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Physico-ecobiogeochemistry of East Antarctic pack ice during the winter-spring transition

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ABSTRACT

Our study provides information on the relationships between physical, chemical, and biological properties of East Antarctic sea ice sampled as part of the Sea Ice Physics and Ecosystem eXperiment (SIPEX) during the winter-spring transition in 2007. The sampled sea ice showed a high contribution of granular ice, indicating the turbulent conditions during sea ice formation off East Antarctica. The sea ice was cold, with brine volumes often below or very close to the theoretical percolation threshold of sea ice. Dissolved inorganic nutrient concentrations showed both positive and negative deviations from theoretical dilution lines, indicating both nutrient uptake as well as nutrient remineralisation in sea ice brines. Cold temperatures, high brine salinities, and low brine volumes limited high ice algal biomass to the warmer and more porous sea ice layers at the ice–water interface. We hypothesise that East Antarctic sea ice shows generally low ice algal biomass accumulation due to a combination of relatively low snow–loading, relatively cold ice temperatures, and short persistence of sea ice into the warm forcing regime, all of which prevent the development of significant internal and surface communities.

1. Introduction

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 of 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). The sea ice cover influences energy and mass fluxes between atmosphere and ocean and strongly affects pelagic production due to its effects on under-ice light availability and coupled physical-biological processes at retreating ice edges during spring and summer (e.g. Smith and Nelson, 1985; Lizotte, 2001; Fitch and Moore, 2007).

Antarctic pack ice is an extremely dynamic and variable habitat both temporally and spatially (Eicken, 1992; Ackley and Sullivan, 1994). Even in mid-winter surface melt may result from incursions of warm and moist air in the wake of cyclones, and divergent drift patterns may result in open water creation and new ice formation, while convergence may rework the existing ice cover through dynamic ice growth due to rafting (Massom et al., 2008; Worby et al., 2008). Thermodynamically, East Antarctic pack ice can grow to a thickness of about 0.5-0.8 m before deformation and rafting occur (Worby et al., 1998). Thickening of an ice cover can also occur due to ice surface processes such as snow melt and refreezing producing superimposed ice, and/or flooding producing snow ice, both of which are found to be important across much of the Antarctic pack ice (e.g. Haas et al., 2001; Ackley et al., 2008).

During ice formation physical processes such as scavenging and wave-field pumping incorporate particles into newly forming sea ice, making it a temporal reservoir for particulate matter and nutrients (Garrison et al., 1990; Ackley and Sullivan, 1994; Gradinger and Ikävalko, 1998). Some organisms trapped within the ice matrix subsequently start growing, which results in the formation of ice-associated (sympagic) communities consisting of various organism

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groups, including bacteria, algae, heterotrophic protists and metazoans (Horner et al., 1992; Mock and Thomas, 2005; Thomas and Dieckmann, 2010). In terms of biomass, these communities are generally dominated by algae.

Besides gas inclusions and small amounts of precipitated salts, the interior of the sea ice consists primarily of two phases: solid ice and brine (hypersaline water inclusions) (Weeks and Ackley, 1986). Brine salinity is a function of sea ice temperature, whereas brine volume is a function of both ice temperature and ice bulk salinity (Frankenstein and Garner, 1967). The brine fills a network of pores and channels, referred to as the brine channel system, which is a semi-enclosed habitat that, depending on the sea ice physical properties, can be isolated from the underlying water column (Gleitz et al., 1995; Papadimitriou et al., 2007; Meiners et al., 2009). A theoretical threshold of 5% brine volume fraction is considered to inhibit brine percolation in columnar ice, and a higher threshold is predicted for granular ice due to its more random distribution of brine inclusions (Golden et al., 1998). During winter and early spring sea ice is generally characterised by strong vertical gradients in temperature and brine salinity and overall small brine volumes (Eicken, 1992), affecting the exchange of brine between different layers within the sea ice and with the water column. Biological activity in the sea ice brine channel system and other semi-enclosed sea ice habitats has been shown to strongly affect sea ice biogeochemistry (Gleitz et al., 1995; Papadimitriou et al., 2007, 2009). Nutrient demand by ice algae can exceed resupply and result in depletion of the major nutrients nitrate, silicic acid, and phosphate. In contrast, heterotrophic processes, as well as mechanical and osmotic destruction of cells, can drive remineralisation, resulting in an increase of dissolved inorganic nutrient concentrations when compared to the water mass from which the sea ice has formed (Thomas and Dieckmann, 2010).

Recent observations showed that East Antarctic pack ice is mostly characterised by bottom communities colonising the lowermost centimetres of ice floes at the ice-water interface (Grose and McMinn, 2003; McMinn et al., 2007; Becquevort et al., 2009). In contrast to other regions of the Southern Ocean, East Antarctica shows a relatively narrow latitudinal extent and a highly dynamic pack ice zone, that in some regions expands only 300 km from the coast at maximum annual ice extent (Worby et al., 1998; Massom et al., submitted). The East Antarctic pack ice season is shorter than that in the big embayments (Weddell and Ross seas), with a rapid ice breakup in November/December, and shows relatively low snow accumulation, which combined may result in a smaller likelihood for the development of surface communities. Surface communities are characteristic of older sea ice that has been subject to surface melt and refreezing and/or surface-flooding due to snow-loading (Fritsen et al., 1994; Kattner et al., 2004; Ackley et al., 2008).

The aim of the present study was to investigate the relationships between physical, biogeochemical, and ecological parameters in East Antarctic sea ice and describe its characteristics during the winter-spring transition. We report the vertical distribution of physical parameters, macronutrients, chlorophyll *a*, particulate organic carbon, and particulate nitrogen from the main biological sampling sites of the Sea Ice Physics and Ecosystem eXperiment (SIPEX) (Worby et al., 2011). In addition, we present data on ice algal abundance and biomass from bottom sea ice communities. This provides a background and basis for companion papers on sea ice meiofauna abundance and biomass (Kramer et al., 2011) and sea ice dissolved organic matter (DOM; Norman et al., 2011).

2. Material and methods

During SIPEX we sampled fourteen sea ice floes in September and early October 2007 in the 115-130°E sector off East Antarctica onboard RSV *Aurora Australis* (Fig. 1, for an overview see Worby et al., 2011). Sampled ice floes were several hundred meters to several kilometers in diameter and were all composite floes showing different degrees of deformation (Worby et al., 2011). The immediate surroundings of the main biological sampling sites were free of surface deformation. Snow thickness at the sampling sites was determined prior to ice coring from 5-10 measurements with a ruler within a 1 m^2 area. At each station, five ice cores (A-E) were sampled from the same 1 m^2 area using a Kovacs Mark II ice corer (0.09 m internal diameter) powered with an electric drill. Sea ice thickness and freeboard measurements (n=5) were taken from the resulting ice core holes.

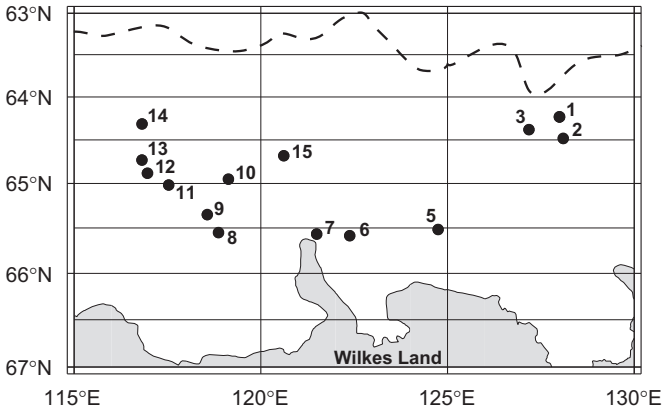

Fig. 1. Locations of ice stations sampled during SIPEX. Dashed line indicates the approximate 75% ice concentration contour line for the 20th of September 2007.

Ice core A was sealed in clean plastic tubing after retrieval, immediately transported to the ship's freezer lab (−24 °C), and used for analysis of ice texture and stable oxygen isotopic composition. Ice texture was determined by thin-section analysis using cross-polarised light (e.g. Lange, 1988). Based on crystal size and orientation, we distinguished three stratigraphic units: granular, columnar, and mixed/intermediate granular/columnar ice (Eicken and Lange, 1989). The remaining core material was cut into sections according to the stratigraphic information. These samples were melted in sealed plastic containers at room temperature and subsamples were stored in sealed glass vials for stable oxygen isotope ($\delta^{18}O$) analysis with a VG Isogas SIRA mass spectrometer. The oxygen isotope ratios are expressed relative to the Vienna Standard Mean Oceanic Water (V-SMOW) standard, and the standard deviation for repeated measurements of laboratory reference water samples was less than 0.07‰. Based on the isotopic characteristics, ice sections with a granular stratigraphy were classified either as granular ice ($\delta^{18}O > 0‰$) or snow-ice ($\delta^{18}O < 0‰$) (cf. Lange et al., 1990). Hence, we distinguished four ice types: snow ice, granular ice, mixed granular/columnar (g/c), and columnar ice.

Sea ice temperatures were measured with a Testotherm720 thermometer (accuracy ± 0.2 °C) from Core B immediately after ice core retrieval from small holes drilled in the core at 0.10 m intervals. Thereafter we sectioned the core in 0.05 to 0.15 m sections using a stainless steel saw. Ice core sections were placed in Milli-Q water washed polyethylene (PE) containers and melted at 4 °C in the dark within 24 to 36 hours after sampling. Ice bulk salinity was determined on the melted samples with a WTW-Tetraconn 325 conductivity meter. Subsamples of known volume were subsequently filtered onto Whatman GF/F filters and stored frozen (−80 °C) until extraction with methanol for 24 hours at 4 °C in the dark and determination of chlorophyll *a* (Chl *a*) concentration with a Turner Designs 10AU fluorometer according to Holm-Hansen et al. (1965). Ice core C was also cut on the ice into 0.05 to 0.10 m sections which were placed in acid-washed PE containers and melted in the dark at 4 °C. Melted segments of core C were