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Biogeochemical variability in the southern Ross Sea as observed by a glider deployment

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ABSTRACT

High-resolution autonomous glider data (including temperature, salinity, fluorescence, and optical backscatter) collected during the 2010–2011 austral summer identified variations in phytoplankton biomass along two glider sections near 76°40′S. Sea surface temperatures were warmer during the latter, westward section, while mixed layer depths were deeper. Substantial quantities of Modified Circumpolar Deep Water, identified by neutral density criteria, were located within both sections. Chlorophyll (Chl) concentrations computed from fluorescence exhibited daily quenching near the surface, and deep chlorophyll concentrations at 200 m became periodically elevated, suggesting substantial export on small space and time scales. The concentrations of particulate organic carbon (POC) computed from backscatter increased abruptly during the latter, westward section, concurrent with a decrease in chlorophyll. These higher POC:Chl ratios were not strongly correlated with presence of MCDW or with shallower mixed layer depths, but were strongly associated with higher surface temperatures and wind speed. The observed POC:Chl increase suggests a marked spatial and temporal transition between a *Phaeocystis antarctica*-dominated assemblage characterized by modest POC:Chl ratios to a diatom-dominated assemblage. Finally, a subsampling analysis highlights the capability of high-resolution glider data to resolve these biological/physical parameter correlations that are not discernible from lower frequency data typical of traditional cruise stations.

1. Introduction

In situ observations and satellite-derived data from the Ross Sea have revealed high phytoplankton biomass and productivity compared with much of the rest of the Southern Ocean (Arrigo et al., 2008; Smith and Comiso, 2008). In addition, these data have demonstrated considerable variability on a suite of time and space scales, yet the mechanisms responsible for this variability are not yet well understood (Peloquin and Smith, 2007). An improved understanding of mesoscale controls on phytoplankton biomass and composition will provide important insights into the dynamics of the Ross Sea food web and reveal how this food web is responding to physical changes that are already occurring, such as freshening (Jacobs et al., 2002; Jacobs and Giulivi, 2010), increases in ice extent (Massom and Stammerjohn, 2010), decreases in ice-free duration of the polynya (Stammerjohn et al., 2012), and wind changes (Bracegirdle et al., 2008).

Previous cruise-based observational programs within the Southern Ross Sea have revealed that two dominant bloom-forming phytoplankton groups, haptophytes and diatoms, commonly occur and show distinct seasonal cycles of growth (Smith et al., 2010) that help support the region's sizeable contribution to the biogeochemical cycles of the Southern Ocean (Arrigo et al., 2008). Phytoplankton growth begins early each austral spring (late October) when the dominant haptophyte, *Phaeocystis antarctica* grows rapidly and reaches maximum biomass in mid- to late-December (Smith et al., 2000). Growth and biomass then decline rapidly (over a few weeks). Although the mechanism for this sudden decline is not well understood, it has been hypothesized to be a result of iron limitation and rapid sedimentation of aggregates (Smith et al., 2000; Arrigo et al., 2003). Elevated chlorophyll concentrations in the euphotic zone have been shown to be associated with rapid (on the order of days) sinking and flux of phytoplankton to depth in summer (Smith et al., 2011b). In contrast to the strong seasonal cycle of *P. antarctica*, diatoms are present at varying concentrations throughout the growing season; however, a late summer secondary bloom has been observed in some years (Peloquin and Smith, 2007; Smith et al., 2011a).

The domains in which these two phytoplankton groups dominate are often spatially distinct and exhibit distinct ratios of

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particulate organic carbon (POC) to chlorophyll (Chl). Lower POC:Chl ratios are often associated with *P. antarctica*, and higher ratios are associated with diatoms during late summer (DiTullio and Smith, 1996; Smith et al., 2000). *Phaeocystis antarctica*, which exists in both solitary and colonial forms (Schoemann et al., 2005), typically dominates in the central Ross Sea polynya where there are relatively deep mixed layers (Arrigo et al., 1998; Smith et al., 2010); conversely, diatoms dominate in regions with shallow mixed layers, such as near retreating ice edges and in summer (Arrigo et al., 1998). Even within regions dominated by a single taxon, however, both taxa are likely to co-exist (Smith and Asper, 2001).

Temporal and spatial gradients between *P. antarctica*- and diatom-dominated waters result from a combination of multiple physiochemical controls (Smith and Asper, 2001), including mixed-layer depths, micronutrients, and temperature distributions. For example, lower irradiance requirements of *P. antarctica* explain their dominance over diatoms in waters with deeper mixed layers (Kropuenske et al., 2009). Mixing of Circumpolar Deep Water with surface waters to produce Modified Circumpolar Deep Water (MCDW) has been hypothesized as a substantial source of iron to the assemblage, though a recent study has shown the Ross Sea iron budget dominated by benthic remineralization and sea ice input (D. McGillicuddy, pers. comm.). The timing and distribution of iron inputs may affect not only phytoplankton biomass, but also composition due to potentially distinct iron requirements of *P. antarctica* and diatoms. However, data on the relative requirements of each functional group are inconsistent (Alderkamp et al., 2012; Strzepek et al., 2012). Finally, higher temperatures have been correlated with higher diatom abundance, and lower temperatures with higher *P. antarctica* abundance (Liu and Smith, 2012), although it is not yet clear whether there is a causal mechanism behind this correlation.

Throughout the ocean, mesoscale processes on scales of 10–100 km and hours to days have first-order impacts on phytoplankton physiochemical controls, and are critical in determining growth patterns and distribution. For example, Friedrichs and Hofmann (2001) demonstrated how internal gravity waves, with periods of 6–8 days, can either stimulate growth or dilute chlorophyll concentrations in the euphotic zone by vertically advecting low-chlorophyll, iron-enriched water into the euphotic zone at rates greater than phytoplankton uptake. McGillicuddy et al. (2007) demonstrated that wind and eddy interactions could have varied effects on production at the mesoscale, with enhanced production associated with mode-water eddies and diminished production associated with cyclonic eddies. Indeed, the largest chlorophyll concentrations ever observed in the Sargasso Sea were associated with eddies (McGillicuddy et al., 2007). Finally Mahadevan et al. (2012) demonstrated that eddies generate mesoscale stratification in the North Atlantic to initiate the spring bloom prior to the effects of increased temperatures.

In the Ross Sea physical features such as tidal variations and wind-driven events have a substantial mesoscale impact on hydrodynamic variability. For example, diurnal tides produce continental shelf waves that, in turn, amplify shorter semidiurnal tides (Robertson, 2005). Variations in current velocity, salinity, and temperature have been attributed to this diurnal tidal forcing (Kohut et al., 2013). In addition, katabatic winds and synoptic forcing generate conditions favorable to atmospheric mesoscale cyclones over the Ross Sea (Heinemann and Klein, 2003). Episodic variations of wind speed and direction can lead to restratification as a result of Ekman advection across lateral density gradients (Long et al., 2012). Partly because of the difficulty obtaining high frequency observations within the Ross Sea, the effect of these physical processes on biological distributions is poorly known, but is likely to be significant. For example, the relief of irradiance limitation through stratification may be critically important to determining the timing and distribution of the seasonal phytoplankton bloom in the Ross Sea (Long et al., 2012).

Given the theoretical size of mesoscale features in the Ross Sea (10 km or less and on the order of days), such features cannot be well resolved by traditional oceanographic sampling from ships. However, autonomous underwater vehicles can successfully resolve this variability, as they have done in other regions of the Southern Ocean (e.g., Heywood et al., 2014). In the analysis presented here, an autonomous glider was deployed in the southern Ross Sea from December 2010 to January 2011 to characterize the biogeochemical mesoscale variability and highlight potential mechanisms contributing to this variability. We describe the glider deployment, sampling strategy, and ancillary data available for this analysis. The observed physical and biological distributions are presented along with significant correlations among these distributions; factors controlling these biological distributions are then discussed. Our results suggest a marked spatial, and presumably temporal, transition from a *P. antarctica*-dominated assemblage to one dominated by diatoms. Furthermore, frequent vertical penetrations of chlorophyll were observed, emphasizing the importance of mesoscale events to regional biogeochemistry.

2. Methods and data analysis

2.1. Glider platform

An iRobot Seaglider™ model 1KA (SN 502) completed two transects between 172.1°E and 179.9°W (~200 km) in the southern Ross Sea (Fig. 1) between December 19, 2010 and January 16, 2011. During this 28-day period, 370 dives were completed, 191 on the eastward section from December 19 through January 2, and 179 dives as the glider moved westward from January 2–16. The region surrounding the glider track was largely free of ice during both sections. Successive dives were separated by roughly 1 km, and extended to 600 m depth (except in shallower waters). The dives were divided into two portions, a down- and up-sampling phase, each of which were treated as separate "casts"; locations were computed for each cast as opposed to each dive. Because the glider obtains GPS positions only when at the surface, locations for down- and up-casts were interpolated to coordinates one-quarter and three-quarters, respectively, of the distance between the pre-dive and post-dive GPS-fixed locations. The glider's sensor suite provided measurements of conductivity and temperature (Seabird CTD), as well as fluorescence and optical backscatter (Wetlabs *Environmental Characterization Optics* Triplet Puck optical sensor

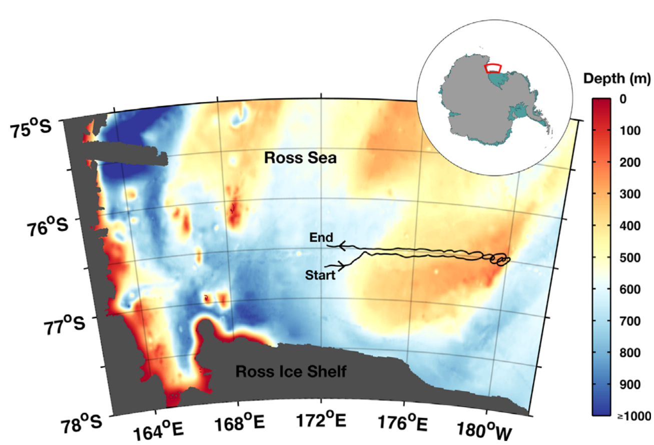

Fig. 1. Southwestern Ross Sea with glider track (black line). The glider's eastward (outbound) section began December 19, 2010, and the westward (return) section ended January 16, 2011. Gray areas represent topography above sea level or ice shelf. Bathymetric data obtained from the Bedmap2 dataset (Fretwell et al. 2013).