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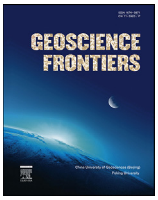

Research paper

Dynamics of sea-ice biogeochemistry in the coastal Antarctica during transition from summer to winter

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ABSTRACT

The seasonality of carbon dioxide partial pressure (pCO$_2$), air-sea CO$_2$ fluxes and associated environmental parameters were investigated in the Antarctic coastal waters. The in-situ survey was carried out from the austral summer till the onset of winter (January 2012, February 2010 and March 2009) in the Enderby Basin. Rapid decrease in pCO$_2$ was evident under the sea-ice cover in January, when both water column and sea-ice algal activity resulted in the removal of nutrients and dissolved inorganic carbon (DIC) and increase in pH. The major highlight of this study is the shift in the dominant biogeochemical factors from summer to early winter. Nutrient limitation (low Si/N), sea-ice cover, low photosynthetically active radiation (PAR), deep mixed layer and high upwelling velocity contributed towards higher pCO$_2$ during March (early winter). CO$_2$ fluxes suggest that the Enderby Basin acts as a strong CO$_2$ sink during January (-81 mmol m^{-2} d^{-1}), however it acts as a weak sink of CO$_2$ with -2.4 and -1.7 mmol m^{-2} d^{-1} during February and March, respectively. The present work, concludes that sea ice plays a dual role towards climate change, by decreasing sea surface pCO$_2$ in summer and enhancing in early winter. Our observations emphasize the need to address seasonal sea-ice driven CO$_2$ flux dynamics in assessing Antarctic contributions to the global oceanic CO$_2$ budget.

1. Introduction

Predicted future changes in the polar seas and continued sea ice retreat (Arzel et al., 2006) will affect future marine biogeochemistry, with important feedbacks on climate and marine ecosystems, some of which have already been observed (Montes-Hugo et al., 2009; Wassmann et al., 2011). As polar regions are rapidly changing, understanding the large-scale polar marine biogeochemical processes and their future evolution is of high priority. Covering approximately 40% of the Southern Ocean's surface during maximum extent in September/October, sea ice is an important component of Earth's climate system and through a variety of feedback mechanisms acts as an agent and indicator of climate change (Thomas and Dieckmann, 2010). Sea ice is also a structuring force in Antarctic marine ecosystems and plays a crucial role in the primary productivity and biogeochemical cycling in the Southern Ocean (Brierley and Thomas, 2002; Arrigo and Thomas, 2004; Lannuzel et al., 2007; Thomas and Dieckmann, 2010). Ice algae primary production can contribute up to 25% to the overall production of ice-covered waters in the Southern Ocean (Lizotte, 2001; Arrigo and Thomas, 2004). Iron concentrations in sea ice can be much higher than in the ocean and sea ice can act as a seasonal Fe reservoir in the Southern Ocean (Lannuzel et al., 2007), which can be released later into surface waters when the ice melts.

Sea-ice covered regions show large spatial and temporal variability in sea surface CO$_2$ (Bakker et al., 1997; Hoppema and Goeyens, 1999; Hoppema et al., 2000; Alvarez et al., 2002; Bellerby et al., 2004; Shim et al., 2006). Under saturation of surface ocean pCO$_2$ has often been found during summer (Popp et al., 1999). The observations during winter show values close to, or in some areas, well above atmospheric equilibrium (Goyet et al., 1991; Rubin et al., 1998). The sea ice cover influences energy and mass fluxes between atmosphere and ocean, and strongly controls pelagic production by reducing light availability (Smith and Nelson, 1985; Lizotte, 2001; Fitch and Moore, 2007). Another important mechanism of interest is the sinking of CO$_2$-rich brine which is

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released to the surface ocean during sea ice formation (Rysgaard et al., 2007).

In order to understand the processes regulating the $p\text{CO}_2$, we studied hydrographical and biological variability in three contrasting months. Our primary objective was to characterize the seasonal and spatial heterogeneity of surface water $p\text{CO}_2$ in the Enderby Basin in order to gain insight into seasonal biogeochemical dynamics and the scale of variability.

2. Material and methods

Three research cruises were conducted in the eastern Antarctica region (Enderby Basin) onboard the Ivan Papanin, ORV Sagar Nidhi and R/V Akademik Boris Petrov, during January 2012, February 2010 and March 2009. The samplings were carried out along the Antarctic coast (horizontal transects) during all study periods with two additional vertical transects during February 2010 (Fig. 1). Satellite derived parameters such as sea-ice coverage, upwelling velocity, sea surface temperature (SST), photosynthetically active radiation (PAR) and Chlorophyll-*a* were mapped to understand the biogeochemical processes in the eastern Antarctic coastal region.

2.1. Satellite derived environmental parameters

2.1.1. Sea-ice

We used the sea-ice data set which was generated using the Defence Meteorological Satellite Program (DMSP) −F8-F17 Special Sensor Microwave Imagers (SSMIs) at a grid cell size of 25 km × 25 km (Cavalieri et al., 1996). The algorithm developed by the Oceans and Ice Branch, Laboratory for Hydrospheric Processes at NASA Goddard Space Flight Center (GSFC) was used to generate the sea-ice product.

2.1.2. Computation of upwelling velocity

The MetOp-Advanced Scatterometer (ASCAT) measured Level-2 wind vectors are derived from Level-1b data, by using a Geophysical Model Function (GMF), which relates normalized radar cross-section (σ_0) to wind speed and direction (Hersbach et al., 2007). For our analysis, the science quality Level-2 daily swath data files available at 12.5 km wind vector cell (WVC) spacing were composited for valid data pixels for generating monthly images. Wind stress was calculated from the ASCAT Level-2 swath data using the Tropical Ocean Global Atmosphere – Coupled Ocean Atmosphere Response Experiment (TOGA–COARE) algorithm (Fairall et al., 1996). The curl was calculated using centered differences for the derivatives, based on gridded files of the individual orbits (Gill, 1982). Further, Ekman upwelling is computed as $(\text{curl} \times \tau)/(\rho \times f)$ where, τ is the wind stress, ρ is the density of surface water and f is the Coriolis parameter (Pond and Pickard, 1983; Jena et al., 2012, 2013).

2.1.3. SST from Aqua-MODIS

SST derived from Moderate Resolution Imaging Spectroradiometer (MODIS) channels using short-wave SST algorithm (3.959 and 4.050 μm) and long-wave SST algorithm (11 and 12 μm) are available in various spatial and temporal resolutions. The atmospheric correction and SST retrieval method from MODIS have been documented by Brown and Minnett (1999). MODIS SST derivation is similar to non-linear (NL) SST approach (Walton et al., 1998) used in Advanced Very High Resolution Radiometer (AVHRR) processing whereby the coefficients are determined by regressing MODIS brightness temperature to known measured SST (Brown and Minnett, 1999). In this study, we have used the Level-3 monthly SST images (spatial resolution of 4 km × 4 km), composited for valid data pixels.

2.1.4. Photosynthetically Active Radiation (PAR)

Aqua-MODIS derived photosynthetically active radiation product is available in varied spatial (1 km to 1°) and temporal resolutions (up to yearly composite). We used level-3 monthly composite product of PAR with a spatial resolution of 4.6 km. PAR is crucial for determining photosynthetic rate of phytoplankton growth and ocean primary production. The irradiance model of Gregg and Carder (1990) uses a mixture of marine and terrigenous aerosols and forms the basis for the algorithm for the MODIS PAR product.

2.1.5. Chlorophyll-*a* observations

Retrieval of Chlorophyll-*a* pigment from Aqua-MODIS involves two major steps namely atmospheric correction of visible bands (0.41 to 0.55 μm) to measure water leaving radiance (Shettle and Fenn, 1979; Gordon and Wang, 1994; David et al., 2000; IOCCG, 2010) and development of suitable bio-optical algorithm to measure Chlorophyll *a* concentration (O'Reilly et al., 2000). NASA's Ocean Biology Processing Group (OBPG) processes the global Level-

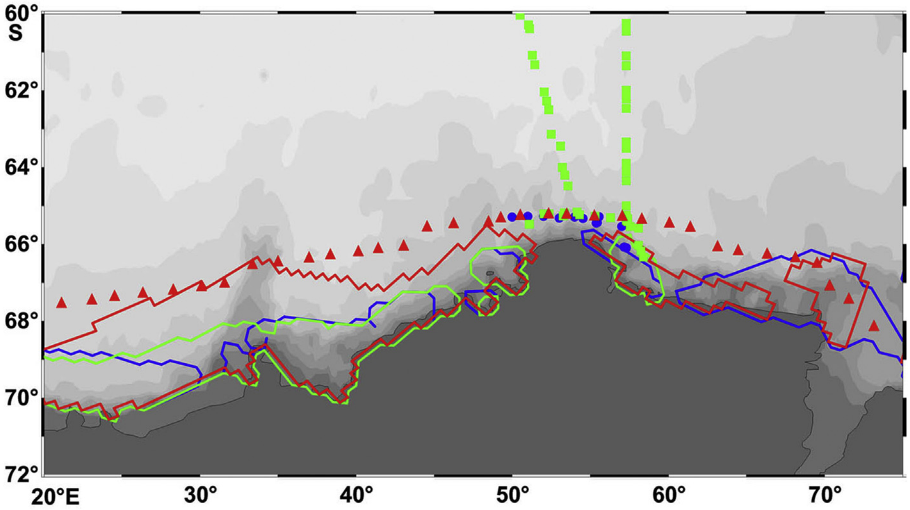

Figure 1. Study area map, with station locations. Red dots are the stations occupied during January expedition, green dots are the stations occupied during February expedition and blue during March. The sea ice extent is marked with the corresponding colour for each year.