KADI

Report describing importance of riverine, oceanic and atmospheric processes in coastal carbon dynamics

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Executive Summary

Fossil fuel combustion, land use change and cement manufacture has caused massive quantities of CO_2, a potent Greenhouse Gas (GHG) to enter the atmosphere, raising concentrations from approximately 280ppm in the preindustrial to 430ppm today and causing multiple adverse effects on planetary functioning. However, this increase would have been substantially larger were it not for the presence of the so called 'natural sinks' on land and ocean which have together absorbed approximately 50% of the CO_2 emitted in approximately equal propositions. The coastal sink is a significant element of this, with a range of key processes contributing to this, including the emission of CO_2 from inshore systems, the continental shelf pump which leads to an uptake of CO_2 in offshore shelf regions and the burial of carbon in coastal vegetated sediments. The total contribution that the entire coastal zone plays in the global carbon cycle is the sum of these processes integrated globally, hence any global synthesis demands the consistent understanding and quantification of fluxes in multiple representative systems. Within South Africa this concept is delivered via the SAEON (South African Environmental Observation Network) network, which we can regard as a blueprint or pioneer of activity across Africa. Within the Coastal Ocean the key site is in Algoa Bay, immediately adjacent to Gqeberha where a long-term research infrastructure investment programme has enabled observations of sea surface CO_2 and blue carbon to be initiated and maintained. Recent work also included the measurement of Greenhouse Gas fluxes from estuarine habitats around the coast of South Africa, including at another site in St Helena Bay. The Algoa Bay and St Helena Bay sites are suitable locations where all stages of the value chain linking observations through to policy advice can be piloted. These include innovating and trailing technologies, observations, data archiving, data synthesis and communications with end users. In this report we describe some early results, the status of the observing system and offer some perspectives on the prospect of upscaling this model across the African continent.

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1. Introduction

The confidence and effectiveness of African and global mitigation measures such as the NDCs for the Paris Agreement of 2015, and in the near future, the additional likely need for negative emissions interventions, depend critically on the degree of uncertainty in the quantified trends and variability of the ocean and land carbon sinks (Canadell et al., 2021; Friedlingstein et al., 2023; Monteiro and Midgley, 2023). Thus, the short to medium term future challenge to effective climate mitigation is threefold: Firstly, Net-zero greenhouse gas targets have become a central element for national and global climate action (Sun et al., 2021). Secondly, it is now almost certain that marine Carbon Dioxide Removal (mCDR) will become an essential intervention to both achieve net-Zero CO_2 as well as to drive critical negative emissions that will enable Africa and the global community to stay under the threshold range for dangerous climate change. Thirdly, the confidence in model projections that are critical to evaluate policy options depends critically on low uncertainty levels in both ocean observations and the observations-based reconstructions of CO_2 and CO_2 fluxes. All these societal and scientific challenges depend critically on a well-founded scale sensitive and low uncertainty sustained carbon observing system and associated machine learning multi-decadal reconstructions that allow the observations to be turned to resources in support of both science and policy (Monteiro and Midgley, 2023). Critically, Africa does not yet have a sustained coastal carbon observatory essential to both provide confidence in models and model projections as well as to assess the effectiveness of policy interventions. Africa's sustained coastal carbon – climate observations have long been neglected as part of the long term sustained coastal observations policies with most existing observations unevenly distributed regionally and focused on local research questions or decadal mean estimates with high degrees of uncertainty (Monteiro and Midgley, 2023).

2. General description of Global Carbon Cycle emphasising the importance of coastal processes

One of the major scientific challenges of the century is to understand and project the regulation of the Earth's climate system and the emerging regional risks. On a Global scale, warming of the climate system is unequivocal and due in large part to the atmospheric increase of the greenhouse gases (GHG) such as carbon dioxide (CO_2) (Canadell et al., 2021). Atmospheric CO_2 concentration averaged over 2021 reached 414.71 ± 0.1 ppm (Dlugokencky and Tans, 2022; Friedlingstein et al., 2022). The CO_2 levels in the atmosphere today (~425 ppm) are nearly 50% higher than during pre-industrial times (~278 ppm), which has brought the planet almost up to 1.5 - 2°C of warming, now considered to be a threshold for dangerous climate change (IPCC 2023).

The ocean acts as a major carbon sink, which reduces the amount of carbon dioxide in the atmosphere, most of which is emitted as greenhouse gas from anthropogenic activities (Canadell and Monteiro et al., 2021). Roughly a quarter of the total anthropogenic CO_2 emissions has been taken up by the ocean (Friedlingstein et al., 2022; Gruber et al., 2023), increasing seawater dissolved inorganic carbon (DIC) and decreasing pH in a process referred to as Ocean Acidification (OA)(Doney et al., 2009; Feely et al., 2009). Increasing CO_2 emissions into the atmosphere not only results in the reduction of the pH but simultaneously increases temperature and decreases dissolved oxygen in the ocean. The combined effects of these multiple stressors have a major impact on marine life (Feely et al., 2018; Keeling et al., 2010).

These biogeochemical changes plus concomitant changes in ocean circulation will have a profound effect on some of the ocean's key services, that is its capacity to mitigate climate change by removing anthropogenic CO_2 from the atmosphere, and its provision of important services such as food and biodiversity.

However, this increase in atmospheric CO_2, and hence the associated temperature rise and other consequences would be much smaller were it not for the so called natural sink which together remove approximately half of the fossil CO_2 emitted. Classically we assume that these are dominated by the open

ocean and ‘intact’ terrestrial ecosystems (Figure 1, left panel). However recent data synthesis work suggests that freshwaters, estuaries and coastal seas play a key role as a carbon sink (Figure 1, right panel).

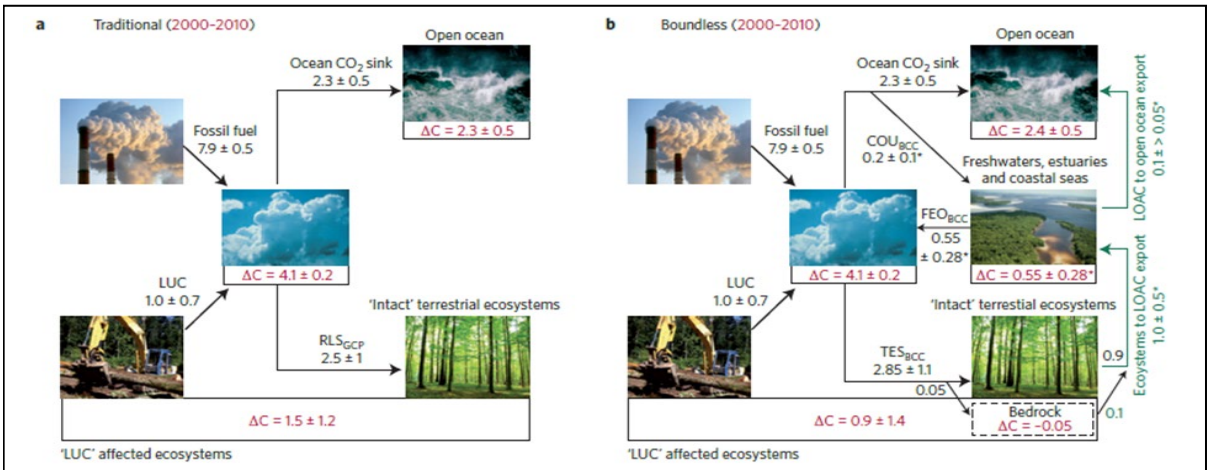


Figure 1. *Global budget of anthropogenic CO_2 (from Regnier et al., 2013).*

This reflects the crucial role the Land – Ocean Continuum from rivers to coastal marine ecosystems play in the global carbon cycle where individual elements serve as important sinks or sources of GHGs, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). While the atmospheric CO_2 sink is reasonably well-constrained for the open ocean, the air–sea fluxes of GHGs from or to coastal ecosystems is not very well constrained. These fluxes can vary markedly, depending on discharges from the watershed, upwelling, productivity and//or eutrophication and warming. Although fluxes from individual systems can be small they collectively scale up to a global impact on atmospheric CO_2 variability as well as on local impact on ocean acidification (Goulven et al., 2010; Morgan et al., 2019).

Estuaries are known sources of carbon dioxide (CO_2) and methane (CH_4) because of net remineralization of terrestrial organic carbon (Capone et al., 2013; Noriega et al., 2014), whereas coastal shelf areas can often behave as a sink for atmospheric CO_2 (Borges et al. 2005). Beyond increasing global CO_2 emissions, increased phytoplankton blooms as a result of eutrophication further contribute to coastal ocean acidification (c-OA) through the release of CO_2 during bloom senescence and decomposition. This circumstance can also lead to oxygen depletion in on-shelf waters, which enhances the production of N_2O, a GHG over 300-times more potent than CO_2 on a per molecule basis (Myhre et al., 2013). The carbon budget of the coastal zone also includes coastal wetland ecosystems (e.g. salt marshes, mangroves and seagrasses) that sequester and store large quantities of organic carbon in the plants and the sediment, known as Blue Carbon. The heterogeneity and complexity of these highly active biogeochemical environments at the interface between the land and the ocean implies that observations made during short term campaigns will not capture the full range of flux variability. This makes it necessary to implement long-term as well as autonomous observational technology.

The coastal oceans play a disproportionate role in anthropogenic CO_2. South African coastal regions act as a sink of CO_2 (Anorne et al., 2017). The quantification of coastal CO_2 flux trends from observations is still impacted by poor spatial coverage and short duration of the time series (Resplandy et al., 2024). Hence, empirical algorithms and models offer an alternative means of assessing long-term trends. At both global and regional scales, the coastal ocean is currently viewed as a sink of atmospheric CO_2 (Chen et al., 2013; Laruelle et al., 2018; Resplandy et al., 2024) with some studies indicating that the CO_2 uptake is intensifying (Dai et al., 2022; Mackenzie et al., 2005). Exceptions have been given to areas such as the California Current, South and Mid Atlantic Bight and Baltic seas where coastal ocean pCO_2 increases at a similar rate or even higher rates than the atmospheric pCO_2 (Dai et al., 2022; Laruelle et al., 2018; Reimer et al., 2017).

A Coastal GHG Observing System will be better suited to quantify the carbon budgets in Land-Ocean Aquatic Continuum (LOAC), and the variability and trends of long term GHG fluxes and ocean acidification. This will constrain the variability and trends of regional carbon budgets and its transport through the adjacent coastal regions. A long-term ambition of the project is to deploy observing systems to track carbon fluxes in the coastal region, extending ultimately to include the coasts of east, west and north Africa, including important upwelling systems and western boundary currents, which are rich fisheries grounds and often sources of CO_2 to the atmosphere. Such observing systems need to be robust, use common standards, well calibrated, capable of delivering data in near real time and support both international climate policy development and domestic management of ecosystem services.

3. Specific processes of relevance, Estuarine Outgassing, The continental Shelf pump, Blue Carbon & Ocean Acidification

Multiple processes that are key within the LOAC that need to be integrated into coastal carbon budgets include the following:

i) the flux of CO_2 and other greenhouse gases to the atmosphere. The LOAC ranges from the inshore zone including rivers, estuaries, salt marshes through to the shelf environment. In general, estuarine environments tend to be sources of CO_2 to the atmosphere, driven by the mobilisation of organic matter and geological courses into freshwater. In contrast, shelf environments tend to be sinks for atmospheric CO_2 driven by cooling, biological productivity and the offshore transport of super saturated waters.

ii) the burial of organic matter in coastal vegetated systems (Blue Carbon). This has recently become a key research focus due to the potential for this sink to be enhanced as part of individual country contributions to their NDCs (Nationally determined contributions). Multiple systems are recognised including mangroves, kelp forests, salt marshes and seagrass beds.

iii) the gradual increase in atmospheric CO_2 levels leads to CO_2 entering the surface ocean as a result of gas exchange processes. Once dissolved in seawater CO_2 dissociates leading to an increase in Hydrogen ion concentration and a reduction in pH. This acidification of the oceans can have severe consequences for marine ecosystems and food webs.

Understanding the dynamics of coastal air-sea CO_2 fluxes is crucial for comprehending the global carbon cycle and its impacts on global and regional climate change (Roobaert et al., 2024). Globally, the oceans play a role as a carbon sink significantly influences the atmospheric concentrations of CO_2 and, consequently, the climate regulation. Takahashi et al. (2009) provide a comprehensive analysis of the ocean's role in global carbon cycling, highlighting the spatial and temporal variability of CO_2 fluxes across different oceanic basins. In the South African context, the Benguela Upwelling System for example, and the Southern Ocean as a whole are of particular interest due to their dynamic biogeochemical processes, which significantly impact regional and global carbon budgets (Monteiro et al., 2015). These areas are characterized by complex interactions between physical oceanography and marine biology, making them key regions for focused studies on air-sea CO_2 exchanges, and ideal areas to prototype a carbon / GHG observational programme for Africa.

4. State of coastal biogeochemistry observations in Africa

The coastal biogeochemistry observations in Africa are so sparse it is convenient to describe the status of these observations in terms of bioregions of importance, i.e. Large Marine Ecosystems. Eight of the sixty-four Large Marine Ecosystems (LMEs) identified in the coastal waters of the world ocean are around Africa (Figure 2). From Figure 2 five of the eight LMEs have some observations, with the highest concentration in the Agulhas and Benguela Currents LMEs. LMEs with the least observations are the Mediterranean Sea, Red Sea and the Arabian Sea, although observations are extensive on the European coast of the Mediterranean Sea LME. It should be noted though that observations are country specific and several countries within well observed LMEs have no accessible records of observations, e.g. Namibia.

From Figure 2 it is clear that many coastal countries in Africa are active in blue carbon research, although the map does not accurately convey the levels of expertise as several countries with known expertise have not published their results or archived their data (https://shiny.si.edu/coastal_carbon_atlas/). Greenhouse Gas flux measurements are sparser in Africa, and except for South Africa, have mostly been conducted by external research entities that collaborated with local African researchers.

Figure 3 highlights the 24 countries that belong to the Global Ocean Acidification Network and the six countries (South Africa, Mozambique, Mauritius, Ghana, Nigeria, Cameroon and Benin) that received GOA-ON in a box kits. Research outputs have been limited, although several manuscripts have been published on the impact of OA on tropical and subtropical coral reefs as well as temperate oceans (South Africa).

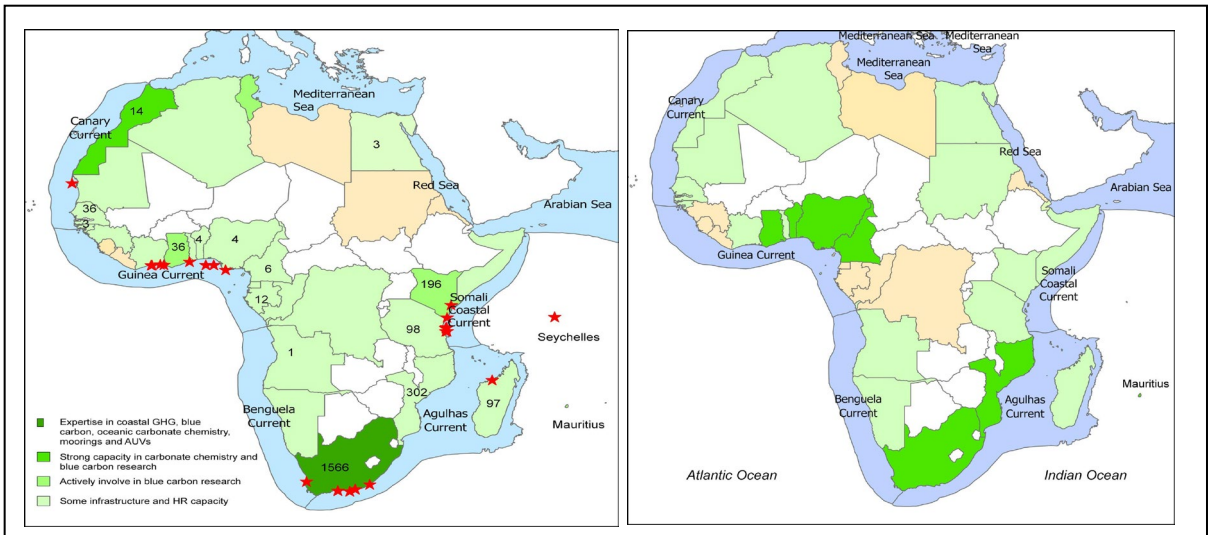


Figure 2. *Map of Africa showing the state of coastal blue carbon and GHG observations in Africa. Red stars indicate sites where GHG samples have been collected. Figures within countries indicate the number of blue carbon samples collected and archived with the Coastal Carbon Network (https://shiny.si.edu/coastal_carbon_atlas/). The colour of the countries indicate the level of current capacity to conduct coastal biogeochemical research.* ***Figure 3.*** *Countries that belong to the Global Ocean Acidification Network (24 countries) and those that received GOA-ON in a box kits (i.e. South Africa, Mozambique, Mauritius, Ghana, Nigeria, Cameroon and Benin).*

5. Selection of coastal carbon prototype sites

5.1. Introduction

The geographical advantage of South Africa's coastal ocean system derives from its “peninsula” position at the southern tip of Africa between the Atlantic, Indian and Southern Oceans (Biastoch et al., 2024; Brandt et al., 2023). This makes it one of the most important crossroads for ocean circulation that connects the tropical ocean to the Southern Ocean both at the surface and in the interior and in doing so play a critical role in the regional and global carbon and heat budget imbalances of the planet (Biastoch et al., 2024).

The South African coastal ocean is further divided into 3 sectors: the Benguela upwelling sector, the Agulhas Bank sector and the Agulhas Current sector. While the Benguela system is better studied in terms of CO_2 and some of the processes that influe4nce its trends and variability in its biogeochemical cycles are currently undergoing fundamental changes, largely as a consequence of not fully understood carbon-climate feedbacks. In contrast the carbon fluxes in both the Agulhas Bank and Agulhas Current systems are almost completely unconstrained due to the absence of experimental and sustained observations. The outcome of this status is that the drivers of the trends and variability of CO_2 in the SA coastal systems are not quantitatively constrained nor understood sufficiently to support greater confidence in model predictions and to support the assessment of climate mitigation measures.

Recently, Ford et al. (2022) identified a weakening sink of atmospheric CO_2 within the Benguela Upwelling system (positive CO_2 flux trends) by using satellite estimates of pCO_2 from the South Atlantic Feed Forward Neural Network (SAFFNN). Based on the extended Multi-Linear Regression(eMLR) reconstruction, it has been found that the surface pCO_2 increased significantly during the period 2000-2019 in the Benguela Upwelling System (BUS). It has also been found that the trend in the atmospheric pCO_2 is weaker than in sea surface pCO_2 in BUS, indicating that the upward trend in sea surface pCO_2 is weakly linked to the changing air-sea flux of anthropogenic CO_2. More research work needs to be done to reduce the uncertainties of these estimates and to understand the drivers of the fast-rising sea surface pCO_2 trend. On the west coast (southern Benguela region), the mean annual flux (mol C/m^2 per year) reported is -1.62 (Santana-Casiano et al., 2009), -1.17 to -3.24 (González-Dávila et al., 2009), -1.36 (Monteiro et al., 2010), -1.53 (Gregor and Monteiro, 2013). Anorne et al., (2017) reported -4.27±0.07 mol C/m^2 per year for the west region, -4.39±0.08 mol C/m^2 per year for the southern region, and -5.037±0.11 molC/m^2 per year for the south-east region. Siddiqui et al., (2023) has integrated the annual mean fluxes over the upwelling area and reported a CO_2 emission of 15.64 Tg C/y in the northern Benguela and a CO_2 uptake of -2.94 Tg C/y in the southern Benguela.

Given the complexity of coastal processes and the fact that the global integration of such processes is dependent on bringing together multiple estimates from individual systems it is logical to begin with creating national nodes or hubs. One such is Algoa Bay, located on the Southern Coast of South Africa. This forms the Algoa Bay Sentinel Site (ABSS) which operates within the South African Environmental Observation Network (SAEON), which has been operational since 2008. A significant investment known as the Algoa Bay project has been underway over the course of KADI supported by multiple projects and national and international funding agencies. A second node is St Helena Bay on the West Coast of South Africa. Algoa Bay is situated in the South Coast Marine Province and the Agulhas Bioregion and St Helena Bay is located in the West Coast Marine Province and the Namaqua Bioregion (Figure 4) (Stephenson 1948; Emanuel et al., 1992; Bolton and Anderson, 1997; Lombard, 2004). It is anticipated that these two contrasting sites would create different blue carbon, GHG and ocean acidification results from at least two of the LME’s that surround Africa.

5.2. Algoa Bay Sentinel Site for LTER

The Algoa Bay Sentinel Site is the most comprehensive coastal observation network in South Africa, spanning > 300 km of coastline along the warm-temperate Agulhas Bioregion. The long-term maintenance of this network of *in situ* sensor moorings, acoustic receivers and ecological sampling sites enables intensive observation and research of dynamics associated with a myriad of essential ocean (EOV) and biodiversity variables (EBV), thereby making a meaningful contribution to the Global Ocean Observing System. Figure 5 shows the extent of the observing system. A shortcoming of this observation network is that most of the observations are delayed by 3-6 months and does not provide real-time or near real-time data.

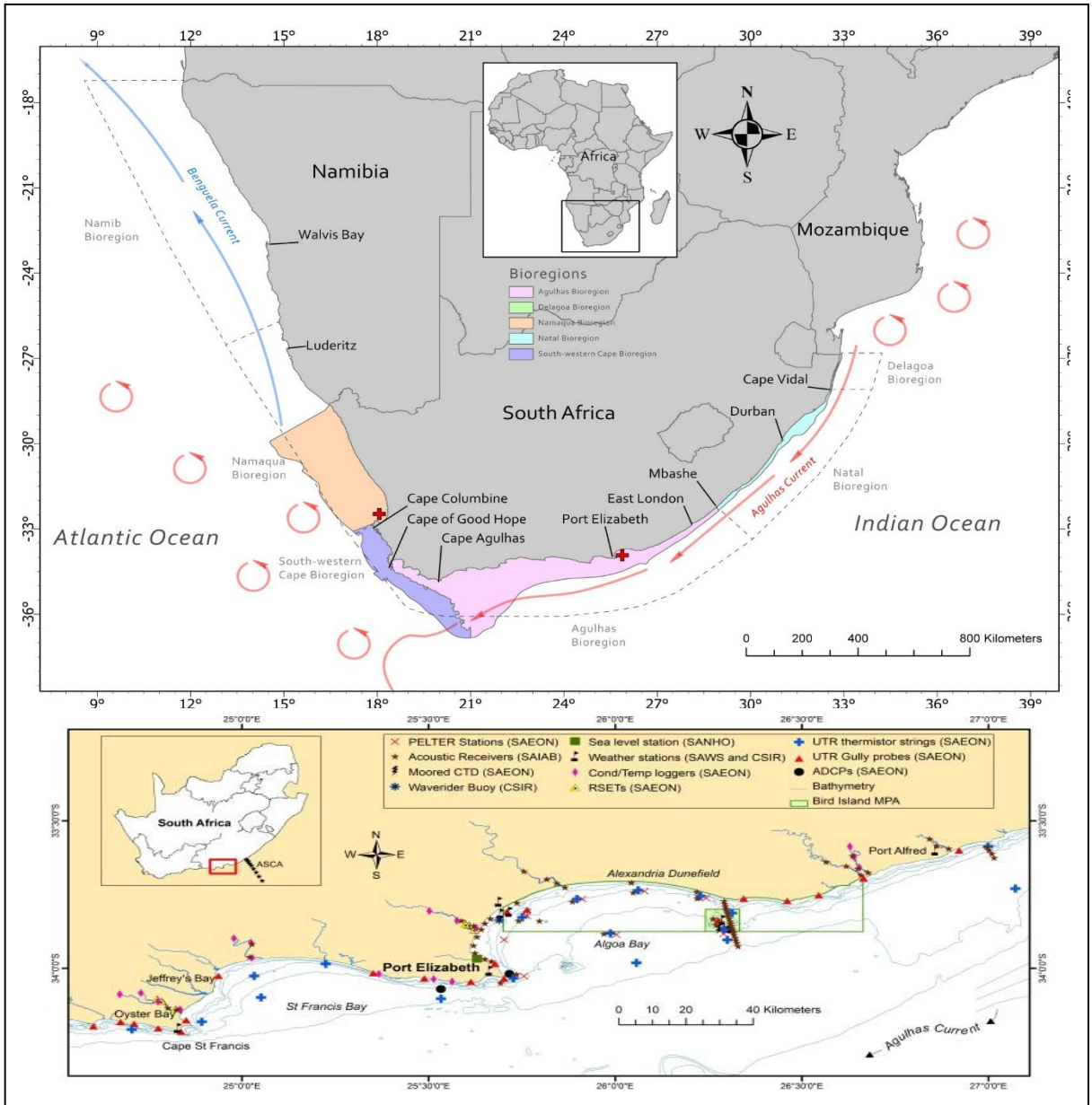


Figure 4. *Study site map showing the location of Algoa Bay and St Helena Bay (red crosses) in South Africa. Dominant marine provinces, bioregions and currents are also shown.* ***Figure 5.*** *Algoa Bay Sentinel Site for LTER. Symbols denote long-term observations of a range of Essential Ocean Variables.*

5.3. St Helena Bay Satellite Sentinel Site for LTER

St Helena Bay on the West Coast of South Africa (Figure 6) is one of SAEON's emerging Satellite Sentinel Sites for LTER. Long-term observatories have been deployed in the Berg Estuary that flows into St Helena Bay and include estuarine water column and bottom sediment carbon stations, Rod-Set Elevation Table stations, GHG sites in various salt marsh and mud flat habitats and blue carbon stock sites (above ground biomass, below ground biomass and sediment stock). These sites were established in 2024 and have been sampled twice already and will provide a good assessment of carbon flux from the terrestrial environment, through the estuary to St Helena Bay. St Helena Bay has a long history of research by the Department of Forestry, Fisheries and the Environment (DFFE) and they still maintain a survey transect of 8 stations that is sampled with a large research vessel (Figure 6). SAEON is planning to deploy a large MetOcean Coastal Observation Mooring at Station 4 of the transect (30 m depth) and will be equipped with pCO_2 and pH sensors (see Section 5.4 below).

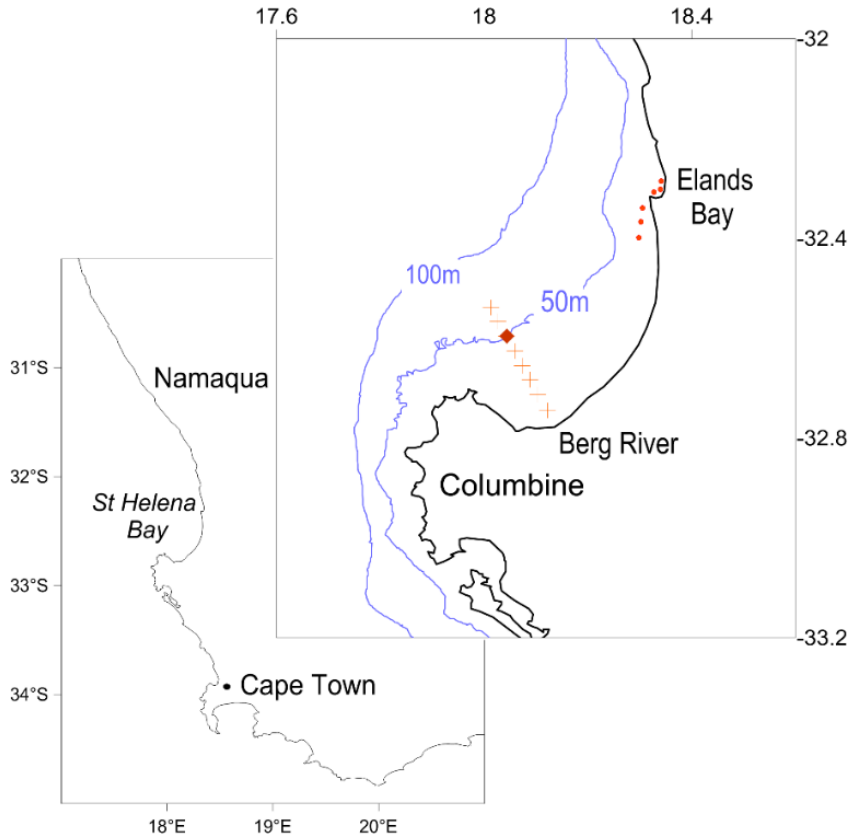


Figure 6. *Map showing St Helena Bay along the West Coast of South Africa. Red crosses indicate location of long-term stations sampled by DFFE. Red diamond indicates the location of a mooring that was deployed for 20 years. The Berg River drains into St Helena Bay to the north of the stations.*

In the following sections we describe some of the new technology, data gathering, archiving and synthesis work that has been undertaken at these two sites relevant to ocean carbon together with some experiences on communications with end users.

5.4. New technology

SAEON is planning to deploy a network of real-time MetOcean moorings around the coast of South Africa. The first moorings will be deployed in St Helena Bay and Algoa Bay and will deliver the first real-time mooring observations of pCO2 (surface water and air) and pH (surface water) in Africa. A schematic of the mooring design is shown in Plate 1 and 2 below. The moorings will measure a wide range of Essential Ocean Variables on an hourly basis, including Salinity, temperature, pH, oxygen, Chl-a, turbidity, nitrate, current direction & strength, waves, swell, climate (weather station on buoy), pCO2 (in the water and on the buoy using a modified VeGAS system) and acoustic tracking of tagged species. It was hoped that these moorings would have been deployed in 2024 so that they could have contributed data to the KADI project, but due to unforseen delays, these moorings will now be deployed in the first half of 2025. Dockside testing is currently underway. It is planned to have these moorings labeled as ICOS Marine Stations contributing data to the global database as soon as possible. Lessons learnt from developing moorings in-house in Africa will be communicated to the KADI stakeholders as a possible option for roll-out to other African countries.

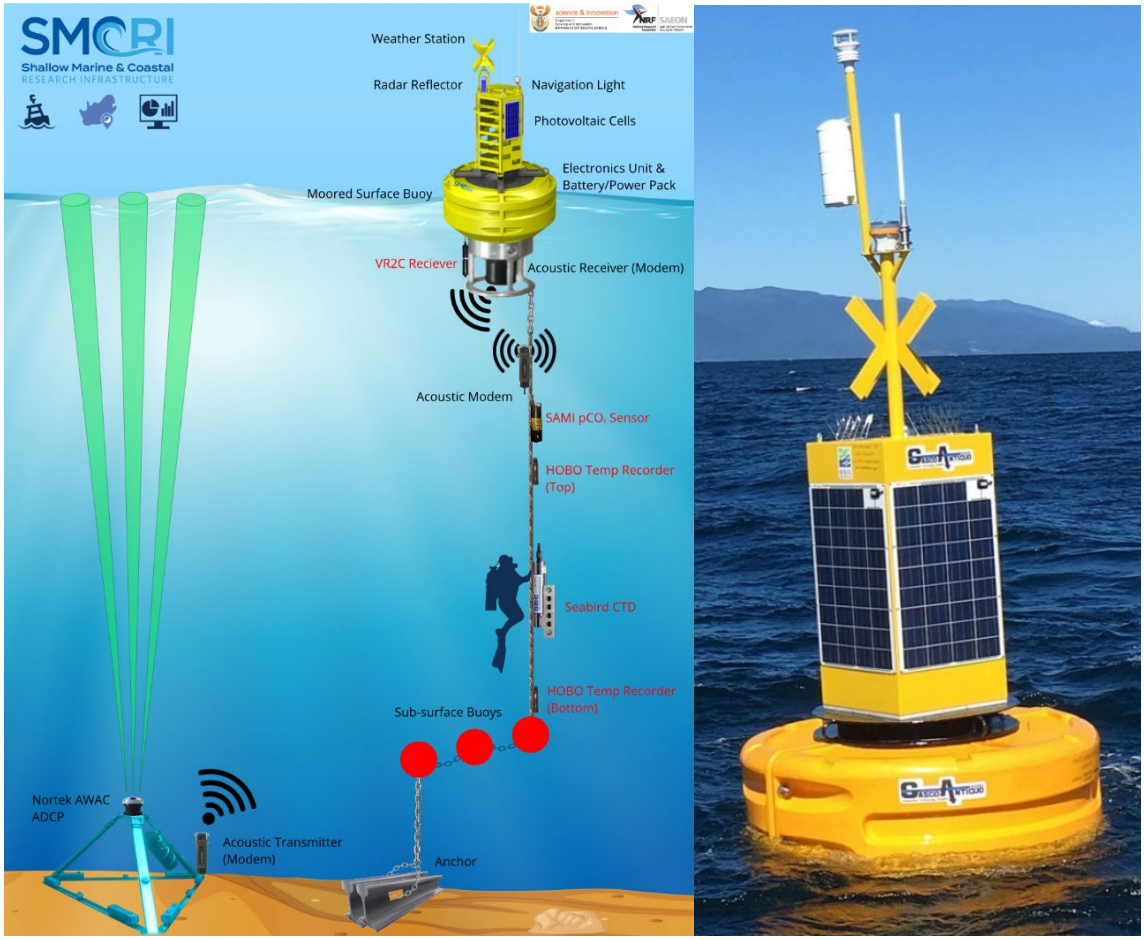


Plate 1. *Schematic of MetOcean mooring to be deployed in Algoa Bay and St Helena Bay.* ***Plate 2.*** *Surface mooring is an OSIL buoy*

5.5. Data Gathering

5.5.1. Ocean Carbon concentrations

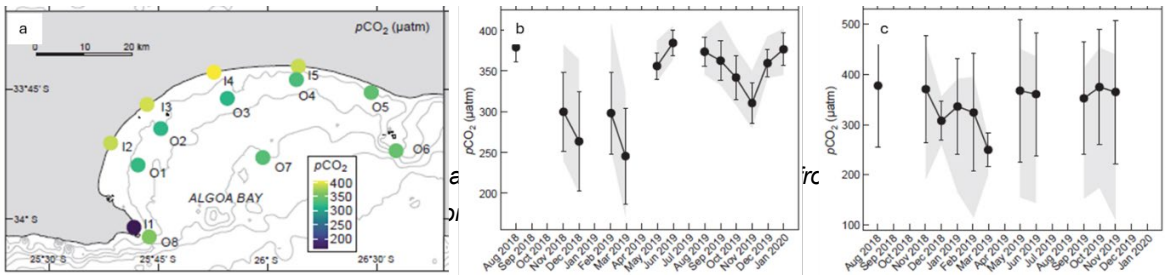


***Figure 7**. Spatial pCO_2 results from Algoa Bay (a), temporal pCO_2 data from the offshore stations (b) and temporal pCO_2 data from the inshore stations (c).*

Edworthy *et al.,* (2022) report a comprehensive survey of the ocean carbon system in Algoa Bay in 2020. At that time atmospheric pCO_2 was 414 pm (Atmospheric CO_2 ppm by year 1959-2024 | Statista). Figure 7 shows that on average levels inshore were approximately 400 ppm, declining offshore. Hence on average the system served as a net sink for CO_2. The inshore and offshore data are shown resolved by season in the other two figures, with all data being below 400 ppm suggesting that the system is an all year round sink for carbon.

5.5.2. Blue Carbon

The Algoa bay project (Home | The Algoa Bay Project) has a significant focus on blue carbon systems within WP6 (Work Programme 6 | Algoa Bay Project). This focuses on blue-carbon-estuary-habitat with the Ocean Accounts Framework of the OAF. It aims to determine how the OAF can be used to measure changes on key blue carbon terms. It is broken into various activities.

1. The viability of a carbon-offset mechanism for South Africa's Blue Carbon ecosystems.
2. Applying Ecosystem Accounting approaches to Algoa Bay systems (includes extent, condition, pressure and ecosystem service accounts).
3. Estimating Carbon stocks and assessing short and long-term threats to these stocks at selected study sites.
4. Investigating the restoration of estuarine habitats to increase carbon storage capacity.
5. Integrating WP6 findings to provide input to the study site ocean accounting reports.

Results from the first study on Blue Carbon in the Swartkops Estuary that enters Algoa Bay have been published in Human et al. (2022) and Wasserman et al. (2023). These studies showed that the sediment in the subtidal and intertidal salt marshes contained significant carbon stocks and were an important carbon sink, especially for *Spartina maritima* (Figure 8).

The above ground biomass stocks were also higher than the below ground biomass stocks (Figure 9), with *S. maritima* again storing the most carbon in its biomass. Wasserman et al. (2023) calculated that as much as 315 970 ± 217 111 Mg C could be stored in South Africa's 1755 ha of *Z. capensis* (seagrass) habitats. Similar studies are being conducted at the Berg Estuary within St Helena Bay to determine if the carbon sequestration potential of these three salt marsh species are different on the cold-temperate West Coast, compared to the warm temperature south-east coast (Algoa Bay).

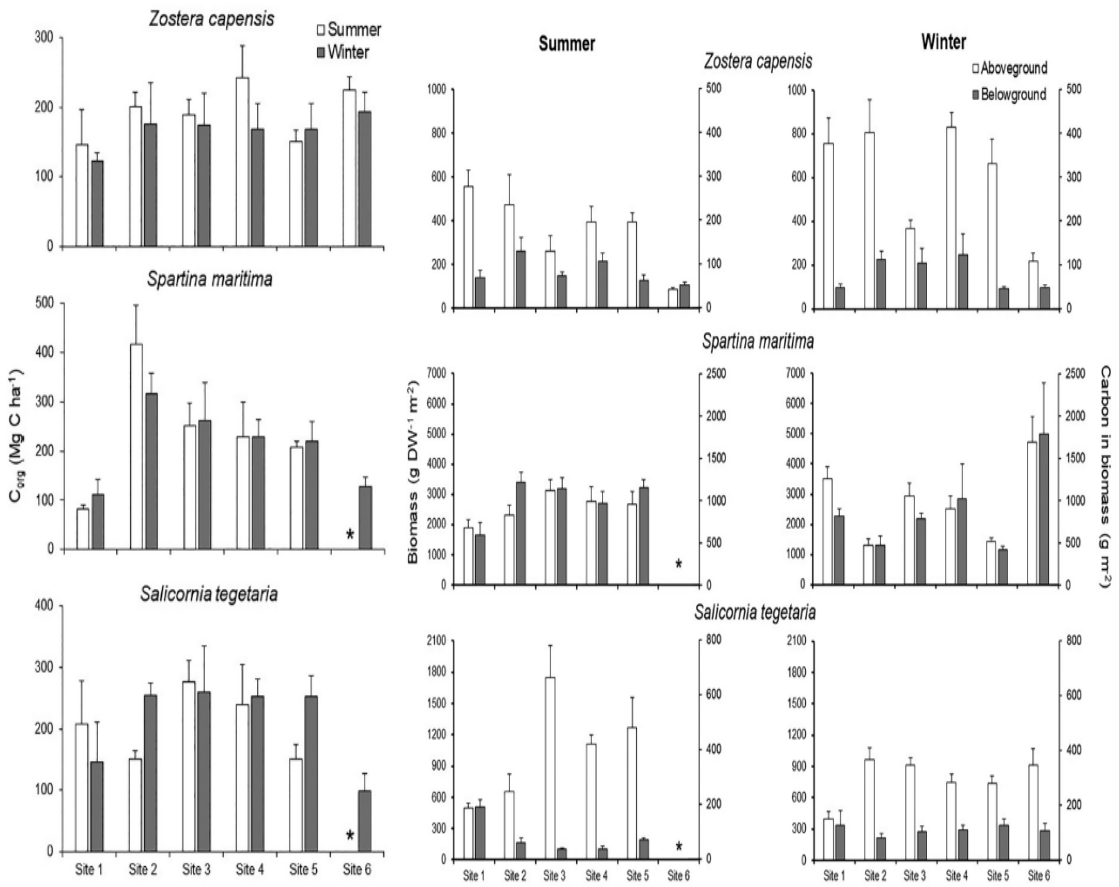


Figure 9. *Mean biomass (primary axis) and carbon content (secondary axis) of Z. capensis,* S. maritima*,* S. tegetaria *(n=36 per species, + SD).*

5.5.3. Greenhouse Gas Flux:

Greenhouse Gas fluxes were measured in the Swartkops and Berg estuaries in Algoa Bay and St Helena Bay during winter (August 2024) and summer (January 2025) to determine GHG flux from different salt marsh habitats and mud flats. Additional data were also collected in a mangrove forest in the subtropical east coast of South Africa to determine if GHG fluxes are markedly different in this important African habitat type. Preliminary data indicates no significant difference in GHG fluxes between the two estuaries in winter, although the flux of CO_2 was higher in the Berg Estuary than the Swartkops (Figure 10). The reason for the higher CO_2 flux could be related to a freshwater flood that had inundated the Berg estuary salt marsh in winter, causing more outgassing as a stress response. Samples were also collected from the sediment and water column throughout the entire estuary, which, combined with the GHG flux data, will enable the determination of the carbon input from the river and terrestrial sources into both bays.

Figure 11 indicates that mangrove forests at their most southern extreme limit in Africa are significantly larger emitters of methane than salt marsh, but that their CO_2 flux is lower. The summer dataset will indicate whether this pattern holds true across seasons, but more data is urgently needed from other regions in Africa to calculate whether these habitats are net sources or net sinks of GHGs and particularly blue carbon.

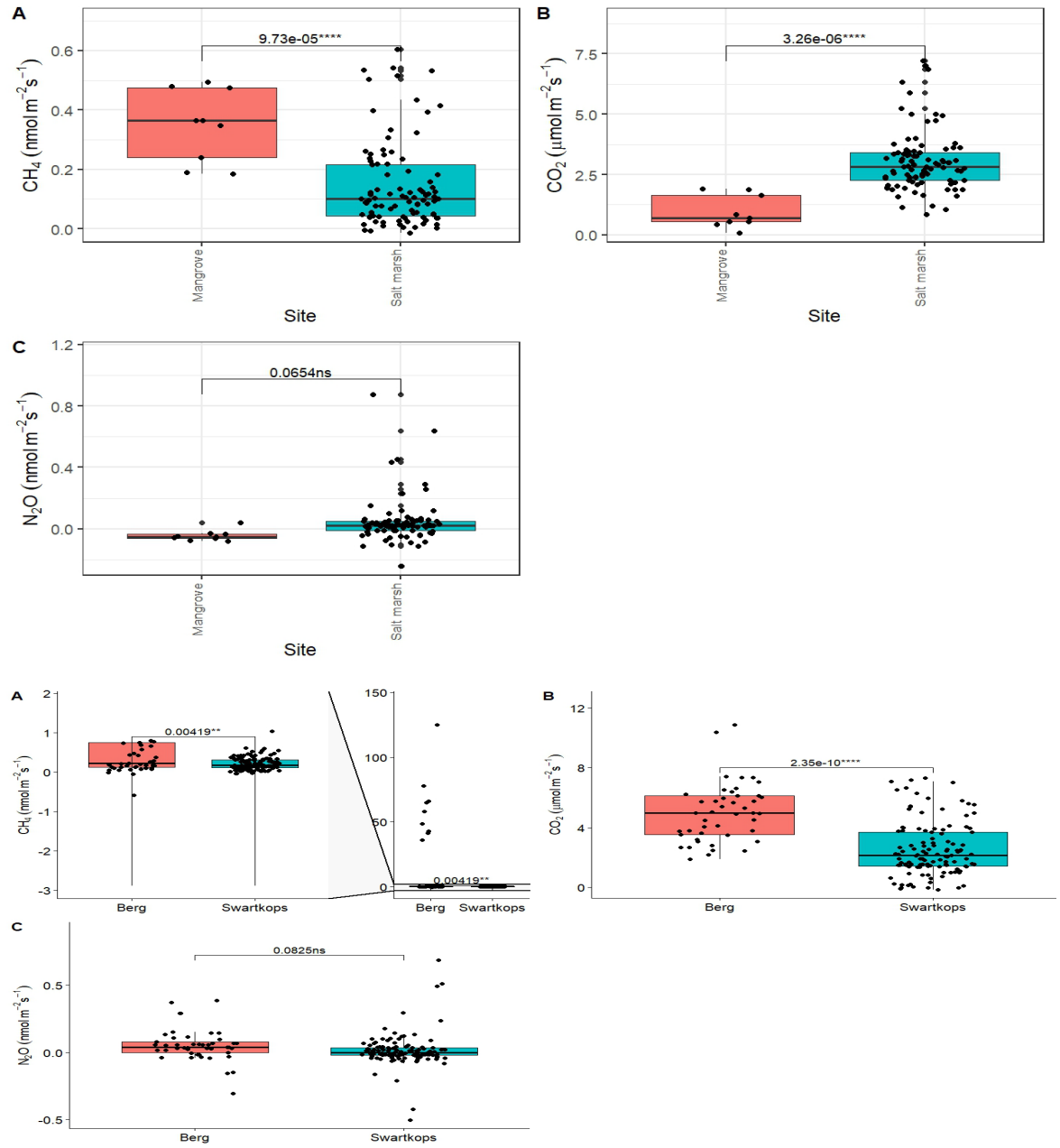


Figure 10. *GHG flux from salt marshes in the Berg (St Helena Bay) and Swartkops (Algoa Bay) estuaries (unpublished data)* ***Figure 11.*** *GHG flux from salt marshes vs mangrove forests from the east coast of South Africa (unpublished data)*

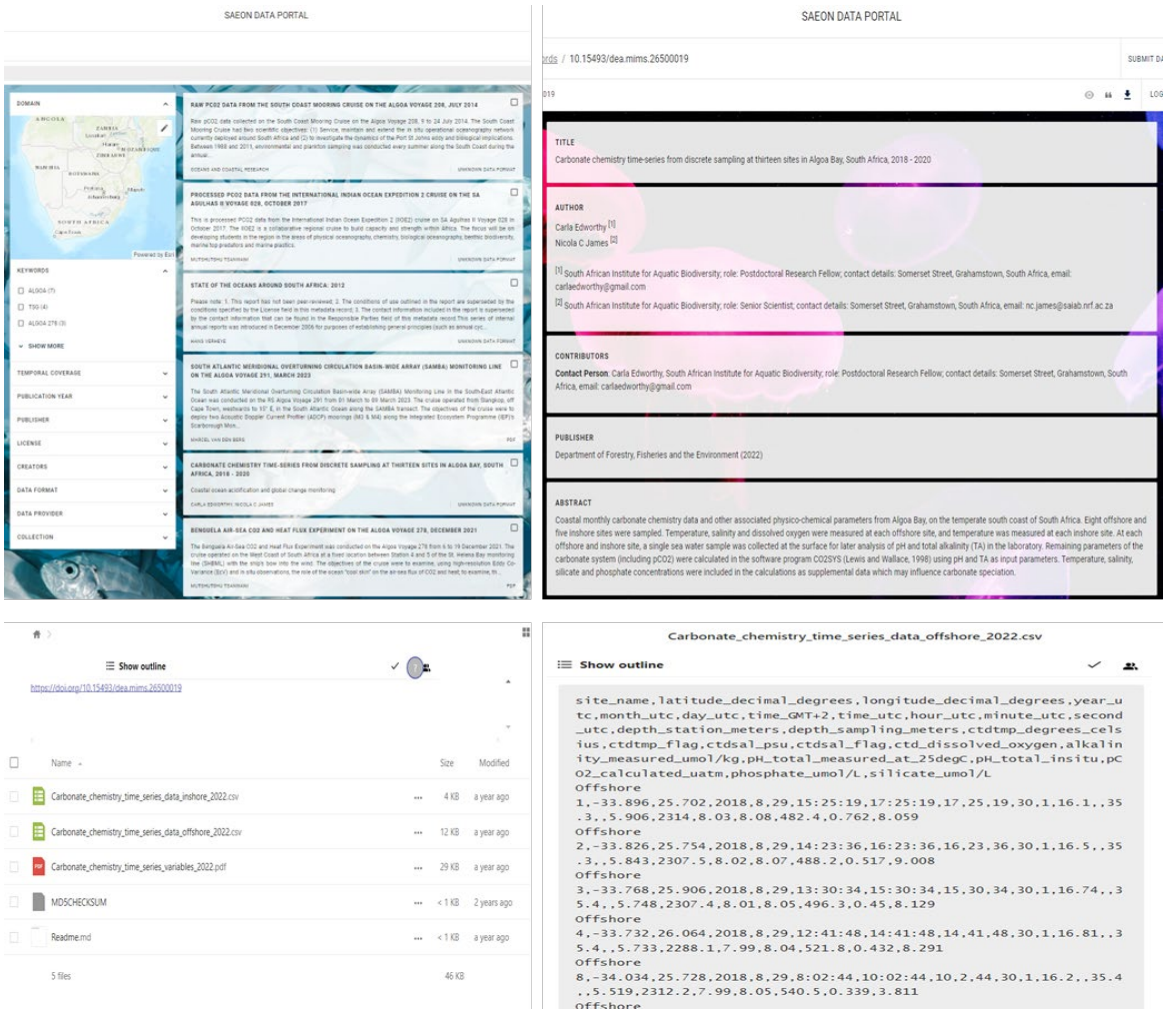
Vegetated coastal ecosystems (VCEs; i.e., mangroves, salt marshes, and seagrasses) play a critical role in global carbon (C) cycling, storing 10× more C than temperate forests. Methane (CH_4), a potent greenhouse gas, can form in the sediments of these ecosystems. Currently, CH_4 emissions are a missing component of VCE C budgets and these new results from South Africa will fill an important gap. A review summarizing 97 studies describing CH_4 fluxes from mangrove, salt marsh, and seagrass ecosystems indicated that CH_4 fluxes from these ecosystems were highly variable yet they all act as net methane sources (Al-Haj & Fulweiler 2020).

The highest fluxes were observed at fresh-oligohaline sites (Arias-Ortiz et al. 2024), which the recent data from Algoa Bay and St Helena Bay supports.

5.6. Archiving

NRF-SAEON has developed an elaborate and sophisticated data portal (see figures 12 below) which allows data from all around South Africa to be archived. As an example of what is available we show the pathway by which the data from the Edworthy et al. (2022) manuscript published under a creative commons licence: Legal Code - Attribution-ShareAlike 4.0 International - Creative Commons can be extracted

Figure 12. Screenshots from data archiving system developed within SAEON to host data



5.7. Links to policy makers

An “Integrated Regional Observation Carbon-Climate Constraints” workshop was held on 16-17 May 2023 in Pretoria, South Africa. The aim of the workshop was to bring together the carbon observing and policy communities in South Africa to identify the needs, priorities and action plans to build and sustain an integrated regional observational constraint for carbon in support of climate - biodiversity science - policy nexus. The evaluation of the effectiveness of regional and global emission reductions (net-Zero) and negative emissions (CDR) as well as the model projections rely critically on the confidence level of the observational constraints. This is a major gap in the Southern African region. High confidence constraints are necessary to increase confidence in model projections as well as to develop effectiveness metrics and to support national and international mitigation policy aims such as mitigation, adaptation and global stocktake as well as in business through carbon pricing. The South African land, ocean and atmospheric carbon observing communities have the skills and infrastructure at the domain level: now, this needs to be scaled up into a high impact set of public integrated regional carbon concentration, carbon flux and inventory products that build towards greater understanding of the changing carbon-climate-water nexus and its impact on all aspects of a just transition. The KADI project was highlighted as one avenue to test the observational capacity and data products it can produce to answer important questions for the research and policy making community. The workshop addressed the following key questions:

- What is the current status of observations?
- What is needed to facilitate the integration of existing observing system capabilities?
- How to coordinate the operational observations and reconstruction, real time emissions and inversion modelling?
- Requirements to facilitate Open Data and data access and data science training?
- Who are the main regional and international partners?
- How should the community organize ourselves to support the research and operational goals and objectives and to coordinate long term co-funding proposals?

Key stakeholders invited to the workshop included:

Name	**Institution**
Gregor Feig	SAEON/EFTEON
Pedro Monteiro	Stellenbosch University
Guy Midgley	Stellenbosch University
M-J Bopape	SAEON
Barney Kgope	Department of Forestry Fisheries and Environment, South Africa
Jongi Witi	Department of Forestry Fisheries and Environment climate change mitigation unit, South Africa
Maesela Kekana	Department of Forestry Fisheries and Environment, South Africa
Thato Mtshali	Department of Forestry Fisheries and Environment, South Africa
Mutshutshu Tsanwani	Department of Forestry Fisheries and Environment, South Africa
Werner L. Kutsch	ICOS
Tim Rixen	BMBF
Tommy Bornman	SAEON SMCRI
Kathleen Smart	SAEON
SAEON data: Marc Pienaar	SAEON
Warren Joubert	SAWS
Sally Archibald	Wits
Francois Engelbrecht	Wits

Sarah Nicholson	Gliders
Sandy Thomalla	SOCCO

Following on from this successful workshop, the scientific community in South Africa successfully submitted a research project for funding to the National Research Foundation (NRF) under the Earth Systems Science Research Programme (ESSRP) with the title “South African Ocean Carbon – Climate Observatory: Towards a strategic Regional mCDR Science – Policy System”. This project started in February 2025 and will continue until 2027. The project will make use of the data and study sites developed during KADI and will expand the network of observations to the subtropical /tropical east coast as well.

6. Upscaling to the African Continent

Upscaling coastal biogeochemical observations to the rest of the continent will require the following key processes to be measured:

a) The measurement of seawater CO_2, CH_4 and N_2O concentrations. This allows the flux to the atmosphere to be calculated via a comparison to atmospheric concentrations and piston or transfer velocity. pCO_2 can be measured using CI_2
b) Coring to assess blue carbon burial, ideally with carbon14 or other dating methods
c) Seawater pH to allow ocean acidification to be monitored, this can either be done via electrode or spectrophotometric methods

6.1. Design specifications for coastal biogeochemistry research infrastructure

6.1.1. Parameters to be measured:

A Coastal GHG Observing System that resolves the scales of variability in air-sea flux will need to quantify the carbon budgets in Land-Ocean Aquatic Continuum (LOAC) and constrain the variability and trends of long term GHG fluxes and ocean acidification. Most countries in Africa have the capability and resources to determine coastal wetland (salt marshes, seagrasses, mangroves, etc.) carbon budgets, but the cost and skills required to quantify GHG fluxes and ocean acidification limits the observations to a few countries in Africa. Methods for the determination of blue carbon is well documented (Howard et al. 2014):

https://www.thebluecarboninitiative.org/manual and Schindler Murray et al. (2023`: https://oceanpanel.org/wp-content/uploads/2023/06/Ocean_Panel_Blue_Carbon_Handbook-1.pdf) and implemented globally. To be able to produce observational data that can provide ocean biogeochemical forecasts and early warnings and, thus, contribute to climate projections, the global scientific community agreed to measure the biogeochemical Essential Ocean Variables (BGC-EOVs). Currently, BGC-EOVs comprise of the nine variables: oxygen, nutrients, inorganic carbon, Transient tracers, Particulate matter, Nitrous oxide, Stable carbon isotopes, Dissolved organic carbon, and Ocean Colour. Comprehensive specification sheets describing each of the variables usage, global observing networks, sensor types, metrology requirements/capabilities etc. can be downloaded from the website of the Global Ocean Observing System (GOOS) https://goosocean.org (see: https://goosocean.org/what-we-do/framework/essential-ocean-variables/). The majority of the BGC-EOVs requires expert scientists and technicians to collect, analyse and interpret the results and only South Africa and Morocco are currently active in this field.

6.2. Instrument and method specifications:

Following extensive workshops and instrument trials in South Africa, the Coastal Biogeochemistry pilot proposes the adoption of a phased roll-out approach of research infrastructure. The first phase consists of low cost observational infrastructure that can easily be implemented in most countries in Africa. The second phase involves the procurement of medium cost research infrastructure with limited training required. The

third and final phase involves the roll-out of high cost continuous and discreet near-shore observations that require specialised scientists and technicians to implement and maintain.

6.2.1. Low-cost blue carbon observatory

Large focus on developing low cost techniques that deliver high quality data:

Specifications:

- Sediment and vegetative carbon pools of salt marsh, mangroves, sea grasses, etc:
  - Sediment corers, e.g. Russian Peat / Sediment Corer (e.g. https://www.vanwalt.com/equipment/russian-peat-corer-set/)
  - Drying oven
  - Ashing oven
  - Consumables, e.g. crucibles
- Rod-Set-Elevation Tables (sediment elevation change)
  - Rods, receivers, SET (https://www.usgs.gov/centers/eesc/science/surface-elevation-table)
- Remote sensing (vegetation density, canopy height, etc.)
- Ocean acidification (GOA-ON-in-a-Box)
  - https://www.goa-on.org/resources/kits.php
- Biogeochemistry (Coastal-Lab-in-a-Box)
  - https://pogo-ocean.org/innovation-in-ocean-observing/activities/coastal-observing-lab-in-a-box-colab/

Staffing: Existing staff, technicians and students
Calibration: Limited calibration required except for GOA-ON in a Box and Coastal Lab in a Box, but programmes provide support.
Supplier support: Suppliers provide support throughout Africa and from regional centres.

6.2.2. Estuarine / freshwater carbon observatory (Medium cost)

- GHG-flux observations through chamber measurements
  - Flux chambers, e.g. https://www.licor.com/products/soil-flux
  - Real-time flux calculations when connected to Gas Analyzers for CO2, CH4, and/or N2O measurements.
  - Static flux chamber for sediment-atmosphere boundary gas exchange determination.
  - Dark and transparent chamber deployments = respiration & net ecosystem exchange
  - Pore-water dissolved concentrations
  - Diffusive flux at water-air interface
  - Quantifying the emission pathways & seasonality in trace gas fluxes from coastal habitats:
  - Diffusion, ebullition & plant-mediated transport = net ecosystem GHG flux
- Measurement of water and soil carbon species (DIC, DOC, TOC, PIC, POC, etc.) using CNS elemental analyzers
  - CNS analyser, e.g. https://www.elementar.com/en/products/organic-elemental-analyzers
  - TOC analyser, e.g. https://www.elementar.com/en/products/toc-analyzers

Staffing: Specialised biogeochemical laboratory technicians
Calibration: Regular calibration and serving of instruments required. Five-year maintenance plans on all instrumentation recommended.
Supplier support: Suppliers available in all regional centres in Africa, but major repairs and calibration will require shipping outside of the continent.

6.2.3. Near-shore GHG Observatory (High cost)

Fixed stations – continuous measurements

- Shallow near shore mooring deployments
- Mooring must observe the following variables:
    - Sea surface pCO_2; Temperature, salinity, pressure, 1 of (TA, DIC), pH, Dissolved Oxygen, 2 of (NO_3, PO_4, $Si(OH)_4$)
    - Additional variables that are desirable: Chl-a, turbidity, currents strength and direction, pCO_2 in the air, surface climate (wind direction and speed, rainfall, barometric pressure, etc.)
    - Frequency: At least 1 per day (ideally once per hour)
    - Ancillary requirements to service mooring and data holdings
        - Research SCUBA dive team for maintenance
        - Research vessel to access mooring
        - Online real-time database and data archiving centre

Fixed stations – discreet measurements

- Water samples collected at fixed stations in the nearshore at regular intervals over the long term
- Variables to sample:
    - Temperature, salinity, 2 of (NO3, PO4, Si(OH)4), DO, pressure, 2 of (DIC, TA, pCO2, pH)
    - Desirable: Chl, DOC, N2O, CH4, CDOM, phytoplankton and zooplankton
    - Frequency: 1/year or 1/month (ideally monthly)
    - Ancillary requirements to service mooring and data holdings
        - Research vessel to access stations
        - Davit/crane to launch instruments and nets
        - CTD (e.g. https://www.seabird.com/profiling/family?productCategoryId=54627473767)
        - 20 / 55 µm mesh phytoplankton ring net
        - 90 and 200 µm zooplankton bongo net
        - Freezer/fridge space onboard
        - Laboratories to analyse chl-a, nutrients, Carbon (DIC, DOC, etc) and plankton (phytoplankton and zooplankton)
        - Online database and data archiving centre

Staffing: Specialised skippers, sea-going technicians, scientific divers and supervisors, biogeochemical laboratory technicians, oceanographic scientists and biogeochemical scientists

Calibration: Regular calibration of seagoing instruments and laboratory instruments.

Supplier support: Suppliers available in all regional centres in Africa, but major repairs and calibration will require shipping outside of the continent.

6.3. Support required:

A long term ambition of the project is to put in place autonomous observing systems to track carbon fluxes and other GHG's in the coastal region, ultimately extending to include the coasts of east, west and north Africa incorporating important upwelling systems and western boundary currents, which support rich a fisheries industry and substantive air-sea CO_2 flux. Such observing systems need to be robust, use common standards, be well calibrated, capable of delivering data in near real time in support of both international climate policy development and domestic management of ecosystem services. This will ultimately be achieved with the assimilation of data into high resolution ocean-atmosphere coupled models with tangible implications for improved climate projections that will benefit society in accordance with adaptation and mitigation strategies through policy implementation. To interpret the observed data correctly, often other supporting variables such as temperature and salinity need to be measured. Moreover, for any African network to produce accurate data that satisfy the requirements of international standards, access to calibration facilities is a must. Furthermore, human resource-wise, this task requires skilled personnel with

minimum oceanographic knowledge and weeks to months long instrument-specific technical and laboratory technique courses depending on the variables in question.

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