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Dissolved iron transport pathways in the Ross Sea: Influence of tides and horizontal resolution in a regional ocean model

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ABSTRACT

Phytoplankton production in the Ross Sea is regulated by the availability of dissolved iron (dFe), a limiting micro-nutrient, whose sources include Circumpolar Deep Water, sea ice melt, glacial melt, and benthic sources (sediment efflux and remineralization). We employ a passive tracer dye to model the benthic dFe sources and track pathways from deep areas of the continental shelf to the surface mixed layer in simulations with and without tidal forcing, and at 5 and 1.5 km horizontal resolution. This, combined with dyes for each of the other dFe sources, provides an estimate of total dFe supply to surface waters. We find that tidal forcing increases the amount of benthic dye that covers the banks on the continental shelf. Calculations of mixed layer depth to define the surface ocean give similar average values over the shelf, but spatial patterns differ between simulations, particularly along the ice shelf front. Benthic dFe supply in simulations shows an increase with tidal forcing and a decrease with higher resolution. The changes in benthic dFe supply control the difference in total supply between simulations. Overall, the total dFe supply from simulations varies from 5.60 to 7.95 μmol m^{-2} $year^{-1}$, with benthic supply comprising 32–50%, comparing well with recent data and model synthesis. We suggest that including tides and using high horizontal resolution is important, especially when considering spatial variability of iron supply on the Ross Sea shelf.

1. Introduction

The Ross Sea, Antarctica is home to a unique ecosystem (Smith et al., 2007). Each spring, a significant phytoplankton bloom starts in the Ross Sea polynya, and spreads to other areas as the sea ice melts, making the Ross Sea among the most productive region in the Southern Ocean (Arrigo et al., 2008). The phytoplankton are dominated by diatom species and *Phaeocystis antarctica*, which provide food for larger plankton, including a keystone species of the region, Antarctic krill (*Euphausia superba*) (Smith et al., 2007). These lower trophic levels support a variety of top predators, including penguins, seals, fish, birds, and whales.

Annual primary production by phytoplankton is limited by the availability of dissolved iron (dFe), an essential micro-nutrient (Sedwick et al., 2011; Tagliabue and Arrigo, 2005). Deep mixing over the winter months sets up a reserve of dFe in the surface ocean, ready to be used by phytoplankton once there is sufficient solar radiation, and then drawn down to growth limiting concentrations (0.1 nM) during spring and summer. Four major sources of dFe to surface waters in the Ross Sea are: glacial melt water, sea ice melt water (including atmospheric deposition on sea ice), Circumpolar Deep Water (CDW), and benthic sources (which can include a direct efflux from sediments and remineralization) (McGillicuddy et al., 2015). The transport of dFe to the surface waters and the subsequent characteristics of the spring bloom are likely influenced by local, mesoscale processes, such as icebergs, sea ice melt, and eddies (Boyd et al., 2012). Thus, the entire ecosystem in this area is heavily influenced by the physical processes that bring dFe to surface waters.

Tides and mesoscale eddies have small temporal and small spatial scales, respectively, that should influence the amount of dFe supplied to the surface mixed layer (SML). In the Ross Sea, tidal flows reach up to 1 m s^{-1} near the continental shelf break (Padman et al., 2009), enhancing cross slope water exchange and increasing the amount of CDW advected onto the shelf (Wang et al., 2013). Tidal rectification has been shown to increase basal melting rates of the Ross Ice Shelf (Arzeno et al., 2014; MacAyeal, 1985), potentially increasing

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glacial contributions of dFe supply. Similar mechanisms have been demonstrated for nearby shelf seas, where tides cause intensification of under ice shelf circulation (Makinson et al., 2011; Mueller et al., 2012; Robertson, 2013).

Mesoscale eddies in the open ocean can produce localized hot spots of primary production, as eddy pumping brings nutrients, including dFe, from deeper waters to the surface (Falkowski et al., 1991; McGillicuddy Jr., 2016). In the case of Antarctic shelf ecosystems like the Weddell or Ross Seas, eddies also may travel beneath the ice shelf, transporting water and flushing the ice shelf cavity (Årthun et al., 2013), increasing the amount of ice shelf melt water that reaches the continental shelf. Recent work shows eddies possibly provide a mechanism to enable meltwater from ice shelves to spread out into the open ocean away from a buoyancy driven ice shelf front coastal current (Li et al., 2017). Through this combination of effects, eddies potentially affect the supply of glacial melt water to the continental shelf and the upwelling of dFe from CDW or benthic sources.

Following the work of McGillicuddy et al. (2015), this study focuses on simulating the benthic supply of dFe to the SML, and compares the strength of this source with other inputs from glacial melt water, sea ice melt water, and CDW. Specifically, we examine the contributions of tides and the effect of horizontal resolution in a regional ocean model, supplemented by data from a recent research cruise. Section 2 describes the data obtained from the cruise, and details the simulations and analysis methods. Results are presented in Section 3 that detail the effects of tides and increased horizontal resolution on the transport pathways of benthic waters, the depth of the SML during austral summer, and the relative contribution to dFe from each identified source. A discussion of the results and their implications on the importance of including tides and high horizontal resolution in future simulations is presented in Section 4.

2. Methods

2.1. PRISM-RS cruise

The project Processes Regulating Iron Supply at the Mesoscale-Ross Sea (PRISM-RS) (McGillicuddy et al., 2015) undertook an oceanographic cruise aboard RVIB Nathaniel B. Palmer from December 24, 2011 to February 8, 2012 (Fig. 1). The purpose of this project is to investigate the potential sources of iron during the spring bloom and to assess their roles in supporting the Ross Sea ecosystem. To this end, the cruise focused on hydrographic and trace metal measurements (Table 1), along with biological surveys of phytoplankton processes. Specifically, the data collected included temperature and salinity measurements from a variety of instruments including CTD casts, the ship's underway system, and a Moving Vessel Profiler (MVP). Iron measurements were made in samples collected

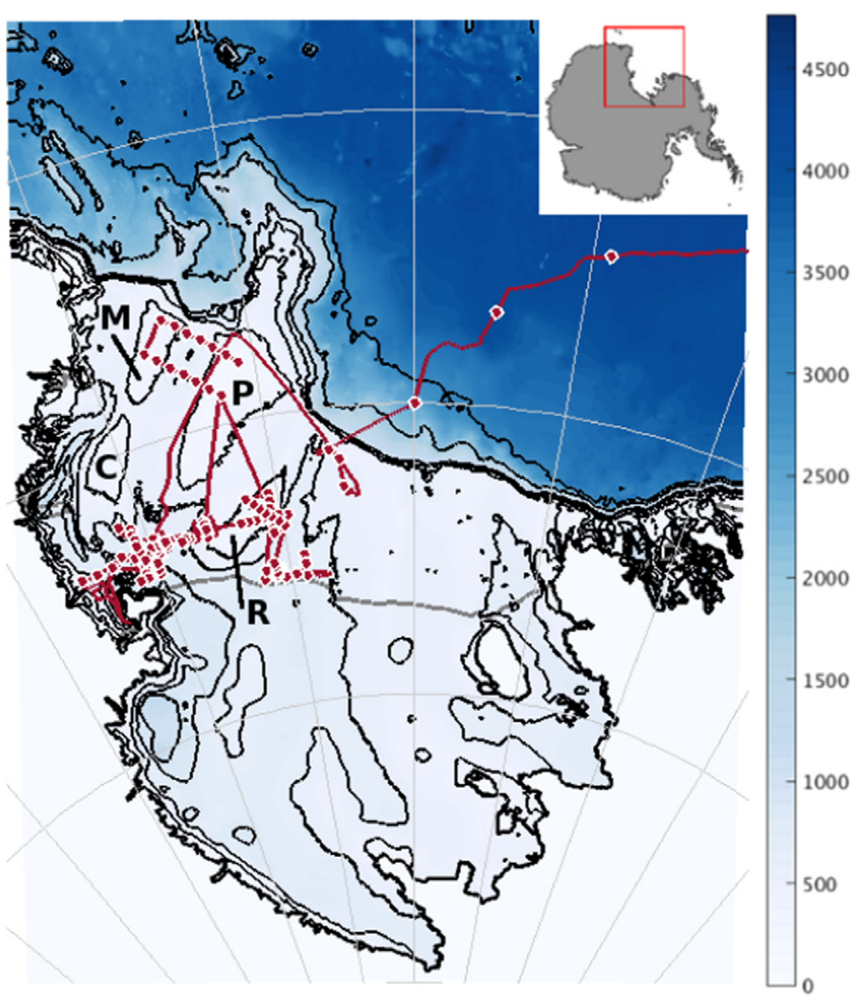

Fig. 1. Model domain of the Ross Sea. Bottom depth is in meters. Red line is the PRISM-RS cruise track, dots are CTD stations. Black lines are bathymetry contours, gray is ice shelf edge. M: Mawson Bank; P: Pennell Bank; C: Crary Bank; R: Ross Bank.