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The seasonal cycle of mixed layer dynamics and phytoplankton biomass in the Sub-Antarctic Zone: A high-resolution glider experiment

S. Swart [a,b,*], S.J. Thomalla [a], P.M.S. Monteiro [a]

[a] Southern Ocean Carbon and Climate Observatory, CSIR, P.O. Box 320, Stellenbosch 7599, South Africa
[b] Department of Oceanography, Marine Research Institute, University of Cape Town, Rondebosch 7701, South Africa

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ABSTRACT

In the Southern Ocean there is increasing evidence that seasonal to subseasonal temporal scales, meso- and submesoscales play an important role in understanding the sensitivity of ocean primary productivity to climate change. In this study, high-resolution glider data (3 hourly, 2 km horizontal resolution), from ~6 months of sampling (spring through summer) in the Sub-Antarctic Zone, is used to assess 1) the different forcing mechanisms driving variability in upper ocean physics and 2) how these may characterize the seasonal cycle of phytoplankton production. Results highlight the important role meso- to submesoscale features have in driving vertical stratification and early phytoplankton bloom initiations in spring by increasing light exposure. In summer, the combined role of solar heat flux, mesoscale features and subseasonal storms on the extent of the mixed layer is proposed to regulate both light and iron to the upper ocean at appropriate time scales for phytoplankton growth, thereby sustaining the bloom for an extended period through to late summer. This study highlights the need for climate models to resolve both meso- to submesoscale and subseasonal processes in order to accurately reflect the phenology of the phytoplankton community and understand the sensitivity of ocean primary productivity to climate change.

1. Introduction

Despite its importance for both ecosystem production and carbon fluxes, little is known about the sensitivity of the Southern Ocean primary production to the complex suite of climate change drivers and the scales at which these mechanisms connect. There is increasing evidence in the Southern Ocean that seasonal to subseasonal temporal scales, meso- and submesoscales may play an important role in understanding the sensitivity of ocean primary productivity to climate change (Boyd, 2002; Fauchereau et al., 2011; Lévy et al., 2012; Thomalla et al., 2011). In the Southern Ocean, the seasonal cycle is known as one of the strongest modes of variability and the mode that couples the physical mechanisms of climate forcing to ecosystem response in production, diversity and carbon export (Monteiro et al., 2011).

Notwithstanding the relevance of the seasonal cycle in accurately predicting long-term trends in the ocean carbon cycle (Lenton et al., 2013), climate forecast models are currently unable to accurately reflect the seasonal timing of the phytoplankton community reliably (e.g., Beaulieu et al., 2013). Mismatches in the phenology of the modeled versus observed primary production data highlight our lack of understanding of the physical forces of the biological system and the scales at which climate and biogeochemistry are linked, thus hampering our ability to understand long-term trends. In addition, there appear to be important regional and basin scale differences in the way that ocean productivity responds to the otherwise regular seasonal forcing (Thomalla et al., 2011). These knowledge gaps in this globally important and vast region provided the stimulus for research focused on characterizing and understanding the drivers of variability of the seasonal cycle of chlorophyll (as a proxy for phytoplankton biomass) in the Southern Ocean (Fauchereau et al., 2011; Joubert et al., 2014; Monteiro et al., 2011; Thomalla et al., 2011).

The seasonal evolution of phytoplankton biomass in the Southern Ocean has been typically attributed to the seasonal cycle of solar radiation, which strongly impacts vertical stability through net heat flux, influencing vertical light and nutrient supply (Arrigo et al., 2008; Boyd, 2002; Boyd et al., 1999; Dandonneau et al., 2004; Sverdrup, 1953). A recent study by Thomalla et al. (2011) proposed a more intricate pattern of spatial and seasonal distribution of chlorophyll that reflected the complex subseasonal nature of the interaction between light and nutrients (iron). Their results show regional differences in the seasonal expressions of high and low seasonal cycle reproducibility that imply distinct regional differences in the physical supply mechanisms of light and iron to the surface waters. Their paper characterized the Sub-Antarctic Zone (SAZ) with high inter-annual and intra-seasonal variability in surface chlorophyll, such that seasonal cycle reproducibility was consequently weak. Regions of high seasonally integrated chlorophyll but low seasonal cycle reproducibility within the SAZ were

* Corresponding author.
E-mail address: sebastiaan.swart@csir.co.za (S. Swart).

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hypothesized to be a direct consequence of high intra-seasonal physical forcing of the mixed layer (nutrient and light supply) at appropriate time scales (Pasquero et al., 2005). These results led to a further study by Fauchereau et al. (2011) investigating the response of surface chlorophyll concentrations to subseasonal variability in mixed layer depth (MLD). Their results showed that transient episodes of increased chlorophyll in summer were related to both a shoaling of the mixed layer when light conditions were suboptimal and a deepening of the mixed layer when nutrients (in particular iron) were limited. They concluded that the strength of iron limitation, relative to light was instrumental in dictating the phytoplankton's response to transient mixing events.

Seasonal dynamics are not only about seasonal forcing (e.g., solar heating, wind stress) but also the interaction of atmospheric forcing with ocean surface boundary layer features, such as fronts and eddies. When observed from high-resolution satellite imagery, researchers have shown that not resolving submesoscale features (1–10 km in size) can result in errors of up to 50% in primary production estimates (Glover et al., 2008; Lévy et al., 2001), while vertical velocity variance, crucial to nutrient supply and carbon export, shows a tenfold increase when numerical simulation resolutions increase from 6 km to 1 km (Klein et al., 2008).

These ideas, drawn from remote-sensed data and models, required testing in the form of a seasonal cycle experiment that used autonomous platforms, which are able to focus on the relevant time (subseasonal to seasonal) and space scales (meso- to submesoscale) important in linking the physical forcing mechanisms to the biogeochemical responses over the annual cycle. The Southern Ocean Seasonal Cycle Experiment (SOSCEx; Swart et al., 2012a; Fig. 1) was set up to reflect a shift from the historical focus on ship-based Southern Ocean oceanography, to system-scale dynamics spanning a much greater range in time and space. SOSCEx provided a new and unprecedented opportunity to gain a better understanding of the links between climate drivers, ecosystem productivity and climate feedbacks in the Southern Ocean.

The aim of this study is to use the high-resolution glider data from ~6 months of sampling to characterize the different forcing mechanisms driving MLD variability and stratification and ultimately to understand how the biogeochemical response to these physical adjustments characterizes the seasonal cycle of the SAZ. We utilize this unique data set to shed light on two particular ideas that relate to upper ocean physical dynamics and its impact on phytoplankton production during the spring and summer periods of the seasonal cycle. The first is to explore the role of meso- to submesoscale ocean features in buoyancy forcing and early rapid re-stratification of the upper ocean and shoaling of the MLD during the spring period. This positively affects primary production by alleviating light limitation in the SAZ. The second relates to how elevated concentrations of phytoplankton biomass can be sustained throughout the summer period in the SAZ. We postulate that this is as a direct consequence of high intra-seasonal variability of the MLD, providing an iron supply.

2. Data and methods

2.1. Experiment set-up and glider deployments

SOSCEx was planned around five cruises to the SAZ between the austral winter of 2012 and the late summer of 2013. Two autonomous Seagliders (SG574 and SG573) were deployed south of Gough Island in the South-East Atlantic Ocean at 42.4°S, 9.9°W and 43.0°S, 11°W, respectively (Fig. 1). Their deployment occurred in the central SAZ region of the Southern Ocean. The gliders were deployed on 20 September 2012 and 25 September 2012, respectively and both were retrieved on 15 February 2013 resulting in continuous sampling for 148 and 143 days (or 5.5 months) per glider. In addition, three gliders were deployed further to the east on the GoodHope line (Gladyshev et al., 2008; Swart et al., 2008) between December 2012 and March 2013. Due to their shorter time series length and different sampling region this data

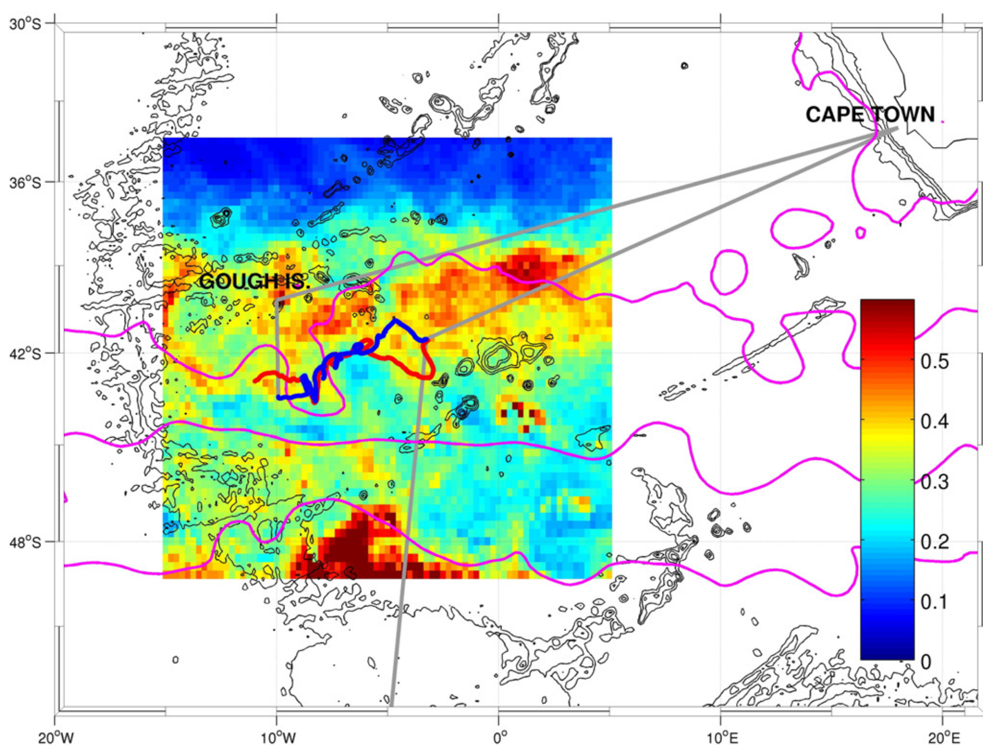

Fig. 1. Mean satellite chlorophyll-a concentration (in mg m^{-3}) for the temporal period of SOSCEx (25 September 2012–15 February 2013) showing the trajectories of the two gliders (SG573 (red) and SG574 (blue)) as well as the ship-based surveys (gray lines). The mean ACC front locations for the period of SOSCEx, as defined using satellite altimetry, are plotted (magenta lines): from north to south, STF, SAF, APF. The bathymetry for the region is overlaid using black contours (500 m, 1000 m, 2000 m and 3000 m isobaths).