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South African carbon observations: CO_2 measurements for land, atmosphere and ocean

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Carbon dioxide plays a central role in earth's atmospheric, ocean and terrestrial systems.[1,2] About 40% of the total anthropogenic emissions since 1750 have remained in the atmosphere, with the balance being removed by the ocean and vegetation sinks.[3] Increasing atmospheric CO_2 concentrations have been well documented,[3] as have widespread impacts on human and natural systems, such as warmer surface temperatures, ocean warming and decreasing pH, loss of ice mass over the cryosphere, increasing global mean sea level, and alterations in the global hydrological cycle.[3,4] The impact of increased atmospheric concentrations of CO_2 on the biosphere includes shifting species extent, seasonal activities, migration patterns and abundances, as well as changes in species interactions.

Monitoring of atmospheric CO_2 and other greenhouse gases (GHGs) has been identified as a priority by international agencies, such as the United Nations Framework Convention on Climate Change and government departments that are interested in mitigating the effects of climate change. South Africa has made a commitment to a low carbon future as part of its role in global climate policy instruments through a national low carbon development strategy.[5,6] At the Conference of the Parties in November 2015 (COP21), high level of agreement by developed and developing countries encouraged stakeholders to urgent action to address climate change. The agreement emphasises the urgent mitigation pledges with respect to GHG emissions by 2020. As South Africa implements its White Paper on Climate Change, to stimulate a shift towards a low carbon economy, it faces a monitoring and evaluation challenge. Currently, the South African GHG emission inventory is based on fossil fuel emissions, as part of the National Atmospheric Emissions Inventory System, under the *National Air Quality Act, 2004* (*Act No. 39 of 2004*). Briefly, emissions are rarely measured directly, but rather based on proxy estimates of activity, extrapolated by an emission factor for the specific activity. There is therefore a need to independently assess the effectiveness of emissions reductions within the context of natural CO_2 fluxes. Understanding the changing driving forces of climate change and evaluation of the carbon emission reduction activities requires long-term and high-precision measurements of CO_2 gas emissions and sinks as well as their evolution.

Land can act as both a source and a sink for GHGs.[7] Currently the baseline GHG emissions from land and agriculture are thought to amount to 3.03×10^{10} kg CO_2 eq per year in South Africa. The land sector is responsible for an uptake of 2.1×10^{10} kg CO_2 eq per year while agriculture is responsible for a release of 5.06×10^{10} kg CO_2 eq per year.[7] The GHG emissions for South African industry amounted to $\sim 5.45 \times 10^{11}$ kg CO_2 eq in 2010[8,9], with approximately 79% from the energy sector – an order of magnitude larger than the emissions from agriculture[7].

Under the proposed White Paper policy, South Africa's GHG peak, plateau and decline trajectory anticipates emissions to peak at 6.1×10^{11} kg CO_2 eq between 2020 and 2025, plateau at this range for about 10 years and decline to $\sim 4.3 \times 10^{11}$ kg CO_2 eq by 2050.[6] Determining these fluxes accurately will facilitate assessment of the proposed commitments to mitigation and adaptation strategies adopted by South Africa. At present there is infrastructure deployed in South Africa for the measurement of the concentrations and fluxes of CO_2, which include observations in the atmosphere, on land and in the ocean.

Carbon dioxide observations in South Africa

Terresterial observations

A number of sites for terrestrial CO_2 observations are in place (Figure 1). These include:

- A network of cavity ring-down spectroscopy analysers for measurement of CO_2, CH_4 and H_2O concentrations. The placement of these instruments was guided by the inverse modelling work of Nickless et al.[10] These instruments have been used by the City of Cape Town for estimation of the CO_2 flux from the city.[11,12] The instrumentation has been set up around the country at the following locations:
  - The Cape Point Global Atmospheric Watch station: -34.35°, 18.48°; 172 metres above sea level (masl); operational since 1991; operated by the South African Weather Service.[13-16]
  - The Elandsfontein Air Quality Monitoring Station: -26.24°, 29.41°; 1747 masl; operational since April 2016; Eskom ambient air quality monitoring station.[17,18]
  - The Medupi Ambient Air Quality Monitoring Station: -23.74°, 27.54°; 900 masl; operational since January 2016.
- A network of eddy covariance flux towers with instruments located at the following sites:
  - Skukuza: -25.02°, 31.49°; 365 masl; savanna site in conservation area; operational since 2000; operated by the Council for Scientific and Industrial Research (CSIR).[19-21]
  - Malopeni: -23.83°, 31.21°; 385 masl; savanna site in conservation area; operational since 2008; operated by the CSIR.
  - Agincourt: -24.82°, 31.21°; 534 masl; savanna in communal area; operational since 2016; operated by the CSIR.
  - Vuwani: -23.14°, 30.43°; 629 masl; savanna site in communal area; operational since 2016; operated by the University of Venda.

- Middelburg: -31.52°, 25.01°; Karoo site in heavily grazed and lightly grazed agricultural area; operational since 2015; operated by Grootfontein Agricultural College and Stellenbosch University.
- Cathedral Peak: -28.9755°, 29.2359°; 1860 masl; operational since 2012; operated by the South African Environmental Observation Network (SAEON) Grasslands–Forests–Wetlands node.
- Welgegund: -26.56°, 26.93°; 1477 masl; grassland site under commercial agriculture; operational since 2010; operated by the North-West University.[22]

Marine observations

A number of different approaches has been adopted to address the needs of understanding and resolving the trends in Southern Ocean CO_2. One of the key gaps is observational-based estimates because of the geographical extent and remoteness of the Southern Ocean.[23] This gap is being addressed in two main ways. Firstly, by increasing the coverage and quality of global data sets through international coordinated efforts such as Surface Ocean CO_2 Atlas (SOCAT)[24] and supplementing these data with linear and non-linear empirical models and proxy variables. Secondly, by expanding the ship-based approaches with autonomous platforms such as floats[25] and gliders[23,26].

The ongoing data coverage in the Southern Ocean since 1995 has a seasonal bias for summer (Figure 2). The Southern Ocean Carbon and Climate Observatory's annual partial pressure CO_2 (pCO_2) observations programme on board the MV SA *Agulhas II* currently operates in the Southern Ocean basin annually. These pCO_2 observations seasonally characterise the drivers and variability of CO_2 fluxes in the Southern Ocean south of Africa. Moreover, these observations reduce the uncertainty of the mean annual flux of CO_2 in the Southern Ocean.[27] Reducing the uncertainty to less than 10% (or 0.1 Pg C/year) of the mean net uptake of CO_2 is critical to resolving interannual variability and trends of CO_2 flux in the Southern Ocean.[25,28]

An integrated carbon observation network which combines the current ongoing initiatives of ocean, atmosphere and terrestrial observations would provide essential information to decision-makers involved in mitigation targets and policy. In South Africa, quantitative measurement and monitoring of high-quality (climate-focused) carbon concentrations in the terrestrial, ocean and atmosphere domains already exist. Integrating these flux measurements across spatial scales and between the marine and terrestrial systems is essential.

Empirical modelling methodologies provide a method to utilise high-precision measurements of CO_2 to estimate CO_2 fluxes or to improve prior estimates of CO_2 fluxes. These methods have been successfully used in terrestrial systems including the City of Cape Town[11,12], and regional and global CO_2 emissions inventories[29,30]. This method relies on high accuracy measurements of atmospheric CO_2 (or other) concentrations to constrain a priori estimates of CO_2 fluxes derived from activity and emission factor estimates.[11,30]

Similarly, within the marine domain, empirical modelling provides an interim solution to estimate CO_2 fluxes accurately enough to estimate inter-annual and seasonal changes, as deterministic ocean models do not yet accurately depict the seasonality of CO_2. Empirical modelling utilises the relationship between in-situ CO_2 measurements and remotely sensed parameters (temperature, salinity, chlorophyll, etc.). The relationship is then applied to remotely sensed data for which there are no CO_2 measurements, to improve CO_2 data coverage. This approach has shown some promising potential in the North Atlantic where data coverage is more extensive[31,32], and has also been extended to the Southern Ocean[33]. Furthermore, the approach has more recently been refined by using artificial neural networks to highlight the importance of input parameters and self-organising maps, to illustrate the usefulness of empirical models as tools to reduce uncertainty of CO_2 estimates.[34]

The currently available CO_2 observation platforms allow the opportunity for spatial integration to provide national and metro policy management with an independent assessment capability of the effectiveness of emissions mitigation measures at local and regional (southern Africa) scales. It is necessary to maintain and expand the CO_2 observation network across ocean, terrestrial and atmospheric platforms in Southern Africa, to link the observations and modelling platforms in order to establish an observation-based CO_2 inventory for South Africa and to develop temporally relevant indicators of the state of the terrestrial, atmospheric and ocean carbon systems that are relevant and accessible to policymakers and the general public.

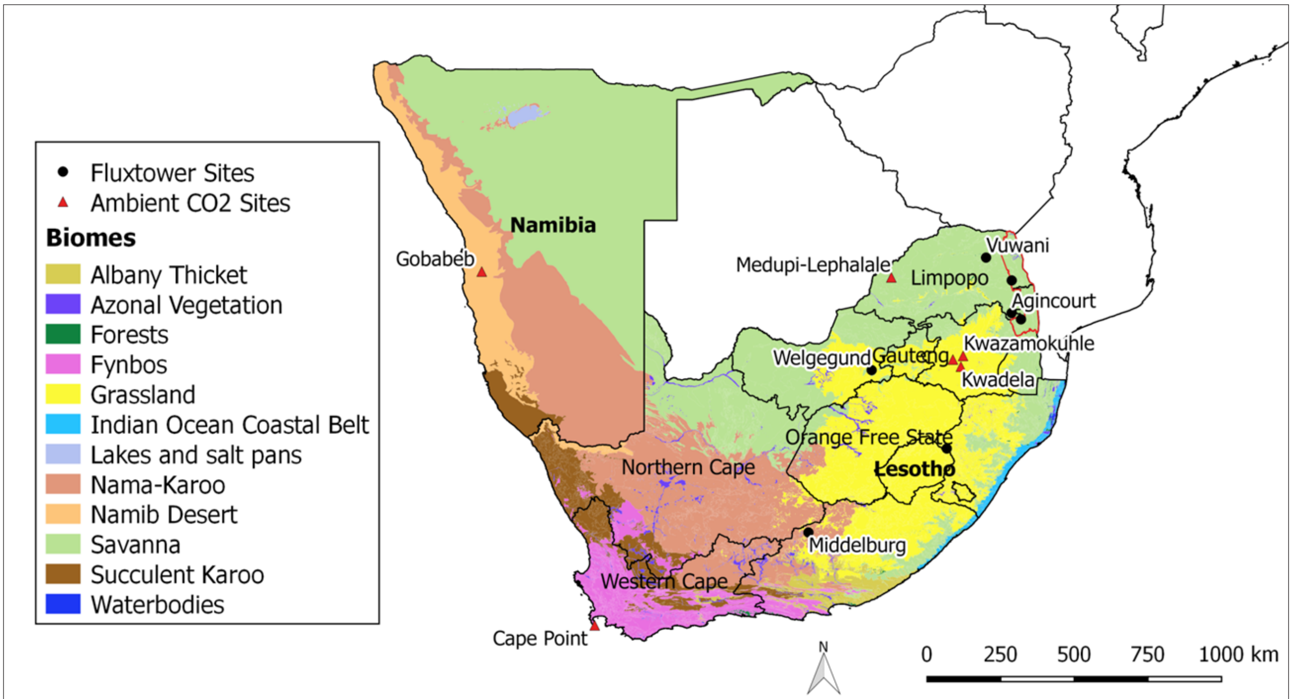

Figure 1: Sites of terrestrial CO_2 measurements in South Africa including both the flux tower locations and the CO_2 measurement sites.

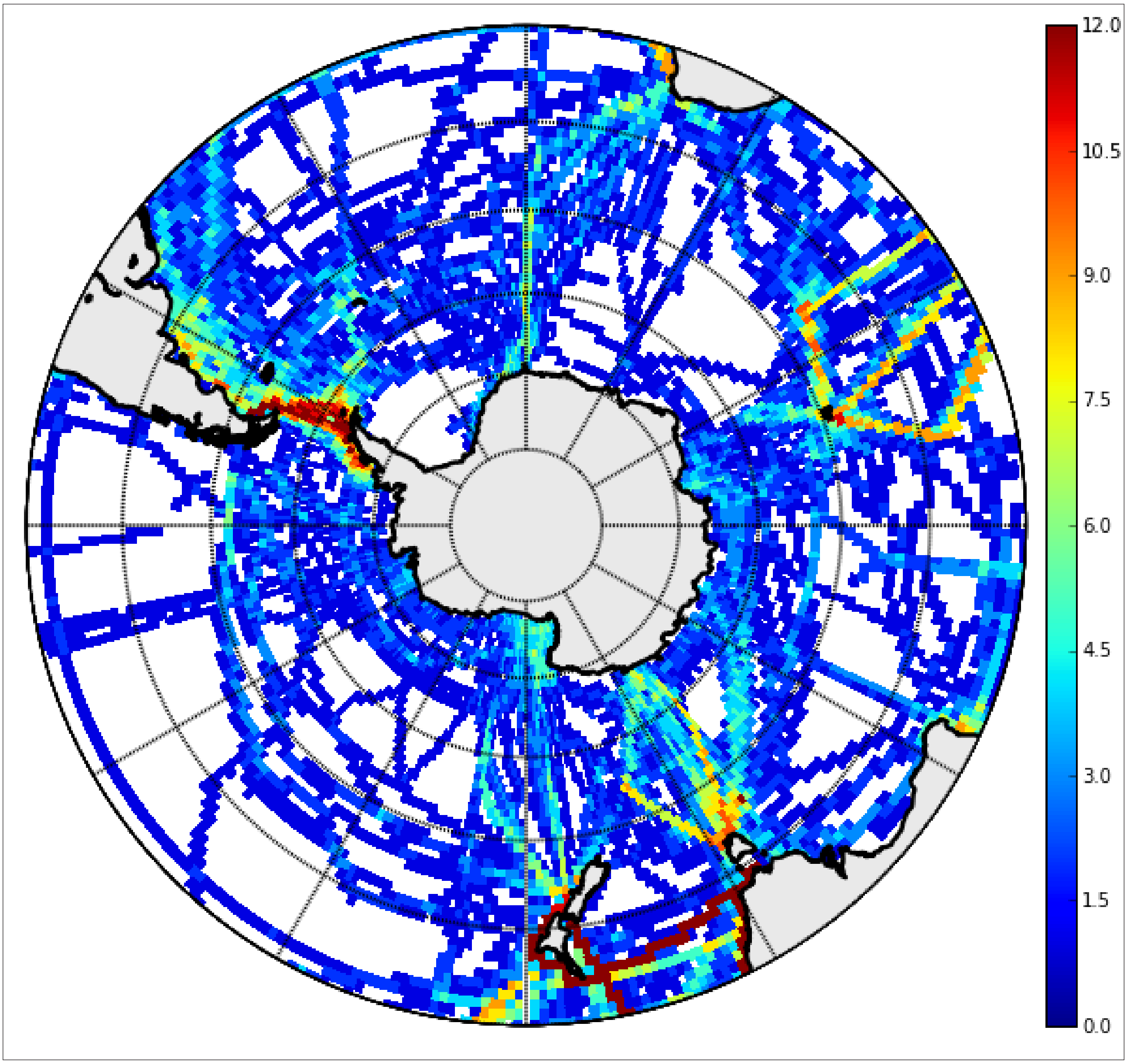

Figure 2. Gridded CO_2 observations in the Southern Ocean between 1995 and 2013 from the Surface Ocean CO_2 Atlas (SOCAT v3). The annual occupation of the seasonal cycle (in months) is shown; white space indicates no data.

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