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# Influence of freshwater inflow on the inorganic nutrient and dissolved organic matter within coastal sea ice and underlying waters in the Gulf of Finland (Baltic Sea)

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## Abstract

A study was conducted to measure the biogeochemical characteristics of freshwater plumes underlying Baltic Sea land-fast ice, and the overlying sea ice. A 40-km long transect was conducted in the northern Baltic Sea in March 2003, following a freshwater plume from its source into the fully mixed open-sea area. The spreading of river outflow below the ice resulted in a well-stratified low-salinity surface layer further out than normally occurs in the open-water period. The freshwaters were high in dissolved organic matter (DOC, DON and CDOM), and inorganic nutrients (ammonium, nitrate and silicate), although the levels of phosphate were low. In general these parameters changed concurrently with salinity in such a way that mixing was conservative. The characteristics of the ice varied from the freshwater source to the open water, with increasing salinity and brine volumes (porosity) occurring in the more open-sea stations. Coinciding with the changes in ice properties there was an increase in sea-ice algal growth in the more marine stations along the transect. Biological activity in the ice was largely confined to bottom ice assemblages. In contrast to the conditions in the underlying water, no relationship between salinity, inorganic nutrients and organic matter was observed in the ice. In particular ammonium, phosphate, DOC and DON were present in excess of those levels predicted from the dilution curves, indicating the presence of considerable DOM production by ice assemblages, inorganic nutrient uptake and remineralization within the ice.

*Keywords:* coastal oceanography; sea ice; river plumes; estuarine chemistry; nutrients (mineral); dissolved organic matter; Baltic Sea

## 1. Introduction

The transfer of inorganic nutrients and dissolved organic matter (DOM) from terrestrial systems to coastal waters is a fundamental issue governing marine systems and the ultimate source of productivity in these waters (Jickells, 1998). Carbon, nitrogen and phosphorus are introduced in both inorganic and organic forms, the proportions of which are highly dependent on the nature of the terrestrial system through which the supplying watercourse flows (Kortelainen and Saukkonen, 1998; Hansell and Carlson, 2002; Mulholland, 2003). However, it is not only the resulting nutrient status that is of consequence, since DOM is also the major light-absorbing agent in coastal waters, both of visible and ultra-violet radiation (Højerslev and Aas,

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2001). The transparency of coastal areas is thus modified and controlled by DOM and hence, the optical properties of DOM have major implications for ecosystem functioning (Stedmon and Markager, 2003).

There has been considerable interest in nutrient loading of the Baltic Sea and the magnitude of inputs in response to land usage and seasonal river discharge dynamics (Rahm et al., 1996; Conley et al., 2000; Wulff et al., 2001; Humborg et al., 2003). There is convincing evidence that riverine nutrient loading comprises the major fraction of the total inputs into the Baltic Sea (Grimvall and Stålnacke, 2001). Riverine organic matter loading has been much less the focus of attention, although rivers carry a substantial organic load (Petterson et al., 1997; Granskog et al., 2005a) and the resulting dissolved organic carbon (DOC) concentrations are 3–4 times higher in the Baltic Sea than in the oceans (Hagström et al., 2001). Another feature that has not received much attention has been the winter–spring situation in which rivers discharge into landfast ice-covered regions (Granskog et al., 2005a). Freshwater plumes extend further into marine systems under the ice than as normally occurs during in ice-free periods of the year, because the ice forms an effective barrier against wind mixing (Alasaarela and Myllymaa, 1978; Ingram, 1981; Ingram and Larouche, 1987; Granskog et al., 2005a). Furthermore the greatest discharges usually occur in spring when river and terrestrial systems thaw; e.g. in Gulf of Finland this usually occurs in April–May (Wulff et al., 2001). At this time the coastal Baltic Sea is usually ice-covered, and therefore the conditions are favourable for development of extensive under-ice plumes that extend far into the sea (Granskog et al., 2005a). The nutrient concentrations in river waters tend to be highest in winter and spring (Humborg et al., 2003).

Although not a universal phenomenon, mixing with coastal waters of matter originated from freshwaters to is somewhat conservative, with the concentrations of nutrients and organic matter decreasing/increasing in a linear relationship with increasing salinity (Ferrari and Dowell, 1998; Müller-Karulis, 1999; Dittmar and Kattner, 2003; Humborg et al., 2003). Ice cover-induced freshwater plumes may change these dynamics, and so in a particular region there may be distinct phases in mixing dynamics due to the ice. This in turn may structure the seasonal biological dynamics under the ice, in particular the start of the spring phytoplankton bloom. In regions with extensive freshwater lenses the nature of the ice and nutrient and organic matter loading within the ice may be very different from that of ice formed where there is little or no river input.

In particular the high nutrient and DOM loading of stabilized freshwater (or fresher) layers under the ice may have significant stimulating effects on the development of bottom-ice microbial assemblages, or blooms of algae in waters at the ice–water interface. Conversely, if the freshwater source is rich in humic substances, coloured or nutrient-poor, the light fields or nutrient availability in the water may be altered to such an extent that development of algal blooms may be curtailed (Alasaarela and Myllymaa, 1978; Dittmar and Kattner, 2003; Granskog et al., 2005a).

The purpose here was to investigate the landfast sea ice and underlying waters in a region where freshwater discharges into the ice-covered Baltic Sea. Although investigations on river plumes have been performed in the Baltic Sea, they have primarily been focused on the open-water period only (Müller-Karulis, 1999; Wasmund et al., 1999; Humborg et al., 2003; Põder et al., 2003). However, one earlier study done in the late 1960s in the same area also included also winter samplings from under-ice water (Niemi, 1973). In particular the present study aimed at investigating the distribution of salinity, inorganic nutrients and organic matter along a transect from a freshwater source to a region of open sea where the water column was fully mixed. The study was conducted in spring when algal blooms in the ice and/or surface waters could be anticipated, thus in general terms the nutrient status of ice and water was also related to algal biomass.

## 2. Material and methods

Sampling was conducted on March 2–3, 2003 on landfast sea ice in the vicinity of the Tvärminne Zoological Station (TZS, University of Helsinki), located in the archipelago at the entrance to the Gulf of Finland, the Baltic Sea (Fig. 1). An inshore–offshore, 40-km, transect with nine stations (about 2–8 km apart) was sampled, from the inner parts of the fjordlike Pojoviken Bay (hereafter Pojo Bay) to the outer archipelago, close to the land-fast ice edge in the Gulf of Finland (Fig. 1). This area has been extensively studied (e.g. Hällfors et al., 1983), although the ice-covered season has not been the focus of as much attention as the open-water period. Station 0 was located at the outlet of the River Svartån, the major freshwater source to the bay with a mean discharge of 17.8 $m^3 s^{-1}$ (1961–1990), and Station 2 on the sill at the entrance to Pojo Bay. The stations were distributed in different zones of the coastal area (Table 1).

The ice thickness and snow depths were recorded at each station. While at Station 0 only water samples were collected. At each station 4 ice cores were taken within an area of about 0.5 $m^2$ by using a MARK II corer (9-cm internal diameter; Kovacs Enterprises, Lebanon NH, USA). After retrieval the cores were immediately divided as follows; two 5 cm sections were cut from the bottom, the remaining lengths were divided into 10-cm sections, with the exception of the topmost sections the lengths of which were dependent on the length remaining after all full 10-cm sections had been cut. One core