Southern Ocean Seasonal Cycle Experiment 2012: Seasonal scale climate and carbon cycle links

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In early May 2012, South Africa will take delivery of a new polar research ship, the SA *Agulhas II*, representing a significant investment of R1.6 billion in polar infrastructure to further strengthen South Africa's presence in the polar region, particularly in support of its stewardship of the Southern Ocean and Antarctic Treaty obligations. This investment follows closely on recent DST–CSIR infrastructure investments in the Centre for High Performance Computing, used to run global ocean–climate models, an ocean robotics observational capability and five other new research facilities. Together, these investments offer opportunities to enhance South Africa's advanced numerical and technological capacity as well as its impact on Southern Hemisphere polar climate and ecosystem science by using its geographical advantage. We are planning the first scientific programme that will capitalise on these major infrastructure investments: the Southern Ocean Seasonal Cycle Experiment (SOSCEx).

The Southern Ocean is arguably the main source of medium-term uncertainty in terms of the effectiveness of global CO_2 mitigation plans. The reason for this is that the Southern Ocean plays both an important role in the uptake of anthropogenic CO_2 (50% of all ocean uptake) as well as in the very large (90 Gt/Cy) natural CO_2 exchange between the oceans and the atmosphere. The Southern Ocean is the only region where deep-ocean CO_2 reservoirs (38 000 Gt C) exchange directly with the smaller atmospheric reservoir (700 Gt C). Moreover, although 85% of all ocean productivity is supported by nutrients derived from the Southern Ocean, little is known about the sensitivity of these carbon and nutrient fluxes to climate change driven adjustments or – most importantly – at what scales these links couple. One of the important gaps in the reliable prediction of the response of the Southern Ocean carbon cycle to climate change is its sensitivity to seasonal, subseasonal forcings (in time) and mesoscales (in space). The Southern Ocean Carbon and Climate Observatory (SOCCO), a CSIR-led consortium, is planning SOSCEx, which will be a new type of large-scale experiment. SOSCEx reflects a shift from the historical focus on ship-based descriptive Southern Ocean oceanography and living resource conservation, to system-scale dynamics studies spanning much greater time and space scales.

Our limited grasp on these climate and climate-feedback sensitivities are linked to key knowledge gaps on the scales that link climate to carbon. Moreover, existing global models show only weak agreement in terms of the seasonal cycle of the upper-ocean in both physical and biogeochemical indicators such as primary productivity (Lenton A, Tilbrook B 2011, personal communication, Aug 01). The seasonal cycle is one of the strongest modes of variability in the primary productivity and the carbon cycle of the Southern Ocean. Additionally it reflects the coupling between climate forcing and important ecosystem responses, such as productivity.[1] The ultimate sensitivity of the ecosystem over seasonal time scales is governed by their adapted phenological characteristics. However, climate forecast models are not able to reflect this seasonal timing reliably, which casts some doubt about our understanding of the scales at which climate and biogeochemistry are linked in the Southern Ocean. In addition, there appear to be important regional and basin differences in the way that carbon and ocean productivity respond to this otherwise regular seasonal forcing. Uncertainties in the understanding of the sensitivities of the biogeochemical cycles to changes in the climate forcing factors, hampers our ability to understand the long-term trends. Thus there is a need for a seasonal cycle experiment using autonomous platforms that focus on these scales (Figure 1), most importantly on the link between the physical forcing mechanisms and biogeochemical responses over the whole annual cycle.

At a recent workshop[2] convened to discuss the role of the seasonal cycle in coupling climate and carbon cycling in the Southern Ocean, two approaches were identified, (1) developing seasonal scale views to understand regional contrasts in the timing of the onset and evolution of phytoplankton blooms and (2) developing targeted ocean physics–carbon–ecosystem process studies in regional 'hotspots'.[2,3] For SOSCEx, it is hypothesised that climate change signals will be reflected in changes to the magnitude, timing and persistence of the seasonal cycle in mixed-layer physics and biogeochemistry and, in particular, the carbon cycle.[2] We also propose that a high-

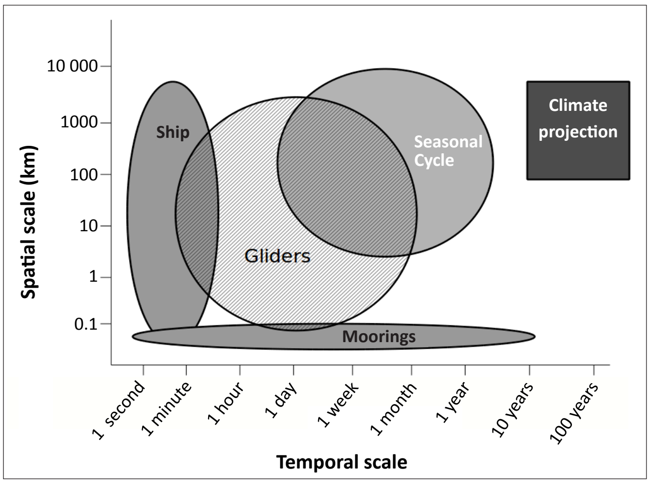

FIGURE 1: A space–time plot showing relative scale magnitudes of a number of platforms (ships, instrumented moorings and gliders), the seasonal cycle and climate projections. This graphical representation emphasises that, even with both ships and moorings observational platforms, it is not possible to address questions on the seasonal cycle sensitivity of climate projections without using autonomous platforms. Ocean gliders are uniquely poised to bridge the spatial and temporal gap between ships and moorings – a bridge which critically covers the seasonal 'window' in the Southern Ocean Seasonal Cycle Experiment.

resolution approach to advancing our understanding of the coupling of carbon and climate will reduce the uncertainty in projections of long-term trends in the ocean's natural carbon fluxes and the anthropogenic carbon sink.

Recent studies highlight substantial variability in the response of Southern Ocean biological productivity to physical forcing on interannual, seasonal and subseasonal timescales.[1,4,5] A key factor in the responses appears to be the variable control of phytoplankton growth by iron or light limitation.[4] The spatially and temporally variable rates of buoyancy (heating) and momentum (wind mixing) forcing define the seasonal evolution of the light–iron status of the euphotic zone – the layer where photosynthesis occurs.[5] These studies emphasise the importance of understanding the coupling of physics to biogeochemistry at subseasonal scales and submesoscales.[6,7] The stark seasonal transition in the seasonal cycle phase between the Subtropical and Subantarctic zones[1] provides an ideal test to understand this coupling. These frontal regions are believed to play pivotal roles in the variability of the mixed layer and vertical velocities caused by submesoscale processes that evolve at the fronts as a result of current meandering and eddy–eddy interaction.[8] Researchers have now recognised that submesoscale structures account for approximately 50% of the total resolved variance[7,8] observed from high-resolution satellite imagery, whilst vertical velocity variance shows a tenfold increase when numerical simulation resolutions increase from 6 km to 1 km.[9] This high variance underscores the potential magnitude of the vertical nutrient supply and gas transport at small scales that impact on the overall primary productivity.

The experiment

SOSCEx has four main themes which address the same intraseasonal and submesoscale questions which link the carbon cycle to climate variability: mixed-layer stratification dynamics; CO_2 and O_2 gas exchange with the atmosphere; carbon export from the mixed layer; and the bio-optics linking water column inherent optical properties to outgoing-satellite visible irradiance. In SOSCEx, concurrent *in-situ* observational and modelling approaches are used to investigate the sampling scales necessary for *in-situ* observations and testing hypotheses at larger temporal and spatial scales. The modelling experiments will initially be used in two ways. The first is an 'upstream mode' in which the model is a surrogate database that enables us – a priori – to try to determine optimal strategies for positioning gliders (Figure 2) by deploying virtual gliders in the model and investigating the effects of different sampling strategies on their recovery in order to anticipate the scales of variability we can expect. By contrast, the second way, a 'downstream mode', will use the model after the experiment in order to test new model parameterisations and to compare modelled and observed scales of variability. The research plan is coordinated to span approaches that encompass *in-situ* and remotely sensed observations, modelling and laboratory experiments.

The experiment is planned to take place around the three annual logistical trips of the ship, starting with the spring voyage to Gough Island, the mid-summer voyage to the South African National Antarctic Expedition (SANAE) base and the autumn voyage to Marion Island with little (5–10 days) additional time required above the existing schedule. *In-situ* sampling will begin in September 2012 during the austral spring relief voyage from Cape Town to Gough Island (located at 40.2°S, 10°E). The four iRobot® Seaglider™ units (Figure 2) will be deployed from the ship (1) south of the Subtropical Front, (2) in the Subantarctic Zone, (3) at the Subantarctic Front and (4) in the northern Polar Frontal Zone. The seagliders will be programmed to profile the water column from the surface to a depth of 1000 m and at a nominal horizontal resolution of every 4 km (4 dives/day). Carbon–explorer floats will be deployed at the same locations as each glider and two Liquid Robotics wave–glider units will be deployed in the Subantarctic Zone and Polar Frontal Zone to sample CO_2 and oxygen to derive their fluxes. Each of the units will then be intercepted during the summer SANAE poleward or equatorward legs and finally retrieved in the autumn on the Marion Island trip. Full-depth water column profiles, including clean casts for iron chemistry, will be undertaken at each release and interception location. This sampling will provide us with the biogeochemical and physics boundary conditions of the system, such as CO_2 levels, nutrients, iron concentrations, phytoplankton species composition and bio-optics. It will also allow for calibration and quality checks of the data received from the temperature, salinity, oxygen, backscatter, fluorescence and photosynthetically active radiation sensors housed on the gliders. Concurrent on-board bio-assay incubation experiments will examine the limiting factor of phytoplankton growth to be determined (light or iron) and contribute to improving model parameterisation in the Southern Ocean. The water column process stations will be

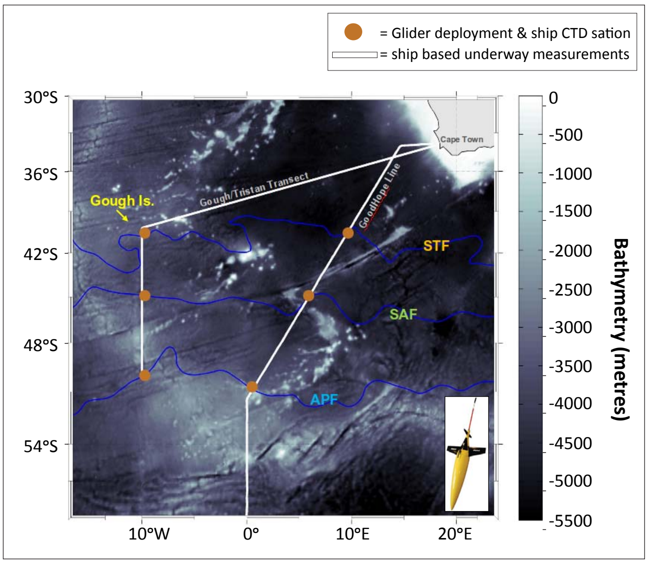

FIGURE 2: Gliders will be deployed south of Gough Island (in September 2012) and then allowed to proceed downstream with the major Southern Ocean fronts (blue lines), before being retrieved at the GoodHope line (between December 2012 and February 2013) or allowed to continue to Marion Island if battery energy can be sustained. The fronts are depicted as the mean position, between 2007 and 2008, derived from satellite altimetry data. The bathymetry is underlaid (greyscale shading in metres below sea level).

supplemented by six profiles to 1000 m along the meridional axis of the sampling. Continuous remotely sensed data will be collected and used as an independent, large-scale data set before, during and after the period of the experiment. These data include, for example, sea surface height and temperature data to inform on the dynamics of ocean circulation, while ocean colour data will be used as an indicator of primary production and biomass accumulation in the surface waters.

SOSCEx provides a new and unprecedented opportunity to gain a better understanding of the links between climate drivers and ecosystem productivity and climate feedbacks in the Southern Ocean. This combined high-resolution approach to both observations and modelling experiments will permit us, for the first time, to address some key questions relating to the physical nature of the Southern Ocean and its carbon cycle.

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