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SOUTH AFRICAN INTEGRATED CARBON OBSERVATION NETWORK (SA-ICON): CO$_2$ MEASUREMENTS ON LAND, ATMOSPHERE AND OCEAN

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It has become essential to accurately estimate the emission and uptake of atmospheric carbon dioxide (CO$_2$) around the globe. Atmospheric CO$_2$ plays a central role in the Earth's atmospheric, ocean and terrestrial systems and it has been recognised as the greatest contributor to the anthropogenic greenhouse gas effect. Increasing atmospheric CO$_2$ concentrations have widespread impact on human and natural systems, such that the last three decades have had successively warmer surface temperatures than any preceding decade in the industrial age. Furthermore increasing energy in the climate system has resulted in increased surface ocean warming and decreasing pH, loss of ice mass over the cryosphere (Greenland and Antarctica), increasing global mean sea level, alterations in the global hydrological cycle (changing precipitation, evapotranspiration and melting snow) through increased moisture in the atmosphere. The impact on the biosphere includes shifting species geographic extent, seasonal activities, migration patterns, and abundances as well as species interactions. Roughly 40% of the total anthropogenic emissions since 1750 have remained in the atmosphere, with the balance being removed by the ocean and vegetation sinks. It has become essential for individual countries to develop strategies to reduce emissions, and accurately monitor their national inventories of the carbon cycle. 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. Long term observations are required to understand current and future behaviour of the carbon cycle, as well as the assessing the effectiveness of carbon emission reduction activities on regional atmospheric CO$_2$ levels. This project aims at setting up an integrated national network of CO$_2$ observation facilities to independently measure both the atmospheric concentrations of CO$_2$ over South Africa and the Southern Oceans and the fluxes of CO$_2$ between the atmosphere and the terrestrial and marine ecosystems. A description of the monitoring network and preliminary results will be presented.

Keywords: CO$_2$, integrated CO$_2$ measurements, southern Africa, Southern Ocean

1. Introduction

It has become essential to accurately estimate the emission and uptake of atmospheric carbon dioxide (CO$_2$) around the globe. Atmospheric CO$_2$ plays a central role in the Earth's atmospheric, ocean, and terrestrial systems and it has been recognised as the greatest contributor to the anthropogenic greenhouse gas effect (Houghton 2007; Denman 2008). Roughly 40% of the total anthropogenic emissions since 1750 have remained in the atmosphere, with the balance being removed by the ocean and vegetation sinks (IPCC 2014). Increasing atmospheric CO$_2$ concentrations, particularly due to human activities, have widespread impact on human and natural systems, such that the last three decades have had successively warmer surface temperatures than any preceding decade in the industrial age. Furthermore increasing energy in the climate system has resulted in increased surface ocean warming and decreasing pH, loss of ice mass over the cryosphere (Greenland and Antarctica), increasing global mean sea level, alterations in the global hydrological cycle (changing precipitation, evapotranspiration and melting snow) through increased moisture in the atmosphere.

The impact of increased atmospheric concentrations of CO_2 on the biosphere includes; shifting species geographic extent, seasonal activities, migration patterns, and abundances as well as changes in species interactions. These impacts have been documented by the (IPCC 2014). Due to the globally significant impact of anthropogenic emissions of CO_2 it has become essential for individual countries to develop strategies to reduce emissions, and accurately monitor their national inventories of the carbon cycle.

Monitoring of atmospheric CO_2 and other greenhouse gases has been identified as a priority by international agencies, such as the United Nations Framework Convention on Climate Change (UNFCCC) and governments departments that are interested in mitigating the effects of climate change. South Africa has made a commitment to a low carbon future both as part of its increasingly influential role in global climate policy instruments (UNFCCC) as well as part of a national low carbon development strategy that makes this global constraint an opportunity for economic development (National Planning Commission 2010; Department of Environmental Affairs 2012).

At the recent session of the Conference of the Parties (COP21) in December 2015, high level of agreement by developed and developing countries encouraged stakeholders to urgent action to address climate change. The agreement emphasises the urgent mitigating pledges with respect to greenhouse gas emissions by 2020, to contain the increase in global average temperature to $< 2^{o}C$ relative to preindustrial levels and pursue efforts to limit temperature increase to $< 1.5^{o}C$ above pre-industrial levels. As South Africa implements it's White Paper on Climate Change-the Climate Change Response Plan-to stimulate a shift towards a low carbon economy, it faces a monitoring and evaluation challenge. There is a need for an independent basis by which to assess both the effectiveness of emissions reductions as well as whether natural fluxes are neutral or limiting the effectiveness of emissions reductions.

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. Long term observations are required to understand current and future behaviour of the carbon cycle, as well as the assessing the effectiveness of carbon emission reduction activities on regional atmospheric CO_2 levels. In response to anticipated climate change, and in order to reverse increasing atmospheric CO_2 concentrations, high quality long term observations are required as a foundation to quantify the effectiveness of projected global emissions reductions.

The greenhouse gas emissions for South Africa (excluding Forestry and Land use change) amounted to roughly 0.545 Gt CO_2 in 2010 (Thambiran & Diab 2011; DEA 2014) (with approximately 79% from the energy sector (power generation). The total global CO_2 fossil fuel emissions for 2010 were ~ 35.8 Gt CO_2 (CDIAC 2016). The annual growth of CO_2 in the atmosphere is determined by the global fossil fuel emissions (and land use change) and the uptake by ocean and terrestrial biospheres. Under the proposed white paper policy, South Africa's greenhouse gas peak, plateau and decline trajectory anticipates emissions to peak at 0.61 Gt CO_2 upper limit between 2020 - 2025, plateau at this range for roughly 10 years and decline to ~ 0.43 Gt CO_2 by 2050 (Department of Environmental Affairs 2012). Determining these fluxes accurately will facilitate the proposed commitments to mitigation and adaptation strategies adopted by South Africa.

The technical capabilities to improve the observation coverage for CO_2 in the terrestrial, atmosphere and ocean already exist within SA. These include the long term atmospheric observations associated with the Global Atmospheric Watch program at Cape Point administered by the South African Weather Services, the terrestrial flux tower network and the Southern Ocean CO_2 observations by the Council for Scientific and Industrial Research Natural Resources and Environment Unit (CSIR-NRE). An integrated carbon observation system/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.

SA-ICON is a project that aims 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 and contribute to the global effort to reduce the CO_2 emissions. SA-ICON will be an operational junction between researchers and stakeholders in carbon data and climate change. The aim is to provide data in support of climate change research, but also to provide the general public with easy accessible visualizations of CO_2 fluxes at local, national and regional scale. The objectives can be summarised as follows:

1. Establish an operational CO_2 flux observation network across ocean, terrestrial and atmospheric platforms in Southern Africa.
2. Acquire and develop the capacity to collect carbon cycle related time-series of sufficient quality, duration and spatial and temporal resolution.
3. Maintain and expand current infrastructure used for CO_2 observations through high level quality assurance of existing observational capabilities.
4. Enable improved carbon accounting approaches to link observations and modelling (such as land and sea-surface models, and emissions reports at the national and metropolitan scale) to establish in a CO_2 inventory for Southern Africa.
5. Develop empirical approaches to determine local and regional CO_2 flux estimates
6. Establish an annual mean CO_2 fluxes using observations and incorporating empirical approaches (such as inverse modelling).
7. Resolve the intra-annual variability of CO_2 fluxes in the region and reduce the uncertainty associated with long term observations.
8. Resolve the interannual variability of CO_2 fluxes in the region and reduce the uncertainty associated with long term observations.
9. Develop monthly and annual indicators of the state of the terrestrial, atmospheric and ocean carbon systems.

2. Approach

Within the terrestrial and ocean domains at the CSIR the basic research and technical capacity enables the integration of these observations across Southern Africa and the surrounding oceans (Indian and Atlantic, Southern Ocean). The goal of integrated carbon observatory network is to provide systematic information on the spatial and temporal distribution of terrestrial carbon sources and sinks, and its role of the in the global carbon cycle. The ongoing terrestrial, atmospheric and ocean observations will be collated to establish current inventory of CO_2 observations and the data quality in the respective domains.

The following discussion highlights the activities planned in the terrestrial and ocean domains in the following year. A phased approach to establish SA-ICON will be followed over 5 years where:

- In the first two years the data quality from ocean and terrestrial observations will be assembled and established.

- The second phase, during years 2 – 3 will focus on establishing empirical approaches relating in situ CO_2 concentrations and fluxes to more readily available remotely sensed observations using inverse models.
- The latter will then be used during the 3rd phase (year 4 to 5) to produce operational outputs such as mean annual CO_2 flux estimates for the Southern African region.

2.1 Terresterial observations

A number of sites for terrestrial CO_2 observations have been set up (Figure 1). These include a network of eddy co-variance flux measurements to measure the ecosystem exchange and a network of high precision CO_2 and methane instruments to measure the absolute CO_2 concentration in the atmosphere

The CSIR has invested heavily in developing the skills for high precision measurements of CO_2, CH_4 and H_2O using Cavity Ring-Down Spectroscopy (CRDS) analysers (Picarro) and CO_2 and H_2O fluxes using eddy covariance analyser (LI-7200).
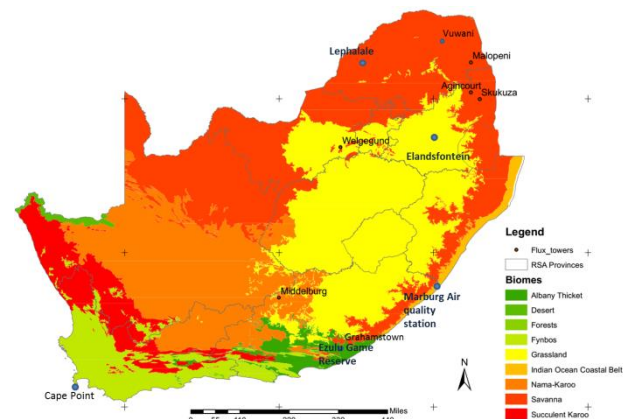

Figure 1 Sites of terrestrial CO_2 measurements in South Africa

2.1.1 Terresterial Flux observations

The CSIR has been operating long term CO_2 flux measurements at Skukuza (since 2000) and Malopeni, Palaborwa (since 2008) (Scholes et al. 2001; Archibald et al. 2009; Stevens et al. 2016; Kutsch et al. 2008), which produce essential validation data and represent a globally-unique long-term observational dataset for semi-arid savanna. Recently a companion flux tower to the Skukuza tower has been installed at outside of the village of Agincourt, approximately 25km NW of Skukuza to assess the ecosystem flux of CO_2 in an anthropogenically influenced savanna site.

Two additional eddy covariance towers were installed in Middelburg, Eastern Cape for monitoring CO_2 fluxes in the Karoo.

2.2 High precision CO_2 observations

The CSIR have operated five Picarro Cavity Ring-Down Spectroscopy (CRDS) analysers for measurement of CO_2, CH_4 and H_2O concentrations. The instruments will form part of a regional integrated carbon observatory network. The purpose of installing these monitoring instruments is to increase the number of sampling stations in the southern land regions which will in turn improve global estimates of CO_2 fluxes and improve monitoring of CO_2 emissions in South Africa.

The CSIR will be responsible of setting up the high precision CO_2 measuring equipment guided by the optimum network design from the Alecia Nickless study (A Nickless et al. 2015). This will include the continued operation of the instruments that have already been deployed at:

- Cape Point (in operation since 2012)
- Kwadela and Kwazamokuhle (Operated by NWU) examining the CO_2/ CO emissions resulting from domestic combustion low income settlement in the Mpumalanga Highveld
- Elandsfontein
- Lephalale

Output from the high precision instrumentation will be used to obtain regional estimates of CO_2 and potentially CH_4 fluxes using inverse modelling as done for the City of Cape Town (Alecia Nickless et al. 2015).

2.3 Marine observations

The mean annual global anthropogenic carbon budget and ocean uptake (1.8 – 2.2 PgC y^{-1}) are now well established, with the Southern Ocean accounting for about 40 - 50% of the total ocean uptake (Takahashi 2009; Le Quéré et al. 2010; Le Quéré et al. 2013). The CO_2 uptake from continental margins constitutes up to ~ 30% of global ocean uptake (Chen & Borges 2009). The ocean mediation of atmospheric CO_2 has two components: the uptake of anthropogenic CO_2 and variability in the exchange of natural CO_2 (McNeil & Matear 2013). While the magnitude of the steady state ocean CO_2 uptake, linked to the increasing CO_2 emissions, is now robustly constrained (Le Quéré et al. 2013) the major challenge to the ocean carbon community is to understand the drivers, magnitudes and trends of the non-steady state driven changes in the ocean carbon fluxes (Waldron et al. 2009; McNeil & Matear 2013) .

A number of different approaches are being adopted to address the needs of understanding and

resolving the trends in Southern Ocean CO_2. One of the key gaps is the observational one (Waldron et al. 2009; Le Quere et al. 2014). This is being addressed in two main ways: firstly the investigation of combining a strengthening of coverage and quality of global data sets through international coordinated efforts such as SOCAT (Pfeil et al. 2013) and supplementing this with linear and non-linear empirical models and proxy variables. A second approach is to expand the presently largely ship based approaches with autonomous platforms such as floats (Majkut et al. 2014) and gliders (Waldron et al. 2009; Swart et al. 2012)

2.3.1 Southern Ocean observations:

The ongoing data coverage in the Southern Ocean since 1995 has a seasonal bias for summer (Fig. 2), mainly due to favourable weather conditions for ship operations. The Southern Ocean Carbon and Climate Observatory's (SOCCO) annual partial pressure CO_2 (pCO_2) observations programme on board the MV SA Agulhas II currently occupy three seasons (spring, summer, and autumn) annually. These pCO_2 observations allow basin scale, and more recently (with the Southern Ocean Seasonal Cycle Experiment (SOSCEx) III initiative) full seasonal characterization of the drivers and variability of CO_2 fluxes in the Southern Ocean south of Africa. The pCO_2 observations are ongoing since 2008, in the Atlantic Basin in September, along the Goodhope to Antarctica in December to March, and in the Indian Basin in April.
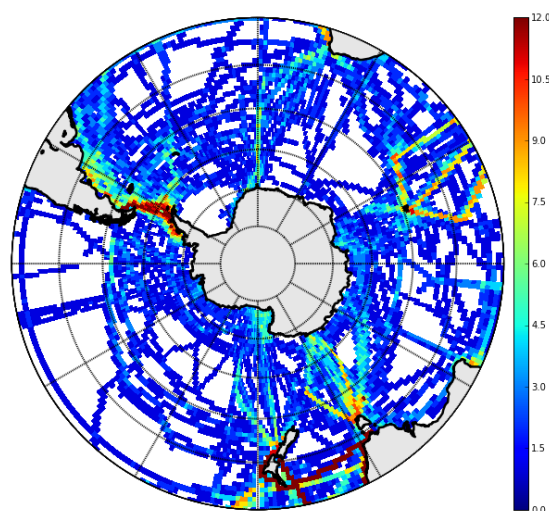

Figure 2. Gridded CO_2 observations in the Southern Ocean between 1995 and 2013 from the Surface Ocean CO_2 Atlas (SOCAT v3). It shows the annual occupation of the seasonal cycle (in number of months), with the white space indicates no data.

Recently, autonomous surface CO_2 wavegliders were deployed to resolve the Southern Ocean seasonal cycle in order to reduce the uncertainty of the mean annual flux of CO_2 in the Southern Ocean (Thomalla et al. 2015). Reducing the uncertainty to less than 10% (or 0.1 Pg C yr^{-1}) of the mean net uptake of CO_2 is critical to resolving interannual variability and trends of FCO_2 in the Southern Ocean (Majkut et al. 2014; Waldron et al. 2009; Landschuetzer et al. 2013).

Empirical modelling (EM) provide 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. This is especially true for the data sparse Southern Ocean. The conceptual methodology for this approach uses an EM to determine 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 where 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 (Levevre et al. 2004; Chierici et al. 2009). Furthermore, they have more recently been refined by using artificial neural networks to highlight the importance of input parameters (e.g. (Jamet et al. 2007)) and Self-Organizing Maps, to illustrate the usefulness of EMs as tools to achieve low uncertainty of CO_2 estimates. Currently, the lowest error is estimated at 10 µatm (Landschuetzer et al. 2013), but highlight importance of improving the data coverage in data sparse regions such as the Southern Ocean. It also highlights the dominance of EM's as a tool for the problem of interannual and seasonal CO_2 fluxes.

Empirical models will be used to determine CO_2 flux estimates for the oceanic region around Southern Africa, by determining relationships between higher resolution surface ocean parameters (temperature, salinity, mixed layer depth) and *in situ* CO_2 observations.

3. Conclusion

The SA-ICON Project aims to develop processes and systems that consolidate the measurements of the concentrations and fluxes of CO_2 between the marine and terrestrial surfaces and the atmosphere. In doing this we aim to develop usable products that track the changes in the emissions and uptake of CO_2 at the interannual and seasonal scales.

4. Acknowledgments

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