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Spatial and temporal scales of chlorophyll variability using high-resolution glider data

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ABSTRACT

In the Southern Ocean, increasing evidence from recent studies is highlighting the need for high-resolution sampling at fine spatial (meso- to sub-mesoscale) and temporal scales (intra-seasonal) in order to understand longer-term variability of phytoplankton and the controlling physical and biogeochemical processes. Here, high-resolution glider data (3 hourly, 2 km horizontal resolution) and satellite ocean colour data (2–4 km) from the Sub-Antarctic zone (SAZ) were used to 1) quantify the dominant scales of variability of the glider time series, 2) determine the minimum sampling frequency required to adequately characterise the glider time series and 3) discriminate how much of the variability measured with a glider is the result of temporal variations versus spatial patchiness. Results highlight the important role of signals shorter than 10 days in characterising surface chlorophyll (chl-a) variability, particularly in spring (97%) and to a lesser degree in summer (27%). These small scales of variability were also evident in the physical indices of SST, wind stress and mixed layer depth. Further analysis revealed that sampling at high frequencies (< 10 days) are required to adequately resolve and characterise the seasonal and intra-seasonal mean state and variability of chl-a in the SAZ. Spatial analysis found that surface chl-a is patchier than surface temperature, as previously found in the North Atlantic. In addition, our seasonal analyses found that patchiness at smaller scales decreases in summer (relative to spring) indicative of a more homogeneous phytoplankton distribution. A spring comparison of the glider and concurrent satellite data at similar spatial scales suggests that the chl-a variability captured by the glider is generally larger than observed in the remote sensing images and may be driven by daily fluctuations.

1. Introduction

Phytoplankton production and associated seasonal blooms play an important role in biogeochemical cycling as they result in substantial transport of organic material from the surface sunlit waters to the ocean's interior. The seasonal cycle is not only the strongest mode of variability in the biological carbon cycle in the Southern Ocean (Lenton et al., 2013; Monteiro et al., 2009; Monteiro et al., 2011) but also the mode of variability that couples the physical mechanisms of climate forcing to ecosystem response in primary production, diversity and carbon export. The Subantarctic Zone (SAZ), and in particular the Atlantic sector, is a region with persistent frontal features both in physical and biogeochemical properties (Swart et al., 2012), which are largely modulated by seasonal variability (Vichi et al., 2011). However, there is increasing evidence from recent studies in the Southern Ocean that processes at finer spatial (meso- to submesoscale) and temporal scales (intra-seasonal), play an important role in characterising regional variability in the Southern Ocean's physical and biogeochemical seasonal cycle (Carranza and Gille, 2015; du Plessis et al., 2017; Swart et al., 2015; Thomalla et al., 2011). As such, not adequately resolving these scales may hamper the simulation and predictive capability of current physical-biogeochemical models used for climate scenarios (Mckiver et al., 2015). It is thus important that we investigate these fine scales in order to better understand the sensitivity of the Southern Ocean biological carbon pump to climate change (Boyd, 2002; Lévy et al., 2012; Thomalla et al., 2011). These fine scale processes are however poorly understood due primarily to the chronic undersampling of the region, which does not resolve inter-annual variability and seasonal and intra-seasonal dynamics in physical drivers and their biological response.

Satellites are an effective way to monitor the spatial and seasonal variation of sea surface chlorophyll (chl-a) (Marrari et al., 2006; Reilly et al., 1998), providing routine, highly cost-effective synoptic measurements over decadal time scales. However, problems with remotely

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sensed data sets exist, mainly due to cloud cover, which limits measurements to a few cloudless days. This leads to a tendency for satellite ocean colour data sets to be averaged both in space and time thus reducing their ability to resolve fine scale features (Kaufman et al., 2014; Lévy et al., 2012; Marrari et al., 2006; Moore and Abbott, 2002). In addition, remotely detected water-leaving radiances emanate from the first optical depth and require assumptions about their representativeness of the vertical structure of the water column. One of the frontiers in ocean observations is adequate and sustained spatial sampling of the subsurface ocean (Rudnick et al., 2004) conducted at an appropriate frequency to define and understand the growth timescales of phytoplankton.

Recent autonomous technological gains contribute to overcoming this space-time-depth gap in biogeochemical ocean observations with bio-optical sensors on glider platforms that collect horizontal and vertical data over long-time periods and at high-resolution (Dickey et al., 2008), particularly in hostile oceans (Niewiadomska et al., 2008; Swart et al., 2015), thereby capturing a vast range of temporal and spatial scale observations. Nonetheless, one of the complexities with collecting such observations lies with the interpretation of the data that is collected in a quasi-Lagrangian nature, i.e. the combined measurements taken from a moving platform in time means that gliders generally do not sample purely in a Eulerian or Lagrangian approach. This combined time and space sampling makes it difficult to disentangle the origin of forms of variability observed in the datasets. For example, the glider is possibly continuously crossing a combination of spatial features in the ocean (such as filaments and eddies) and/or observing intrinsic changes observed within the water column that are an inherent result of evolution in time (e.g. fluxes, phytoplankton growth, evolution of upper ocean physical processes and advection). This has been suggested by Rudnick et al. (2004) who propose that a glider section can confuse temporal variability with spatial structures and therefore should not be considered as suitable platforms to capture snapshots of ocean conditions. Swart et al. (2015) began to address this issue in the SAZ by looking at temporal coherence in mixed layer depth (MLD) observations from a dual glider deployment, as part of the Southern Ocean Seasonal Cycle Experiment (SOSCEx; Swart et al., 2012). During this experiment, there was a time period when the spatial separation of the two gliders was 213 km, yet the variability observed in their MLD characteristics was the same. This supports the idea that both gliders were measuring temporal variability that was being forced by synoptic scale wind forcing, albeit only during the summer portion of the time series.

Further results from the Swart et al. (2015) glider deployment showed that the SAZ was characterised by high intra-seasonal variability in surface chl-a, where data can be separated into two distinct periods, the spring bloom initiation phase and the summer sustained bloom phase. During spring, surface chl-a concentrations were intermittent and patchy. This was found to be the result of the presence of meso- and submesoscale features that act to enhance stratification (Mahadevan et al., 2012), and thereby increase the light supply allowing for the rapid formation of patchy phytoplankton blooms. In summer by contrast, the interplay of enhanced solar heat flux, mesoscale features and intra-seasonal storms were the proposed cause of variability of the MLD around ~40 m allowing a consistent entrainment of limiting nutrients, that results in the formation of larger, more homogenous phytoplankton blooms that are sustained throughout summer (Swart et al., 2015).

The heterogeneity of phytoplankton spatial distribution may arise from a combination of both biological (e.g. production) and physical process (e.g. heat flux) at meso- and sub-mesoscales (Van Gennip et al., 2016), which drives high variability in their concentrations at small scales at the sea surface and can account for the patchiness of phytoplankton in comparison to physical variables (such as temperature) (Mahadevan and Campbell, 2002). In addition, spatial heterogeneity can result from differences in characteristic response times to the processes altering them. For example, the response time of SST to heat flux is usually much longer than the time scales of biological uptake which drives patchier chl-a relative to temperature (Mahadevan and Campbell, 2002).

The aim of this study was to use the same 5.5 month glider study from Swart et al. (2015) in the SAZ to determine the dominant scales of variability and the minimum sampling frequency required to adequately characterise important scales of phytoplankton variability. High-resolution satellite ocean colour data was used to investigate degrees of spatial patchiness of both physical and biological parameters and how these varied seasonally. Finally, the glider and satellite ocean colour data sets were used in conjunction to discriminate how much of the variability being measured with the glider was the result of temporal variability versus spatial patchiness. For this study, length-scales that occur between 10 and 25 days (during which time the glider would cover ~100 to ~250 km in space) are defined as coarse-scales, while fine-scales are defined as variability occurring in the order of 2 to 10 days (during which time the glider would cover ~20 to ~ 100 km in space).

2. Methods

2.1. Field programme

This study focuses on data obtained from the autonomous Seaglider 573 (SG573) deployed, as part of SOSCEx (Swart et al., 2012), in the SAZ during the austral spring to late summer of 2012–2013 from the RV *S.A. Agulhas II*. On the 25th of September 2012 SG573 was deployed in the South East Atlantic Ocean, south of Gough Island at 43.0°S, 11.0°W. The glider was programmed to continuously sample the upper 1000 m in a near-zonal flight path along the SAZ for 143 days (5.5 months) and covered a distance of 1693 km before being retrieved on the 15th of February 2013 (Figs. 1 and 2).

The glider was equipped with a suite of sensors that included CTD (conductivity, temperature and depth), chl-a fluorescence (a proxy for phytoplankton chl-a concentration) and optical backscattering (a proxy for phytoplankton carbon concentrations). Each dive cycle took 5 h on average to complete and covered an average horizontal distance of 2.8 km, providing a total of 1212 profiles. This allowed for a temporal resolution of ~2.5 h and a spatial resolution of 1.4 km between each water column profile. This high-resolution dataset allows for both meso- (10–200 km) and submesoscale (1–10 km) features to be sampled for assessment (du Plessis et al., 2017).

Glider fluorescence was corrected for dark counts, non-photochemical quenching and converted to chl-a as described in Swart et al. (2015). Since chlorophyll profiles were generally uniform in the upper mixed layer (as typically found at higher latitudes > 40° S, Arrigo et al., 2008), we considered surface values to be representative of the mixed layer. Surface chl-a values at 10 m were chosen as the shallowest depth to consistently have data for all dives.

The MLD was calculated using temperature criteria where a change in temperature of 0.2 °C from the reference depth of 10 m denotes the MLD (de Boyer Montegut et al., 2004). The reason this method was used was due to thermal lag errors and biofouling of the glider, which introduced errors in glider salinity measurements in late summer (Swart et al., 2015).

2.2. Satellite products

The wind data were obtained from the SeaWinds blended vector sea surface wind product (Zhang et al., 2006) without taking into account the motion of the ocean current. The wind data was co-located with the gliders in space and time using a 2-dimensional bilinear interpolation and converted from wind speed into a wind stress product using the Large and Pond (1981) relation.

Ocean colour data were obtained from MODIS-Aqua (Moderate-resolution Imaging Spectroradiometer) for analysis of chl-a distribution in