

Physical and bacterial controls on inorganic nutrients and dissolved organic carbon during a sea ice growth and decay experiment



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ARTICLE INFO

Article history:

Received 12 May 2014

Received in revised form 19 September 2014

Accepted 26 September 2014

Available online 5 October 2014

Keywords:

Sea ice

Brine dynamics

Bacterial activity

Inorganic nutrients

Dissolved organic carbon

ABSTRACT

We investigated how physical incorporation, brine dynamics and bacterial activity regulate the distribution of inorganic nutrients and dissolved organic carbon (DOC) in artificial sea ice during a 19-day experiment that included periods of both ice growth and decay. The experiment was performed using two series of mesocosms: the first consisted of seawater and the second consisted of seawater enriched with humic-rich river water. We grew ice by freezing the water at an air temperature of $-14\text{ }^{\circ}\text{C}$ for 14 days after which ice decay was induced by increasing the air temperature to $-1\text{ }^{\circ}\text{C}$. Using the ice temperatures and bulk ice salinities, we derived the brine volume fractions, brine salinities and Rayleigh numbers. The temporal evolution of these physical parameters indicates that there was two main stages in the brine dynamics: bottom convection during ice growth, and brine stratification during ice decay. The major findings are: (1) the incorporation of dissolved compounds (nitrate, nitrite, ammonium, phosphate, silicate, and DOC) into the sea ice was not conservative (relative to salinity) during ice growth. Brine convection clearly influenced the incorporation of the dissolved compounds, since the non-conservative behavior of the dissolved compounds was particularly pronounced in the absence of brine convection. (2) Bacterial activity further regulated nutrient availability in the ice: ammonium and nitrite accumulated as a result of remineralization processes, although bacterial production was too low to induce major changes in DOC concentrations. (3) Different forms of DOC have different properties and hence incorporation efficiencies. In particular, the terrestrially-derived DOC from the river water was less efficiently incorporated into sea ice than the DOC in the seawater. Therefore the main factors regulating the distribution of the dissolved compounds within sea ice are clearly a complex interaction of brine dynamics, biological activity and in the case of dissolved organic matter, the physico-chemical properties of the dissolved constituents themselves.

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1. Introduction

Sea ice is formed from the freezing of seawater, and therefore the dissolved inorganic and organic nutrient concentrations in sea ice depend on those of the parent water (Petrich and Eicken, 2010; Weeks, 2010). Most of these compounds are concentrated in the brine inclusions, as they are not incorporated within the matrix of pure ice crystals (Weeks, 2010).

The two principal regions of sea ice production, the Arctic and Southern Oceans, differ widely in the concentrations of nutrients and dissolved organic matter (DOM) present in the surface waters from which sea ice is formed. The waters of the Arctic Ocean have comparatively lower nutrient concentrations (e.g., nitrate and phosphate), except the Pacific water inflow, but higher input of riverine particulates and DOM, as well as silicate (Dittmar et al., 2001; Wheeler et al., 1997). In contrast, the Southern Ocean generally has high inorganic nutrient concentrations (Gleitz et al., 1994), whereas DOM is of oceanic origin and at comparatively low concentrations (Hansell et al., 2009). A consequence of this fundamental difference is that Arctic sea ice can be expected to have a higher DOM content

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than ice produced in the Southern Ocean (Stedmon et al., 2007, 2011), and as such may promote greater bacterial production, leading to higher pCO₂ concentrations in the brines (Geilfus et al., 2012). In turn, this could result in the air–ice CO₂ exchange in the Arctic and Antarctic being fundamentally different, although this hypothesis is yet to be verified.

In addition to bacterial production, other mechanisms may regulate differences in the dynamics of dissolved constituents (nutrients and DOM) in sea ice. Previous studies have indicated selective incorporation of DOM during sea ice formation (Aslam et al., 2012; Giannelli et al., 2001; Müller et al., 2013), raising the question as to whether or not there is a segregation among dissolved compounds during the incorporation phase, and in particular, whether the incorporation is comparable between Arctic and Antarctic sea ice because of the different compositions of DOM in the parent waters. Various physical mechanisms induce changes in the nutrient pools in ice after the initial incorporation. Among these, brine convection is the most important during ice growth (Notz and Worster, 2009; Vancoppenolle et al., 2010). Flushing (Eicken et al., 2004) and flooding (Fritsen et al., 2013, 2001) may also be significant, but their impact remains difficult to assess (e.g., Pringle and Ingham, 2009).

The aim of the present study was to better understand the differences in sea ice biogeochemistry and bacterial activity, related to additional allochthonous riverine DOC during a whole cycle of sea ice formation, consolidation and subsequent decay. In our mesocosm experiment, we reproduced ice growth and ice decay on two series of mesocosms: One consisting of North Sea seawater and the other consisting of North Sea seawater amended with 10% natural DOM-rich river water. The latter was designed to simulate the dissolved organic matter conditions that occur in Arctic shelf waters where much ice formation occurs. We hypothesized that the dissolved compounds of the parent waters would be predominantly incorporated conservatively into the ice (relative to salinity), and would then deviate from the conservative behavior due to bacterial activity, given that there was no autotrophic component in the experiment. We also expected that a deviation from the conservative behavior would be higher in the river-water amended mesocosms because the higher organic matter content would stimulate bacterial activity, if the riverine DOM is bioavailable.

2. Material and methods

2.1. Experimental setting and sampling routine

The 19-day experiment took place in the Hamburg Ship Model Basin (www.hsva.de). We used 21 polyethylene experimental mesocosms with a volume of 1.2 m³ each. Eleven of the mesocosms were filled with 1000 L of seawater from the North Sea (referred hereafter as SW), and the remaining 10 were filled with 900 L of seawater from the North Sea and 100 L of river water (referred hereafter as SWR). The North Sea water was collected on 24 May 2012 (54°7′N 7°54′E near Helgoland) and transported to Hamburg where the mesocosms were filled within 24 h of collection. The river water was collected during spring freshet in mid-May 2012 from River Kiiminkijoki (NW Finland), just before it enters the estuary, stored one week in the cold (4 °C), filtered through 0.2 μm using Durapore 10 inch (Millipore) and Clariflow G 10 inch (Parker) cartridge filters and added to the mesocosms 2 days afterwards.

As there was a slight temperature gradient in the main test basin, the mesocosms were distributed only partially randomly. As shown in Fig. 1, the units were first randomly positioned into rows, but the respective manipulations (SW and SWR) were located at the same or adjacent row. The unit SW11 was reserved for instrumentation and it was excluded from all subsequent calculations and analysis due to possible contamination from instrumentation that was placed inside it.

The salinities of the SWR mesocosms were adjusted to the SW values by adding aquarium standard salt (Tropic Marin®). Nitrate (NO₃⁻) and phosphate (PO₄³⁻) were also adjusted to concentrations that did not limit bacterial growth in both series of mesocosms. The addition of river water caused large difference in dissolved silicate (Si(OH)₄) and DOC concentrations between the SW and SWR mesocosms, while nitrite (NO₂⁻) and ammonium (NH₄⁺) concentrations were similar (Table 1). Indeed, the differences in the mean starting conditions between SW and SWR were less than 10% (which was about the range of standard deviation within each series of mesocosms), except for Si(OH)₄, DOC, and bacterial production derived from leucine (BP Leu) and thymidine (BP TdR) incorporation, which were about 4, 1.7, 1.3 and 1.2 times higher in SWR, respectively.

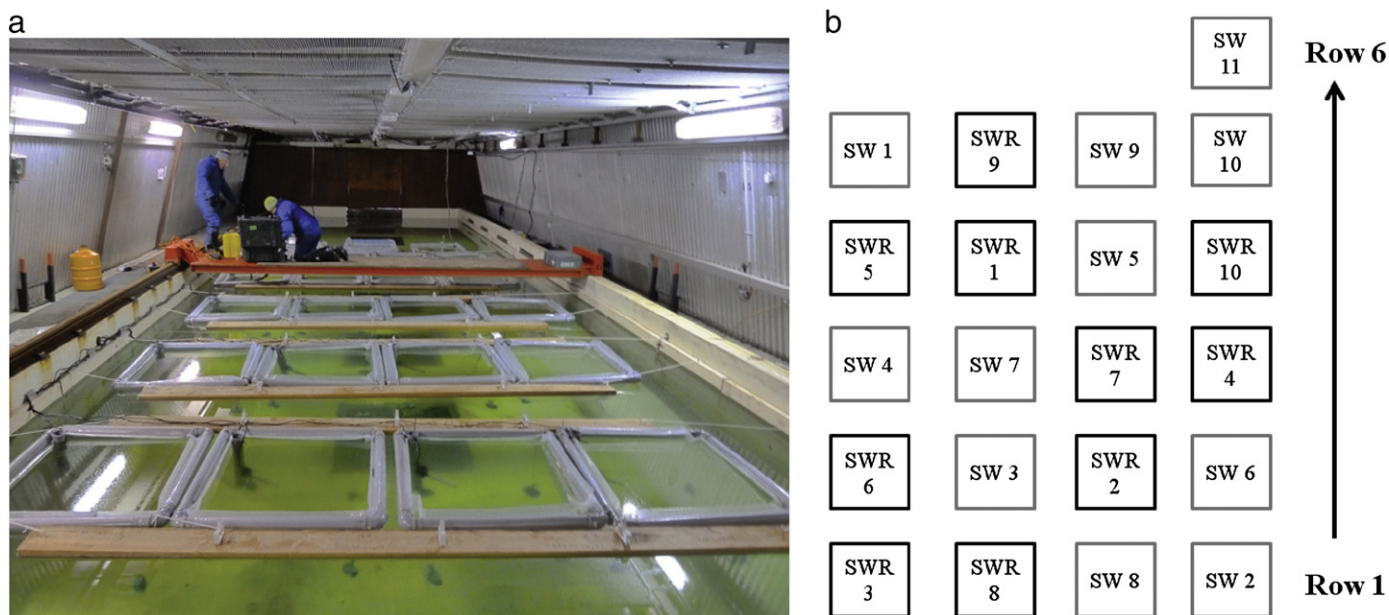


Fig. 1. (a) The experimental basin at HSVA, (b) the spatial distribution of the SW and SWR mesocosms. Note that SW11, although sampled, was not included into the data set, because it was reserved for continuous physical measurements.

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