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Processes influencing formation of low-salinity high-biomass lenses near the edge of the Ross Ice Shelf

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ABSTRACT

Both remotely sensed and in situ observations in austral summer of early 2012 in the Ross Sea suggest the presence of cold, low-salinity, and high-biomass eddies along the edge of the Ross Ice Shelf (RIS). Satellite measurements include sea surface temperature and ocean color, and shipboard data sets include hydrographic profiles, towed instrumentation, and underway acoustic Doppler current profilers. Idealized model simulations are utilized to examine the processes responsible for ice shelf eddy formation. 3-D model simulations produce similar cold and fresh eddies, although the simulated vertical lenses are quantitatively thinner than observed. Model sensitivity tests show that both basal melting underneath the ice shelf and irregularity of the ice shelf edge facilitate generation of cold and fresh eddies. 2-D model simulations further suggest that both basal melting and downwelling-favorable winds play crucial roles in forming a thick layer of low-salinity water observed along the edge of the RIS. These properties may have been entrained into the observed eddies, whereas that entrainment process was not captured in the specific eddy formation events studied in our 3-D model—which may explain the discrepancy between the simulated and observed eddies, at least in part. Additional sensitivity experiments imply that uncertainties associated with background stratification and wind stress may also explain why the model underestimates the thickness of the low-salinity lens in the eddy interiors. Our study highlights the importance of incorporating accurate wind forcing, basal melting, and ice shelf irregularity for simulating eddy formation near the RIS edge. The processes responsible for generating the high phytoplankton biomass inside these eddies remain to be elucidated.

1. Introduction

The Ross Ice Shelf (RIS) is the largest ice shelf (~4.7×10^5 km^2) in Antarctica, located in the southern Ross Sea (Fig. 1). The RIS region plays host to a number of important physical and biological processes. Air-sea interaction and ice dynamics at the edge of the RIS influence High Salinity Shelf Water (HSSW) formation (MacAyeal, 1984; Orsi and Wiederwohl, 2009), which is a dense water mass that is critical in Antarctic Bottom Water formation (Jacobs et al., 1996; Orsi et al., 2002; Whitworth and Orsi, 2006; Gordon et al., 2009). The frontal region also bridges heat and mass exchanges with the open ocean (Rignot et al., 2013; Depoorter et al., 2013). The Ross Sea is one of the most biologically productive areas in the Southern Ocean (Comiso et al., 1993; Arrigo et al., 1998; Smith et al., 2014), and the RIS delimits the southern boundary of the region of high productivity. Iron supply is thought to regulate primary production in the Ross Sea (Arrigo et al., 2003; Martin, 1990; Sedwick et al., 2000). Although recent evidence suggests that the iron supply from glacial ice melt constitutes only a small fraction of the iron supply to this region (McGillicuddy et al., 2015), basal melting is a primary pathway for iron supply in other Antarctic polynyas (Arrigo et al., 2015; Gerringa et al., 2012).

Processes at different depth levels make the cavity underneath the RIS a complex ocean environment. Near the ice shelf front, increased melting is facilitated by occasional warm water intrusions (Jenkins and Doake, 1991) from adjacent upper ocean waters that come in contact with the edge of the ice shelf. At mid-depth, melting is caused by intrusion of modified circumpolar deep water (Jacobs et al., 2011, Dinniman et al., 2007, 2012; Klinck and Dinniman, 2010; Pritchard et al., 2012). In the deepest layer, dense HSSW (a product of brine rejection over the continental shelf from ice formation during the winter months), which is at the surface freezing point, can penetrate into the cavity, causing melting near the grounding line due to the depression of the freezing point of seawater with increasing pressure. As the buoyant meltwaters rise along the ice shelf base, they can refreeze at mid-depth due to the increase in freezing point with

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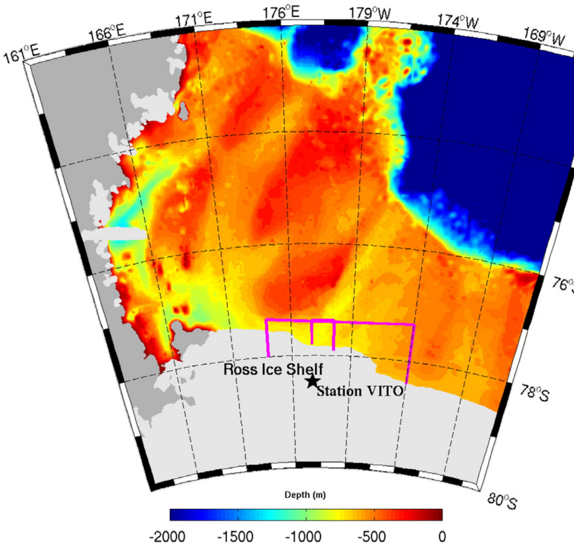

Fig. 1. Bathymetric map of the Ross Sea based on Bedmap2 bottom elevation data made available by the British Antarctic Survey (http://nora.nerc.ac.uk/501469/). White contours are the 400 m isobath. The Pentagram indicates the location for Antarctic meteorological station VITO. The permanent ice shelf is shown in light gray, and land in dark gray. Domains of the satellite images depicted in Figs. 2 and 3 are shown as solid magenta lines. (For interpretation of the references in this figure legend, the reader is referred to the web version of this article.)

decreasing pressure, producing super-cooled Ice Shelf Water (ISW). All these processes interact with each other at various spatial and temporal scales, making for a complex regime of thermohaline circulation (MacAyeal, 1984, 1985).

Of particular interest from the ecosystem perspective is the penetration of glacial meltwater into the surface waters in the interior of the Ross Sea, as this constitutes a source of iron to upper ocean phytoplankton populations. Although the iron supply from glacial meltwater is thought to be small relative to other sources in the Ross Sea (McGillicuddy et al., 2015), physical processes such as oceanic eddies that affect the glacial meltwater may be locally important to the initiation and spatial distribution of regional phytoplankton blooms. In austral summer of 2012, we observed two anticyclonic eddies emanating from the edge of the RIS northward into the Ross Sea. The eddies contained low-salinity lenses with deep mixed layers (ca. 80 m) and very high biomass of the colonial prymnesiophyte *Phaeocystis antarctica* (Smith et al., submitted for publication). Our goal is to identify the processes that lead to generation of these eddy features, which will set the stage for future study of the physical-biological interactions leading to the high biomass observed in their interiors.

The primary surface circulation feature along the front of the RIS in this area is a relatively strong, narrow, and fresh coastal current that flows to the west (Jacobs et al., 1970; Keys et al., 1990). A similar westward current is found along the front of the Ronne-Filchner Ice Shelf (Makinson et al., 2006) where mooring observations at depth (as deep as 200–400 m) also suggest the possibility of eddy-driven variability (Nicholls et al., 2003). Knowledge of ocean variability in the near-surface ocean layer near the RIS remains rather limited due the scarcity of data, with relatively few direct observations available (Jacobs et al., 1985; Smethie and Jacobs, 2005). Arzeno et al. (2014) postulated eddies as being responsible for variability in currents underneath the RIS that was uncorrelated with the wind. Although the process of eddy generation has been examined in many oceanic regimes, relatively few studies have focused on instabilities associated with ice-ocean interactions (Clarke, 1978; Chu, 1987; Dumont et al., 2010; Häkkinen, 1986; Niebauer, 1982). In general, glacial meltwater can create horizontal density gradients that force a baroclinic jet (Niebauer, 1982). Häkkinen (1986) found that when across- and along-ice edge spatial scales are similar enough, such baroclinic jets can generate eddy structures along the ice edge, especially when the wind forcing is time-varying between upwelling and downwelling conditions. In a modeling study in Baffin Bay near Greenland, cyclonic eddies were generated at the edge of landfast ice in response to frequent northerly wind forcing (Dumont et al., 2010). All of these studies pointed to the importance of baroclinic jets and wind forcing in forming eddies near the ice edge.

Earlier efforts utilized idealized two-layer ocean models to study how ice-ocean interactions can excite unstable wave forms. Using a semi-analytical quasi-geostrophic model, Clarke (1978) showed that fluctuations in the flow along fast ice can be described as wind-forced trapped long-waves propagating along the ice edge. Chu (1987) used a similar framework, identifying an air-sea interaction feedback mechanism that excites an unstable mode in the presence of curvature in the ice edge. Both Clarke (1978) and Chu (1987) highlighted the importance of considering multiple factors such as ice shelf edge irregularity and background stratification (initial conditions) in studying the instability processes. However, because their models did not consider basal melting, they were not able to capture the structure of low-salinity features near the ice edge.

Our approach is to use high-resolution models with varying levels of complexity to understand the mesoscale phenomena we observed at the edge of the RIS. In Section 2 we present the observations, consisting of both satellite imagery and in situ measurements. We describe the model configuration in Section 3, followed by Sections 4 and 5 showing its implementation in three- and two-dimensional configurations respectively. The former is used to investigate the process responsible for eddy generation, whereas the latter provides insight into the mechanisms responsible for the thickness of the low-salinity surface layer. Section 6 offers further analysis and discussion of the dynamics via sensitivity analyses. A summary and conclusions are presented in Section 7.

2. Observations

2.1. Satellite imagery

A sequence of satellite images in January 2012 captured the signature and evolution of several eddies near the RIS. On January 22, there were a number of cold eddies along the edge of the ice shelf (Fig. 2a), including some that were already separated from the RIS (e.g., near 177.5°E), and some that remained connected to the ice shelf edge (e.g., Eddy 1 and Eddy 2). Eddy 1 (radius ~12 km) was flanked by warm anomalies to the east and northwest. Eddy 2 was slightly smaller (radius ~8 km), separated from Eddy 1 by a warm filament protruding south to the edge of the RIS. Satellite ocean color imagery indicated a ca. 20 km wide strip of low chlorophyll *a* (Chl-a) concentrations extending along the edge of the RIS, with much higher concentrations to the north (Fig. 2b). The signatures of Eddies 1 and 2 in ocean color are barely discernible in the January 22 image as northward perturbations to the frontal boundary separating high and low Chl-a.

Three days later, the two eddies had moved away from the RIS and evolved in the process (Fig. 3). Both eddies appear to be warmer, and have similar radii that are still larger than the local Rossby deformation radius (~5 km). Eddy 1 moved north-northwest, whereas Eddy 2 moved northwest, narrowing the gap in between them. Both eddies propagated westward, as is commonly the case due to meridional variation in the Coriolis parameter (Cushman-Roisin et al., 1990), although the background westward flow in this region may play a crucial role. Compared to three days prior, Eddy 1 took on a more circular shape. By January 25, Eddy 1 had almost completely separated from the RIS, connected to the shelf edge by only narrow cold filaments running southwest from the southern flank of the eddy and south from the eastern flank of the eddy (Fig. 3a). The warm anomaly previously to the east of Eddy 1 on January 22 appeared to have been swept southwestward by January 25. However, this movement is opposite in

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