidal height lowers pCO$_2$ and DIC in mangrove and coral reef habitats. The TA in mangroves decreases with rising tides.

![Figure 3.2: Seawater carbonate chemistry parameters a) DIC, b) pCO$_2$, c) pH and d) TA sampled in mangrove, seagrass, and coral reef habitats of Bagamoyo, Kunduchi and Rufiji](image)

Table 3.1: Summary statistics of pH from different habitats in coastal waters of Tanzania

<table>
<thead>
<tr>
<th>Habitat type</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral reef</td>
<td>8.00</td>
<td>8.10</td>
<td>8.05± 0.04</td>
</tr>
<tr>
<td>Mangrove</td>
<td>7.11</td>
<td>8.10</td>
<td>7.77± 0.29</td>
</tr>
<tr>
<td>Seagrass</td>
<td>7.79</td>
<td>8.34</td>
<td>8.07± 0.16</td>
</tr>
</tbody>
</table>
3.5. THE EFFECT OF KEY PROCESSES

Organic metabolism, i.e., photosynthesis and respiration, sulfate reduction, and inorganic metabolism – calcification and dissolution) and variables (temperature, salinity, tidal height) on seawater carbonate chemistry parameters (pCO$_2$, pH, DIC, and TA) varies among mangrove, seagrass, and coral reef habitats and the carbonate chemistry parameter in question. Temperature influenced pCO$_2$ and pH in seagrass habitat; salinity and tidal height influenced pCO$_2$, pH, DIC, and TA in mangrove habitat; and tidal height influenced pCO$_2$ and pH in coral reef habitat.

The dominant processes driving seawater carbonate chemistry parameters in mangrove habitat are organic metabolism (respiration), sulfate reduction, and inorganic metabolism (dissolution); only organic metabolism (photosynthesis and respiration) is the dominant process driving carbonate chemistry parameters in seagrass habitat; and inorganic metabolism (calcification) and organic metabolism (photosynthesis and respiration) are the dominant processes driving carbonate chemistry parameters in coral reef habitats.

The Revelle factor ranged from 8 to 17, and the DIC/TA ratio ranged from 0.77 to 1.03 across all coastal habitats, both of which are within the global ocean ranges of 9–15 and 0.84 to 0.95, respectively. The Aragonite saturation states (ΩAr) are both oversaturated in the mangrove, seagrass, and coral reef habitats, implying that the underlying water, particularly in coral reef habitats, supports calcification and prevents CaCO$_3$ dissolution.
During the day, water from mangrove habitats characterised by high \( \text{pCO}_2 \), DIC and TA and low pH, and \( \Omega\text{Ca} \) can support seagrass photosynthesis, lowering \( \text{pCO}_2 \) and DIC, while increasing seawater pH and aragonite saturation state, which, when combined with high TA water from mangrove habitats, can buffer coral reefs from ocean acidification effects (Figure 3.4). The scheme depicts the buffering potential of mangrove and seagrass habitats for adjacent coral reef habitats against ocean acidification. The blue arrow indicates the fate of freshwater flowing through mangrove and seagrass habitats. Reduced seagrass cover due to anthropogenic disturbances reduces pH and aragonite saturation state \( (\Omega\text{Ar}) \) in seawater, as well as increases \( \text{pCO}_2 \) and DIC, reducing seagrass meadows’ ability to buffer adjacent coastal habitats against ocean acidification.

![Figure 3.4: The scheme depicts the buffering potential of mangrove and seagrass habitats for adjacent coral reef habitats against ocean acidification. The blue arrow indicates the fate of freshwater flowing through mangrove and seagrass habitats.](image)

### 3.6. RELEVANCE OF THE FINDINGS AT THE COUNTRY, REGIONAL AND GLOBAL LEVEL

The findings of this study have set the stage for ocean acidification monitoring and experimental studies on the effects of future ocean acidification on Tanzanian coastal habitats, and will contribute to establishing long-term regional and global investigations into the effects of ocean acidification. The findings have shed light on the potential for freshwater and underground water discharge with high total alkalinity flowing through mangroves and seagrass meadows to buffer coastal habitats and ecosystems against ocean acidification. The findings, also, indicate that healthy seagrass meadows can buffer nearby coastal habitats from ocean acidification effects during the day. These findings thus contribute to the understanding of potential impact of seagrass meadow loss both in Tanzania, the region and globally.

Anthropogenic disturbances can hamper the ability of seagrass meadows to mitigate ocean acidification at all scales. It is, therefore, critical that the information contained in this report be used to inform nature-based mitigation measures of ocean acidification. This study also stressed the need to conserve and restore seagrass meadows in Tanzania and the region at large. These findings have contributed to a body of knowledge about ocean acidification in the WIO region and around the world. It is because of this study that Tanzania has for the first time contributed data to the SDG 14.3.1 data portal, which is a tool for the submission, collection, validation, storage, and sharing of ocean acidification data and metadata submitted towards the Sustainable Development Goal 14.3.1 indicator.
WIO-REGION RECOMMENDATIONS

i. Develop policies and strategies that encourage regional researchers, institutions, and countries to collaborate to develop infrastructure and standardized methods for generating scientific data and information, as well as for knowledge transfer, in order to achieve SDG 14.3 within countries and the larger WIO region;

ii. Establish regional ocean acidification monitoring stations to generate data that reflects the state of ocean acidification in the region and allows cross-country comparisons.

COUNTRY SPECIFIC RECOMMENDATIONS

i. Develop a protocol for determining TA and DIC tailored to the local context to improve ocean acidification measurements at the national scale, and the use of modern equipment for TA and DIC measurements.

ii. Future manipulative experimental studies on the effects of ocean acidification on coastal organisms should consider carbonate parameter ranges established in coastal habitats in order to produce results that are realistic and representative of natural environments.

iii. Promote management strategies for the protection and restoration of degraded mangrove and seagrass habitats, as these habitats have been shown in this study to play a key role in buffering the effects of ocean acidification when they are healthy and co-occur.

iv. More research is needed to confirm the potential of mangrove habitats as natural alkalinisation in the presence of seagrass meadows to mitigate the effects of ocean acidification on adjacent coral reefs, as was suggested in this study to increase the buffer capacity of seawater.

v. Continue to monitor ocean acidification at existing sites to collect long-term data sets that will help researchers better understand changes in seawater carbonate chemistry in Tanzanian coastal waters and predict changes under future ocean acidification conditions, and add more potential monitoring sites experiencing upwelling events that are not currently represented in the existing monitoring sites.
CHAPTER FOUR
MOZAMBIQUE’S PROFILE

SUMMARY

Recent projections have shown accelerating carbon emissions that result in a lowering of the pH of the sea surface. The decrease in pH has a serious effect on the survival, growth, development and physiology of marine invertebrates, including ecosystem engineers and keystone species. Despite evidence showing the WIO region is vulnerable to global warming, information relating to ocean acidification is limited. This chapter presents baseline information on ocean acidification in Mozambique.
4.1. BACKGROUND AND RATIONALE

Marine and coastal biodiversity provide enormous benefits for human well-being, by providing critical life supporting services to the global population and underpinning global productivity. Oceans are also critical to many important global geochemical processes, such as climate regulation and carbon cycling (SCBD, 2014). Most of the excess of CO\textsubscript{2}, however, is absorbed by the oceans, which are a significant CO\textsubscript{2} sink. Continued uptake of CO\textsubscript{2} alters the carbonate chemistry of the ocean and increases the concentration of hydrogen ions, thereby reducing pH, a phenomenon called ocean acidification.

According to recent predictions, anthropogenic carbon emissions will cause an estimated 0.2 to 0.4 unit drop in ocean surface pH by the year 2100 and up to a 0.7 unit drop by the year 2300 (Caldeira and Wickett, 2003; IPCC, 2021). A growing body of research shows that ocean acidification can affect marine invertebrates, including keystone species and ecosystem engineers, in terms of their survival, growth, development, and physiology (e.g., Gaylord et al., 2015; Gaitan-Espitia et al., 2017). As highlighted in the last report of the Intergovernmental Panel on Climate Change (IPCC), ocean acidification will induce major changes in marine species, ecosystems, and associated services and products (SCBD, 2014).

At a biological level, organismal response is highly species-specific and even population specific, thus it is not possible to extrapolate from one region to another (Gaitan-Espitia et al., 2017). Studies on the biological and socioeconomic impacts of ocean acidification in the WIO range from scarce to non-existent (e.g., Mozambique), despite evidence showing that this region is vulnerable to global warming. In light of the foregoing, a deeper comprehension of these effects in Mozambique’s systems may help predict future effects and develop local management strategies to safeguard marine populations and ecosystems.

To establish a monitoring station, experimental facilities, and to transfer best practices for ocean acidification measurements to Mozambican researchers, Global Ocean Acidification Observing Network (GOA-ON) and the Ocean Acidification International Coordination Center have already begun. Therefore, this project provides a great opportunity to build an ocean acidification initiative in Mozambique by developing a sustained monitoring of relevant water parameters and developing experiments to assess the impacts on marine organisms and important coastal ecosystems along part of the country’s coastline. It gives the nation the ability to generate baseline data and provide the GOA-ON with validated information. The specific objectives are:

i. Assess spatial and temporal fluctuations of seawater physico-chemical properties on seagrass in Inhaca Island;

ii. Identify water mass distribution using multiple hydrographic tracers;

iii. Investigate how the changes of seawater pH will influence the fertilization and larval survival and development of marine invertebrates;

iv. Assess the potential socioeconomic impacts of OA on economically important intertidal invertebrates in the study area; and

v. Promote local capacity building, in collaboration with regional and international centers and ocean acidification specialists.
4.2. SAMPLING

This project was carried out in coastal ecosystems at Inhaca Island – Maputo Bay, southern Mozambique, mainly in seagrass meadows and intertidal rocky outcrops. The study sites were selected based on the characteristics of their geographical locations in southern Mozambique.

4.3. FINDINGS

4.3.1. Assessment of spatial and temporal fluctuations of seawater physico-chemical properties on seagrass meadows in Inhaca Island

A monitoring plan was developed to assess spatial and temporal fluctuations of the seawater carbonate chemistry in seagrass meadows at Inhaca Island. The field survey was performed in two seagrass meadows (single species: *Thalassodendron ciliatum* and mixed meadows: *Thalassodendron ciliatum/Cymodocea serrulata*) and adjacent bare sand in front of the Inhaca Marine Biological Station (EBMI) at Inhaca Island. We focused the sampling effort at neap and spring

![Map of study area in Inhaca – southern Mozambique, where sea urchins, rock oysters and seagrass were sampled](image)
tides (during day time: around 12.00h and at night: around 18:00h) from August to October in 2020 and from September to December of 2021.

The seawater sampling methods for the carbonate chemistry analysis followed the Standard Operating Procedures (SOP) described by Dickson et al. (2007). Water samples were collected, treated and stored in accordance with SOP 1. The pH and TA were the two considered parameters of the carbonate system. The pH was determined using the spectrophotometer method described in SOP 6b by Dickson et al. (2007) a short-time after sampling. To ensure quality control, a duplicate sample of each bottle was considered. The TA analysis was attempted using an open cell TA titration principle described in SOP 3b by Dickson et al. (2007). The iSAMI pH sensor was also deployed during 24 hours in each sampling station at spring and neap tide to get continuous pH measurements. However, it was not performed during all monitoring periods due to operational issues.

Monitoring results indicate differences in carbonate chemistry during the day/night cycle between seagrass meadows (showing high variability in *T. ciliatum* at spring tides [DpH= 0.06, DΩcalc=0.5, and DΩAr=0.3]) compared to mixed meadows: *T. ciliatum/C. serrulata* at both spring (DpH= 0.04, DΩcalc=0.4, and DΩAr=0.2) and neap tides (DpH= 0.02, DΩcalc=0.1, and DΩAr=0.1). The continuous pH measurements of the 2020 monitoring survey also showed maximum diel cycle variability (DpH= 0.4) in *T. ciliatum* meadow at spring tide (Figure 4.2). The monitoring results indicated that the magnitude of diurnal pH variation might be influenced by the type of meadows and tides, even though the use of discrete measurements in the variable ecosystem such as seagrass may not capture small changes in pH over diel cycle (Figure 4.2).

**Figure 4.2:** Variation in pH (pH on total scale) in Inhaca Marine Biological Station (Mozambique) based on monthly data in 2020

### 4.3.2. Identification of the characteristics of water masses using multiple hydrographic tracers

Physico-chemical characteristics of seawater play a crucial role in productive coastal and marine ecosystems such as coral reefs and seagrasses. Monitoring variations induced by natural processes and anthropogenic stressors in seawater are crucial for designing strategies to enhance ecosystem services and improve the coastal community’s well-being. Hydrographic surveys to monitor the temporal and spatial variations of physico-chemical parameters at Inhaca Island were conducted in the framework of the Ocean Acidification Monitoring Program in Mozambique.
Seven hydrographic stations located nearshore at depths ranging from ~0.5 to 10 meters were surveyed monthly during July and December 2020, and July to December 2021. The July to September and October to December surveys represent the dry and rainy seasons respectively. Vertical profiles of salinity, temperature (°C), dissolved oxygen (mg/l), sigma-t and depth (m) were recorded by means of a Conductivity-Temperature-Depth (CTD) profiler, Serial 795, model SD204. The read out and processing of the recorded data was based on the software Minisoft SD200W provided by the CTD manufacturer. Further processing included quality control of the downcast data to remove erroneous records and spikes caused by drifting in the water column during the CTD casts. Descriptive statistics of the salinity, temperature, dissolved oxygen and sigma-t (proxy of water density) averaged over the water column of all stations during the eight surveys held in July to December 2020, and July to December 2021 are shown in Table 4.1.

Table 4.1: Water masses’ characteristics averaged over the water column at sampled stations at Inhaca Island during summer (wet) and winter (dry) seasons (2020 – 2021)

<table>
<thead>
<tr>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean± SD</td>
<td>Mean± SD</td>
</tr>
<tr>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Salinity</td>
<td>34.7</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>19.2</td>
</tr>
<tr>
<td>Oxygen saturation (%)</td>
<td>65.1</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/l)</td>
<td>4.9</td>
</tr>
<tr>
<td>Sigma-t (°C)</td>
<td>24.3</td>
</tr>
</tbody>
</table>

4.3.3. How the changes of seawater pH will influence sea urchins and oyster populations

Fertilization and larval survival and development experiments were conducted in sea urchin (*Tripneustes gratilla*) and rock oyster (*Saccostrea cucullata*) populations to test potential impact of future ocean acidification conditions in Maputo Bay. We hypothesized that populations of *S. cucullata* and *T. gratilla* inhabiting areas characterized by wide fluctuations in seawater acidity should be able to tolerate the pH regime they are currently experiencing and their physiological threshold would approximate the lower limit of their experienced natural variability. In order to find a physiological threshold for growth and calcification of embryos and larvae, the boundaries were pushed to test larval performance at even lower pH.

Adult individuals of *S. cucullata* and *T. gratilla* were collected randomly from intertidal sites (Ponta Torres and Farol for *S. cucullata*; Bangua and Sangala for *T. gratilla*) and a subtidal site (Nolwe for *T. gratilla*) at Inhaca Island in Maputo Bay. Spawning was induced, in sea urchin, by intracoelomic injection of sodium chlorate hyper-saline solution in two males and four to five females per site. For *S. cucullata*, gametes were obtained through mechanical extraction of the gonads which consists of opening the upper valve of the shell and exposing the gonad. Fertilization of sea urchins’ and oysters’ gametes was carried out and sea urchin larvae were cultured for the first part of their development under artificial pH conditions (control 8.1; treatments: 7.8, 7.7, 7.5, 7.3 and 6.9).

The carbonate chemistry was monitored daily and before fertilization (Annex 1). Fertilization took place in 1 to 2 hours, and confirmed through the formation of two polar bodies in *S. cucullata* and
fertilization membrane in *T. gratilla*. Fertilization success was calculated based on the random count of 100 embryos per treatment. The embryos from the control treatment were used to test the effect of ocean acidification on *T. gratilla* larval development and growth in five days. Density, larval size and total skeleton were registered once a day. Measurements for mortality, growth and calcification rates of sea urchin larvae were digitized with the Image J package.

Fertilization success decreased with pH in all populations of both species, except the *T. gratilla* population from Nolwe, which was stable (fertilization rate >80%; *R*=0.3; *P*=0.04), in all the treatments (Figure 4.3). Our results demonstrated that fertilization in the Nolwe population is robust and plastic to a pH variation that is broader than they might experience in nature today or even that predicted for the future. The lower fertilization success of the Sangala population under present day pH conditions may indicate maladaptation of this population to their local habitat. Below pH ~7.3, fertilization success was ≤ 50 % in sea urchin populations from Bangua and Sangala, and oyster populations from Farol (Figure 4.3).

Reduced fertilization success in low pH may be associated with sperm inactivation as pH medium below 7.3 inactivates the dynein ATPase (Christen et al., 1982, Christen et al., 1983). Reductions in fertilization success may lead to a reduction in larval production, changes in dispersal patterns and gene flow between populations. These may affect recruitment, population replenishment, and species persistence, potentially leading to significant changes in the community structure of ecosystems and their socioeconomic value (Munday et al., 2008; Munday et al., 2009; Lenz et al., 2018). These findings will be complemented by data on the effect of ocean acidification on *T. gratilla* larvae for a better understanding on the role of local variability modulating the sensitivity of these populations to ocean acidification.

![Figure 4.3: Relationship between mean pH and percentage fertilization success of *T. gratilla* from Bangua, Nolwe and *S. cucullata* from Farol and Ponta Tores. Each dot represents the mean value for each replicate per each pH treatment](image)

**4.4. RELEVANCE OF THE FINDINGS**

The implementation of the project created an opportunity to increase local capacity in ocean acidification-related topics. This occurred through the participation of the project principal investigator, students, laboratory technicians and researchers from Inhaca Marine Biological Station in regional training opportunities and interactions with regional and international specialists in
the use of field measurement equipment, water collection techniques and the design, implementa-
tion and collection of data at all stages of biological experimentation. Biology, chemistry
and social sciences undergraduate students were involved in the implementation of this project.
Around 80% of the trainees were women and six of them used data produced in this project to
perform their final projects. Two students completed their course in Marine Aquatic and Coastal
Biology:

i. Sea urchins as a biological model for ocean acidification impact studies: The case of *Tripneustes gratilla* fertilization;

ii. The effect of ocean acidification on major resources;

iii. Fertilization success of rocky shore oysters *Saccostrea cucullata* under different levels of pH;

iv. The impact of different levels of seawater pH on the formation and calcification of sea urchin *Tripneustes gratilla* larvae spicules;

v. Ocean acidification effect on sea urchin *Tripneustes gratilla* fertilization at Inhaca Island: Unexperimental study; and

vi. Spatial and temporal variation of pH at Inhaca Island.

These research projects provided a unique opportunity for multidisciplinary, academic and
community engagement towards the understanding of ocean acidification in Mozambique. The
interaction of scientists with local residents created an enabling environment to tackle and
broaden the understanding of ocean acidification in a multidimensional way.

Table 4.2: Summary of the project findings at country, regional and global level

<table>
<thead>
<tr>
<th>Experiments (sea urchins and oysters)</th>
<th>Country level</th>
<th>Regional level</th>
<th>Global level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Assist in projection of future biological impacts of OA and development of local management strategies to protect marine populations and ecosystems.</td>
<td>Improve understanding of physiological tolerance of marine species to OA.</td>
<td>Assist in projection of future biological impacts of OA and development of global management strategies to protect marine populations and ecosystems.</td>
</tr>
<tr>
<td>Country level</td>
<td>Regional level</td>
<td>Global level</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td><strong>Monitoring carbonate chemistry on seagrass meadows</strong></td>
<td>Establishment of monitoring sites of OA in seagrass meadows that can help to support conservation and restoration initiatives.</td>
<td>Assist in projections of how variable coastal environments (seagrass) might act as refugia habitat for the impacts of future OA through their fluctuations in carbonate chemistry.</td>
<td></td>
</tr>
<tr>
<td>The physico-chemical properties information constitutes an essential baseline with potential application for management purposes and for the design of future studies related to the coastal and marine environment.</td>
<td>Increase monitoring capacity of OA in the region, particularly in coastal habitats.</td>
<td>Data submitted to SDG 14.3.1 Portal.</td>
<td></td>
</tr>
<tr>
<td><strong>Physico-chemical characteristics</strong></td>
<td>The results have potential application in studies addressing other issues such as climate change related studies.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Socioeconomic</strong></td>
<td>Daily routines of Inhaca island fishing communities seem to be affected by climate change – related impacts. People report the reduction in quantity and quality of seashell invertebrates in the island. This affects the livelihoods of islanders who are heavily dependent on marine resources. Further, further studies are needed to confirm connection to OA.</td>
<td>The findings in Inhaca Island are in line with global trends of the effects of OA on seashell invertebrates.</td>
<td></td>
</tr>
</tbody>
</table>
WIO–REGION RECOMMENDATIONS

i. To continue with the regional capacity building in ocean acidification issues;

ii. To develop regional protocols for lab and field water chemistry measurements;

iii. To develop common methodologies for environmental multiparameter experiments;

iv. To develop physiological stress markers, including genomic tools, for key functional groups and economically important species; and

v. To incorporate other disciplines that complement the research such as: anthropological, social sciences and local knowledge for experience exchange or dissemination of good practices.

COUNTRY SPECIFIC RECOMMENDATIONS

i. To establish a wider program on ocean acidification monitoring, to cover key geographical areas and habitats;

ii. To include in the ocean acidification program measurements of ocean physics and other ancillary data;

iii. Future studies aiming to assess the influence of variability of the carbonate chemistry on marine organisms should consider factors such as habitats and ecosystems;

iv. That future studies on adaptation potential of marine resources populations and the underpinning mechanisms are needed for a better understanding of the impact of global changes on marine life. Once synergistic and antagonistic effects of different parameters in the natural environment may occur, multiparameter experiments may be the next step forward;

v. The incorporation of local knowledge in search of sustainable experiences.

vi. To continue with the local capacity building in ocean acidification seawater monitoring and experiments; and

vii. To improve synergies and collaboration with interested parties to enable greater impact, and predict changes under future ocean acidification conditions, as well as add more potential monitoring sites experiencing upwelling events that are not currently represented in the existing monitoring sites.
The Oceanographic Research Institute has initiated the first ever ocean acidification monitoring project on South Africa’s coral reefs, located in the iSimangaliso World Heritage Site. The project has provided the first estimates of reef accretion and dissolution in the Delagoa coral province, and the first time series data on coral reef pH levels and ocean acidification in the region.
5.1. BACKGROUND AND RATIONALE

The increase in anthropogenic CO$_2$ has two primary effects on the warming due to increased energy uptake, and ocean acidification driven by the direct absorption of CO$_2$ into seawater. The oceanographic Research Institute (ORI) has been monitoring sea temperature continuously since 1994, and salinity and the carbonate system (pH and total alkalinity) for several years. This monitoring has revealed variability in these parameters, with changes in temperature, salinity and pH driven by seasonal variation and episodic events. A shortcoming, however, that needed to be addressed, was the lack of a continuous record of pH and pCO$_2$ to investigate variability over multiple timescales.

To overcome this there was a need to acquire long-term monitoring equipment for accurate measurement of seawater pH (the SeaFET), for deployment at Sodwana Bay. This would complement and expand the current monitoring network at Sodwana Bay. In addition, this continuous monitoring needed to be supplemented with regular, seasonal sampling to validate pH, salinity and temperature measurements and to determine total alkalinity and the spatial and temporal variability of the whole ocean carbonate system.

ORI has also undertaken in situ and ex-situ experiments on ecological processes affected by acidification and warming, including measurement of the accretion and dissolution of CaCO$_3$, a critical determinant of reef growth and health; and the individual and combined effects of increased temperature and pH on two coral species, representing sensitive and robust clades. This included studying physiological responses of coral such as growth, bleaching and transcriptional changes using next generation sequencing (RNA-Seq), and the effects of changes in temperature and pH on fertilization success, larval development, and recruit survival. However, there was a need to expand these studies, especially as far as examining the seasonal dynamics of accretion and dissolution on South Africa’s high-latitude reefs and how ocean acidification may affect these important reef processes in future.

5.2. AIMS AND OBJECTIVES

The aim of the project was to develop a broad-based, integrated body of knowledge on the potential effects of climate change on these critical ecosystems for dissemination to relevant parties for informed conservation and policy decision making. This is directly relevant to section 14 of the 2030 Agenda for Sustainable Development Goals (SDG14), specifically: increases in global temperature, sea level rise, ocean acidification and climate change impacts on least developed countries and small island developing states. The objectives of the project were:

i. Determine the current baseline of critical physico-chemical environmental parameters including temperature, pH and other aspects of the carbonate system (pCO$_2$, aragonite saturation, DIC) on South African coral reefs.

ii. Investigate how current and projected physico-chemical parameters will influence coral community composition and affect reef function.

iii. Investigate how critical species and groups of species might respond to future physico-chemical conditions and predict and model their future in a changing world in terms of their physiological, transcriptional, reproductive, adaptive and survival responses to these changes.
iv. Collaborate with other regional centres and researchers, fostering capacity building and regional inter-connectedness.

Ultimately, some of these objectives could not be fully achieved due to constraints arising from the impact of the COVID-19 pandemic.

5.3. LINKAGE TO REGIONAL AND GLOBAL PROCESSES

Ocean acidification is recognized as a significant threat by the international community. Consequently, it has been linked to various global initiatives such as the Paris Agreement on climate change and the Convention on Biological Diversity’s post-2020 Global Biodiversity Framework discussions. Ocean acidification is also one of the targets of the Sustainable Development Goals (SDG 14.3) which calls for nations to minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels. Furthermore, the GOA-ON, which is a network of more than 750 scientists and resource managers from 100 countries, has set up guidelines for conducting monitoring and assessments of ocean acidification.

In the WIO, local and regional data are required to understand the potential threat of ocean acidification and to implement adaptation solutions to mitigate its impact as far as possible. Many marine organisms are likely to be negatively affected by the chemical changes resulting from ocean acidification. These species and the habitats they comprise are also key features of some of the ecologically and biologically significant marine areas of the southern Indian Ocean as well as marine protected areas and world heritage sites. Consequently, it is likely to have cascading consequences for regional and local ecological and socioeconomic systems, and even, potentially, human health. The framework for building multi-national ocean governance exists in the WIO region and is facilitated by the UN SDGs, the United Nations Environment Programme’s Regional Seas Framework, and the work programme of the Nairobi Convention.

5.4. SAMPLING

5.4.1. Study site

The monitoring was conducted at several sites on Two-mile and Nine-mile reefs in Sodwana Bay, South Africa. These reefs represent the southernmost coral communities in the WIO and are protected by the iSimangaliso Wetland Park World Heritage Site. Two-mile and Nine-mile reefs are located in the Central Reef Complex and together the three reef complexes cover an area of approximately 40 km². Despite these reefs being small in extent and high-latitude in location, they are remarkably rich in diversity, with soft corals dominating shallow reef communities. They are in a relatively good condition although they experience pressures from chronic agricultural pollution and short-term thermal stress during periods of anomalously warm temperatures. These reefs are generally considered to be non-accretive, with coral communities growing in a veneer on fossilised sand dunes.

5.4.2. Brief methodology

Carbonate water chemistry was monitored at hourly intervals with a permanently moored SeaPhoxTM V2 Ocean CT(D)-pH-DO Sensor at 16 m on Nine-mile reef. In addition, quarterly replicate water samples were collected from Nine-mile reef and from three representative sites on Two-mile reef and were analysed for total alkalinity using an automated titrator (Metrohm 888 Titrando). Accretion and dissolution of biogenic carbonate were assessed at the same three
sites on Two-mile reef where water samples were collected by deploying, respectively, replicate pre-weighed 10 by 10-cm polyvinyl chloride tiles and tissue-free Acropora austera coral nubbins for 6 months during the austral spring-summer and autumn-winter periods. Total alkalinity, aragonite and calcite saturation states were calculated based on the results of the titrations. Accretion was determined by removing all organic material from the tiles with 10% calcium hypochlorite, before reweighing the tiles after oven drying and calculating the change in weight. Dissolution and bioerosion was determined similarly by bleaching the tissue-free coral nubbins before oven drying and reweighing.

5.5. FINDINGS

Temperature derived from the SeapHOx at the Nine-mile monitoring site ranged from 19.6–28.5°C and had an average±standard deviation of 25.6±1.7°C (Table 5.1). An obvious warming trend was evident from October 2021 to mid-January 2022, before temperatures began to cool as autumn approached (Figure 5.2). The maximum temperature of 28.5°C recorded on the 16th of January (Figure 5.2) approached the local coral bleaching threshold of 28.8°C but was not sustained beyond two hours (Figure 5.2). Obvious decreases in temperature...
over a relatively short period of time (<24h) were evident in December 2021, indicating upwelling events, indicated by the overlay box in Figure 5.2.

Table 5.1: Summary statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>Max</th>
<th>Mean±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>4.12</td>
<td>5.54</td>
<td>4.78±0.17</td>
</tr>
<tr>
<td>pH</td>
<td>7.93</td>
<td>8.08</td>
<td>8.05±0.02</td>
</tr>
<tr>
<td>Salinity</td>
<td>35.27</td>
<td>35.65</td>
<td>35.51±0.05</td>
</tr>
<tr>
<td>Temperature</td>
<td>19.55</td>
<td>28.54</td>
<td>25.58±1.71</td>
</tr>
</tbody>
</table>

The pH derived from the SeapHOr at the Nine-mile monitoring site ranged from 7.93–8.08 and averaged 8.05±0.02 (Table 5.1). A general trend of declining pH was evident from late October 2021 with indications of an obvious diel cycle during the entire time series (Figure 5.2). Several anomalous declines in pH were evident in December 2021 and February 2022 corresponding to the temperature declines. Salinity derived from the SeapHOr at the Nine-mile monitoring site ranged from 35.3–35.7ppt (Figure 5.2) and averaged 35.5±0.1 ppt (Table 5.1). Salinity showed a general increasing trend from October 2021, when the instrument was first deployed, until December 2021. Thereafter salinity experienced several obvious declines in late December 2021 and again in January 2022, with no obvious trend during the late summer and early autumn months of 2022. Dissolved oxygen derived from the SeapHOr at the Nine-mile monitoring site ranged from 4.1–5.5 ml/L and averaged 4.8±0.2 ml/L (Table 5.1). No obvious seasonal trend in
dissolved oxygen was evident although there was an obvious diel cycle during the entire time series (Figure 5.2).

Total alkalinity derived from the water samples from Nine-mile and Two-mile reefs averaged 2287.2 µmol kgSW⁻¹ (Table 5.2). Aragonite and calcite saturation states were 3.17 and 4.81 respectively. Most of the accretion on the accretion tiles resulted from amorphous and calcitic calcium carbonate organisms and averaged 122.8 g CaCO₃ m⁻² yr⁻¹ (Table 5.2). Tissue-free coral nubbins decreased in mass indicating dissolution rates averaging 0.13 g CaCO₃ m⁻² yr⁻¹ (Table 5.2).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>Max</th>
<th>Mean±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalinity</td>
<td>2255.59</td>
<td>2327.92</td>
<td>2284.87±16.58</td>
</tr>
<tr>
<td>Aragonite</td>
<td>2.19</td>
<td>4.06</td>
<td>3.22±0.50</td>
</tr>
<tr>
<td>Coral nubbins</td>
<td>-0.20</td>
<td>0.46</td>
<td>0.12±0.20</td>
</tr>
<tr>
<td>Calcite</td>
<td>3.49</td>
<td>5.96</td>
<td>4.57±0.65</td>
</tr>
</tbody>
</table>

5.6. RELEVANCE OF THE FINDINGS

These results are the first time series data on ocean acidification and related parameters from coral reefs in South Africa. The average pH derived from this study falls within the range of 8.04 to 8.31 derived for Sodwana Bay by Hayman (2015) who sampled at routine intervals. The average total alkalinity, aragonite and calcite saturation states also fall within the ranges quantified by Hayman (2015). The results highlight the importance of non-periodic events, such as upwellings, on the temperature and chemistry of the reef and emphasize the necessity of continuous monitoring to capture variation across multiple timescales.

Significantly, the time series results are the first from coral reefs in the Delagoa Bioregion, which harbours the southern-most coral reefs in the Western Indian Ocean. This data provides a critical baseline on which to base experimental studies on the effects of ocean acidification on reef organisms and to measure future changes in carbonate chemistry. These results will provide a foundation and essential first step towards building models for evaluating the effects of ocean acidification in the region. This will help to provide context regarding the relative threat ocean acidification poses to this region in relation to other regions in the world, which will help to prioritise mitigation measures.
WIO–REGION RECOMMENDATIONS

i. South Africa is located strategically at the southern limit of the WIO. Many of the habitats that characterise the WIO, such as coral reefs and mangrove forests, reach their southern distributional limits in South Africa;

ii. It is also where the transition from tropical to temperate bioregions occurs, and it is thus a critical region for both understanding the effects of climate change on multiple ecotypes as well as the combined effects of warming and acidification on organisms and biodiversity. Therefore, South Africa can play a key role in the region by providing data for several ecosystems to support a regional ocean acidification monitoring and research network. As such, it is recommended that regional funding be continued to support and extend ongoing efforts to monitor and elucidate the effects of ocean acidification in the region; and

iii. Adaptation strategies could include protection of ecosystems (e.g., marine protected areas, reduction of other environmental stressors), restoration programs, as well as adaptation such as changes in aquaculture practices. Identification of local priorities should be based on local needs, availability of solutions, and ease of implementation. This approach, involving scientists and ocean users, would allow for the clear prioritization of data gaps and research needs.

COUNTRY SPECIFIC RECOMMENDATIONS

Due to delays caused by the COVID-19 pandemic, this monitoring work has not been able to acquire a full year’s worth of data, let alone three years’ worth of seasonal data on which to determine seasonal patterns in ocean acidification and its associated parameters. Therefore, it is recommended that further monitoring work be supported for at least another two years. In addition, funding should be made available to include salaries for contract research assistants as well as for conducting ex-situ mesocosm experiments aimed at measuring the effects of ocean acidification and warming on marine organisms and habitats native to South Africa.
CHAPTER SIX
MAURITIUS’ PROFILE

SUMMARY
Rising atmospheric CO₂ has elevated temperatures and increased ocean acidity, phenomena that threaten terrestrial and marine biota. Most impacts of ocean acidification are unknown in Mauritius. This study was initiated to monitor pH and TA in the coastal lagoons at Flic en Flac and Ia Cambuse.
6.1. BACKGROUND AND RATIONALE

Global warming and ocean acidification (OA) are both consequences of a rise in atmospheric carbon dioxide (CO$_2$). They are both threats to the atmosphere and marine biota and according to a recent study, atmospheric CO$_2$ resulting from anthropogenic activities has increased from pre-industrial level of 280 µatm to present day concentration of 400 µatm. With the increase in CO$_2$ levels in the atmosphere, there is more of the latter being dissolved, forming carbonic acid. This weak acid slightly lowers the pH of the ocean leading to the phenomenon of ocean acidification. Ocean acidification adversely impacts marine organisms, in particular the calcification process. In terms of the ocean economy, Mauritius may be affected. The purpose of this research work was to monitor pH and TA in the coastal lagoons at Flic en Flac and La Cambuse from August 2019 until December 2021. Sampling was carried out every three to four weeks during the summer (November 2019 to April 2020) and winter (August 2019 to October 2019).

6.2. AIMS AND OBJECTIVES

The objectives of this project were:

i. Determination of pH in coastal lagoons using UV-Vis spectrophotometric methods;
ii. Determination of Total Alkalinity (TA) in coastal lagoons;
iii. Observe the trend of pH obtained from UV-Vis and an iSAMI pH sensor (Sunburst Sensors LLC); and
iv. Statistical comparison for pH and alkalinity (TA) over different summer and winter seasons during the period 2019-2021.

6.3. LINKAGE TO REGIONAL AND GLOBAL PROCESSES

In this study report, we investigated the spectrophotometric determination of pH and open-cell potentiometric titration methods used to determine the alkalinity of seawater. Seawater samples were collected at different stations in Mauritius, namely Flic-en-Flac, Albion, Mont Choisy, Trou d’Eau Douce and La Cambuse lagoons. The aim of this project was to monitor the pH and total alkalinity of seawater in the selected coastal lagoons until December 2021 for both summer and winter. A database was compiled for data analysis and statistical comparisons were made for the different stations.

Furthermore, ocean acidification parameters in the coastal lagoons were investigated using the spectrophotometric method for the determination of pH and the open-cell potentiometric titration method used to determine the total alkalinity of seawater. Seawater samples were collected at the different stations in Mauritius, namely La Cambuse and Flic-en-Flac coastal lagoons. The pH and alkalinity investigation and trends were carried out until December 2021, covering both summer and winter periods for comparison. iSAMI pH sensors (Sunburst Sensors LLC) were used together with the spectrophotometric methods over time intervals to monitor pH in the coastal lagoons. Additionally, for comparisons among the various coastal lagoons, TA was measured using open cell titration using pH electrodes and Gran titration.
6.4. SAMPLING

The glass sampling bottles were washed and the grease on the mouth and lids removed with a solvent. The sampling bottles were sterilized in an autoclave at 160°C for 15 minutes. The salinity and temperature of the seawater were determined at the point of collection. This is to account for the equilibrium constant of HI- being a function of temperature and salinity. Since seawater’s pH is known to vary depending on its depth, seawater was always collected at knee level.

Seawater samples were collected using a Tygon tubing to prevent the formation of bubbles and, hence, atmospheric CO₂ infiltrating the samples. To the very top, the sampling bottles were filled, and 3 cm³ of water was pipetted out. 200μL of saturated mercury (II) chloride was pipetted into the seawater so as to eliminate any living micro-organism and further CO₂ contamination. The bottles were sealed with grease and parafilm. Four samples were collected every 40 minutes. Each site was visited every two weeks. Table 6.1 shows ocean Acidification observation sites with geographical position and variables measured (pH, TA).

Table 6.1: Sampling sites at Mauritius

<table>
<thead>
<tr>
<th>Sites</th>
<th>Geographical positions</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude (S)</td>
<td>Longitude (E)</td>
</tr>
<tr>
<td>La Cambuse</td>
<td>-20.454</td>
<td>57.700</td>
</tr>
<tr>
<td>Flic en Flac</td>
<td>-20.274</td>
<td>57.370</td>
</tr>
<tr>
<td>Albion</td>
<td>-20.210</td>
<td>57.403</td>
</tr>
<tr>
<td>Trou d’Eau Douce</td>
<td>-20.237</td>
<td>57.803</td>
</tr>
<tr>
<td>Mont Choisy</td>
<td>-20.0160</td>
<td>57.5572</td>
</tr>
</tbody>
</table>

Figure 6.1: Sampling using A) iSAMI pH sensor (Sunburst Sensors LLC) deployment in Flic en Flac lagoon and B) iSAMI (Sunburst Sensors LLC) deployment at Flic en Flac for pH measurements in Mauritius
6.5. QUALITY CONTROL

Certified reference materials (CRMs) were obtained from the Scripps Institution of Oceanography, University of California, San Diego, USA. Tris buffers and CO\textsuperscript{2} in seawater reference materials were required to verify the accuracy of pH and AT measurements, respectively. The precision of AT measurements was also evaluated using the CO\textsuperscript{2} in seawater CRMs.

6.6. ISAMI PH SENSOR DEPLOYMENT (SUNBURST SENSOR LLC)

The iSAMI pH sensor was attached to an external battery and to an external bag of nanopure water for storage. While deploying the iSAMI in the ocean, at a depth below knee level, care was taken to avoid pumping air bubbles into the system. The iSAMI was programmed for a sampling time frame of 4 hours (from 10am to 2 pm.). When the time frame was reached, the iSAMI was removed from the seawater, wiped down, and the instrument attached to the bag of nanopure water. In the laboratory, the iSAMI was flushed with deionized water through the sample line. The iSAMI data was downloaded through the communication cable, which was attached to the iSAMI, the external power supply (13 volts), and the computer.
6.7. FINDINGS

The calculated pH at site 1 varied between 7.57 and 8.23, at site 2 between 7.55 and 8.03, at site 3 between 7.40 and 8.02 and at site 4 between 7.39 and 8.14 (Figure 6.3). However, no general trend was observed. The highest pH was recorded in summer for all four sites. Generally, the pH of seawater decreases when the CO$_2$ gas from the atmosphere dissolves in seawater. The uptake of anthropogenic CO$_2$ by the oceans is driven by the difference in gas pressure in the atmosphere and in the oceans and by the air–sea transfer velocity.

Because the pCO$_2$ is increasing in the atmosphere, CO$_2$ moves into the ocean to balance the oceanic and atmospheric gas pressures. The level of CO$_2$ in Mauritius increases because of the burning of fuel by motor vehicles and more and more forest areas are being destroyed for industrialization. The solubility of the gas increases at low temperatures. The pH at La Cambuse was observed to be between 8.02 to 8.16 and the pH at Trou d’Eau Douce was between 8.01
and 8.20. The highest pH was observed during the month of March, 17th working week at La Cambuse and 15th working week at Trou d’Eau Douce that is when the lowest temperatures were recorded. These data show that the pH in the coastal region was surely affected by the change in temperature. The highest TA for each site was observed during the 8th week of sampling. A gradual increase was observed in the 3rd week and a gradual decrease in the 6th to 7th weeks. The TA varied from 1718 μmol/L to 2069 μmol/L at site 1, from 1981 μmol/L to 2152 μmol/L at site 2, from 1916 μmol/L to 2162 μmol/L at site 3 and at site 4 from 1890 μmol/L to 2373 μmol/L. 

The alkalinity of seawater depends on the carbonate and the bicarbonate concentration of the seawater. Both carbonate and bicarbonate depend on the level of CO₂ dissolved in the seawater. The alkalinity changed from 2160 µEq/L to 2520 µEq/L month of October to the month of April in the east and southeast coast. These results show that as the pH of seawater increases, so the TA also increases.

6.8. RELEVANCE OF THE FINDINGS

Spectrophotometric pH measurements were successfully carried out. However, pH values seem to be very dependent on weather and seasonal conditions. As mentioned, the UV absorbance at 434nm is not visible enough. Unpurified dye has been reported to cause an offset of 0.01 pH units. Therefore future research could include following procedures to purify the meta-cresol purple dye. However, purified meta-cresol purple can be rather expensive. Another option that could be explored is the convenient and inexpensive 434Aimp corrective model reported. The user first determines the absorbance contribution of the indicator’s impurities at 434nm and correction for this contribution is then mathematically applied to pH measurements. Analytical measurements performed for both pH and TA was lab–based and therefore inherently different from in-situ measurements that might be produced by pH sensors.
We have seen the on-site temperature dependence of pH and alkalinity. To achieve reliability and precision in our measurements a temperature correction is required in the future to match in-situ measurements (Hunter, 1998). The Albion lagoon site should also be re-evaluated as a site of interest to study ocean acidification in Mauritian waters because it has been reported here to be easily affected by fresh water inputs and estuaries.

i. **Flic en Flac:** from the results obtained, it can be concluded that the seawater at Flic en Flac still has the ability to efficiently buffer against pH variations. The statistical analysis shows non-significant changes in total alkalinity and pH as well as a significant change in pH at site 1. However, in the long run, if anthropogenic CO$_2$ is not reduced, the TA of the ocean will undergo a drastic change and there could be a mass decline in the variety of the marine creatures. Furthermore, this will affect the gross domestic product of Mauritius which is highly dependent on the tourism sector. Coral reefs are at risk with increasing levels of CO$_2$ in the ocean which can result in its disintegration with decreasing pH. The fishing industry is also a fundamental part of the Mauritian economy and is also affected by this phenomenon. Marine organisms may even migrate to other areas where acidification is relatively low. Some species, instead of migrating, respond to the changes in the ocean in different ways. They may undergo mutational adoption, whereby some may not resist the process and may eventually disappear. Therefore, it is of major significance to keep track of ocean acidification.

ii. **La Cambuse:** It is drawn to our attention that La Cambuse Beach is not severely affected by ocean acidification. During the sampling weeks, it was observed that not many people frequent this beach and the pollution level over there is also not very high. The pH and alkalinity values were not significant during the t-testing conducted both during the summer months and the last three winter months on our island. However, if not taken into consideration, we could be seeing a fall in the pH levels in the near future as Mauritius is fully dependent economically on the tourist sector. If overused, the coral reefs might be depleted, which would allow a higher concentration of CO$_2$ gas to be dissolved and by default cause pH imbalances in the seawater.
COUNTRY SPECIFIC RECOMMENDATIONS

The following steps should be taken to address local and regional ocean acidification and other issues:

i. Further monitoring using iSAMi pH sensor and data analysis will be carried out at the different coastal lagoons in Mauritius;

ii. Monitor ocean acidification conditions in coastal waters to identify any potential hot spots or refugia. Share data through the GOA-ON. This data can also be used to meet SDG 14.3 which mandates countries provide data related to ocean acidification conditions.

iii. Determine biological and socioeconomical vulnerabilities, which should be connected to the ocean acidification conditions, and means to reduce them;

iv. An analysis of all species with a human dependence and then review literature for vulnerabilities or conduct experiments to test them; and

v. Reduce local sources of acidification, if documented to be present and feasible.
CHAPTER SEVEN
SEYCHELLES’ PROFILE

SUMMARY

Scleratinian reef corals are among the most sensitive species to climate change due to their low tolerance of environmental variability. An increase in climate and weather events has threatened the existence of these species and ocean acidification is likely to increase these impacts. This study used natural environmental variability in the life history of coral transplants to improve their genetic adaptability and optimize their resilience to climate change.
7.1. BACKGROUND AND RATIONALE

Scleratinian reef corals are among the most sensitive species to climate change due to a low tolerance to environmental variability. The coral bleaching event in 2016, for example, has caused an average of 70% coral mortality in the upper 15 to 20m of the Seychelles inner islands (Wilson et al., 2019). The slow recovery from redundant bleaching events over the past decades motivated ecosystem-based adaptation projects to restore coral reefs (Boström-Einarsson et al. 2020) and such projects were carried out in the granitic islands of Seychelles. The current methodology used in Seychelles for restoration relies on coral nurseries where minute fragments are grown in optimal growth conditions. Nursery sites are selected for the stability of their parameters, in on-shore ponds or off-shore (Frias-Torres et al., 2019). However, in some shallow coastal environments dominated by seagrass, some coral species appear to thrive despite highly variable environmental conditions.

Superimposed on the well-described impact of the rise of atmospheric CO$_2$, the dissolved carbonate system in the coastal ocean exhibits a strong variability from the combination of coastal ecosystems’ metabolisms and external factors. The processes of primary production and respiration on one hand, and of calcification and particulate carbonate dissolution of benthic and pelagic species on the other hand, respond to solar irradiance on an hourly basis. Primary production uptakes bicarbonate ions or dissolved CO$_2$ with the direct effect of increasing pH, aragonite saturation and dissolved oxygen concentration, while calcification reduces alkalinity and aragonite saturation by precipitating carbonate, calcium and magnesium.

Respiration and particulate calcium carbonate dissolution are the reverse processes to photosynthesis and calcification and have the opposite effects on dissolved substances. Tidal amplitude modulates the residence time of dissolved substances and the overall response of water quality parameters on small time scales. Over longer time scales, atmospheric precipitation leaches terrestrial decay products like coloured dissolved organic matter and humic acids that end up in the coastal ocean on medium time scales, from days to weeks, and interfering with the seawater’s ability to act as a buffer.

7.2. AIMS AND OBJECTIVES

Based on how well-adapted a species is to environmental change, coastal species can be classified spatially using the variability of the composition of coastal waters as a key parameter. We believe that artificial stability in the life history of coral transplants is key to the resilience of replanted reefs to climate change and that current practices may ultimately impair the success of reef restoration projects in the coming decades. We agree with scientists who believe that innovation in the domain of coral restoration will come from the selection of more resilient colonies (e.g. Drury 2020). Therefore, we propose to use natural environmental variability in the life history of coral transplants to improve their genetic adaptability to optimize their resilience to climate change.

The main objective was to establish a pilot nursery for coral transplants in a coastal lagoon where natural selective pressure exists. Here, we chose a site that offers strong logistic advantages and monitored some key environmental parameters over the transition period between the dry and the rainy season, where environmental variability is supposed to be the widest. The characterization of this variability will support the design of future projects and expand the range of potential collaborations, locally and regionally.
7.3. LINKAGE TO REGIONAL AND GLOBAL PROCESSES

Along many tropical shorelines, coastal tropical ecosystems like coral reefs, seagrass meadows, and mangroves create a belt of coastal protection and ecosystem services. This belt of ecosystems has high intrinsic value, biodiversity richness, and carbon sequestration potential. The environmental benefits of the entire coastal assemblage encompass the benefits of each ecosystem, when considered individually. Coral reefs and seagrass beds have changed over decades as a result of a combination of anthropogenic pressures and climate change, both in the Seychelles and around the world. Maintaining the connectivity between them is a priority to strengthen climate resilience.

SAMPLING

A YSI ECO-2 CTD was deployed at a bottom mooring in the seagrass dominated Bougainville lagoon (S 4.76231 E 55.52006) in order to describe the variability of environmental condition at high frequency (every 3 minutes) over 1 day (deployment 1) between 12 and 13 December 2021, and during 10 consecutive days (deployment 2) between 25 December 2021 and 3 January 2022. The probe measured and logged the environmental parameters:

i. Pressure, transposed into the vertical position in the water column (m), here showing the height of the water column above the sensor (in m);
ii. Temperature (°C) and conductivity, used to compute salinity (in practical salinity units – PSU);
iii. pHNBS is measured with a glass electrode calibrated against NBS buffers 7.1 and 10.0 at 25°C;
iv. Dissolved oxygen, expressed in percentage of saturation (% sat) with respect to atmospheric levels, or in concentration (mg/L); and
v. Fluorescent Dissolved Organic Matter (fDOM) is a surrogate for Chromophoric (or coloured) Dissolved Organic Matter (CDOM) and refers to the dissolved organic matter in water that absorbs strongly in the ultraviolet (UV) spectrum. It corresponds to the Total Organic Carbon (TOC) that is a proxy for runoff water discharge quality. fDOM is measured in relative fluorescence units (RFU).

During the second deployment, 20 TA samples (2 samples per day) were filtered and preserved with 0.05% (final concentration) HgCl$_2$ in sealed vials for analysis. The first deployment is characteristic of the dry season that lasted until late-December 2021 because of a persistent La Niña situation in the southern Pacific Ocean and a neutral IOD in Seychelles. The second deployment captures the shift to the rainy season with abundant rainfall on the 29th of December and daily, sometimes abundant, rainfall from the 31st of December 2021 to the 3rd of January 2022.
7.4. FINDINGS

Although seawater temperature affects the solubility of dissolved gases, like oxygen or carbon dioxide (i.e. a rise of temperature decreases both dissolved $O_2$ and $CO_2$ concentrations), the observed direction of the dissolved oxygen variations tends to demonstrate that the solubility effect is minor compared to the strength of biological processes in this temperature range (28°C to 34°C). Both pHNBS and dissolved oxygen concentration respond almost synchronously to solar irradiance in a light/night cycle, which suggests that the coupling of primary production and respiration is strong in this lagoon (Figure 7.2).

The autotroph population of Bougainville is mainly represented by a dense seagrass meadow (*Cymodocea sp.*, *Thalassia sp.* and *Syringodium sp.*), with minor contribution by *Halodule sp.* and *Halophila sp.*) in the most proximal area, and phaeophytes (*Sargassum sp.*, *Turbinaria sp.* and *Padina sp.*) that occupy the rocky/rubble substrate close to the reef flat. Because seagrasses are C4 plants their photosynthesis is not limited by high oxygen concentration, unlike brown algae’s photo-
synthesis (C3 plants). Hence, the oxygen level attained around noon may be limiting for algae but not for seagrasses. The high percentage of saturation (up to 300 %sat) measured in the Bougainville lagoon may be due to the dense seagrass bed that contributes to maintain its competitive advantage over fast growing seaweeds.

At high tide, a water circulation that brings oligotrophic oceanic water establishes northward inside the lagoon. However, the configuration in Bougainville is such that the lagoon becomes quasi-isolated from oceanic inputs at very low tide, which increases the residence time of the water mass trapped in the lagoon until the tide rises again. A decrease of salinity around the lowest low tide indicates that the lagoon receives freshwater inputs that dilute the isolated water mass. The absence of water streams on the beach (a high sand dune separates the coastal wetland from the lagoon during the dry season) validates the hypothesis that the lagoon receives groundwater inputs, at least at low tide. The dilution is more visible at low tide, when the residence time is higher, but is supposed to be a continuous process driven by the steep topography of the south of Mahe. It may however be amplified at low tide when the hydrostatic pressure on coastal limestone is the lowest.

Runoff discharge in the lagoon allows CDOM to build up at the lowest low tide and decrease at mid-high tide, when the seawater flow into the lagoon resumes (Figure 7.3). The major source of CDOM in tropical oligotrophic regions is likely the runoff carrying humic acids produced by the decay of the abundant terrestrial vegetal biomass. Hence, the chemical composition of runoff water sources remains to be characterised. It is supposed to be significantly different from the ocean seawater source and contain elevated pCO$_2$, high TA, and be rich in inorganic and organic nutrients.
COUNTRY SPECIFIC RECOMMENDATIONS

i. Seychelles expressed its ambition to preserve 100% of its seagrass meadows and mangroves at the 2030 horizon in its 2021 NDCs.

ii. In the same report, Seychelles committed to strengthen research in the domain of climate resilience. Finally, Seychelles have built a strong reputation in coral reef restoration thanks to several local NGOs.

LESSON LEARNED

i. The feasibility test of coastal monitoring proved successful with promising scientific perspectives despite several constraints imposed by the COVID-19 pandemic, then the freight crisis.

ii. Project funding continuation is envisaged via the current GEF-6 and forthcoming GEF-7 Ridge-to-Reef projects. Implementation of the Marine Spatial Plan is underway (2022-2023) and OA parameters (continuous/discrete pH and discrete Talk) have been recommended for the monitoring of protected areas, including coastal seagrass meadows).
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