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Development of under-ice stratification in Himmerfjärden bay, North-Western Baltic proper, and their effect on the phytoplankton spring bloom

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ABSTRACT

Seasonal sea ice cover reduces wind-driven mixing and allows for under-ice stratification to develop. These under-ice plumes are a common phenomenon in the seasonal sea ice zone. They stabilize stratification and concentrate terrestrial runoff in the top layer, transporting it further offshore than during ice-free seasons. In this study, the effect of sea ice on spring stratification is investigated in Himmerfjärden bay in the NW Baltic Sea. Distinct under-ice plumes were detected during long ice seasons. The preconditions for the development of the under-ice plumes are described as well as the typical spatial and temporal dimensions of the resulting stratification patterns. Furthermore, the effect of the under-ice plume on the timing of the onset and the maximum of the phytoplankton spring bloom were investigated, in terms of chlorophyll-a (Chl-a) concentrations. At the head of the bay, bloom onset was delayed on average by 18 days in the event of an under-ice plume. However, neither the maximum concentration of Chl-a nor the timing of the Chl-a maximum were affected, implying that the growth period was shorter with a higher daily productivity. During this period from spring bloom onset to maximum Chl-a, the diatom biomass was higher and *Mesodinium rubrum* biomass was lower in years with under-ice plumes compared to years without under-ice plumes. Our results thus suggest that the projected shorter ice seasons in the future will reduce the probability of under-ice plume development, creating more dynamic spring bloom conditions. These dynamic conditions and the earlier onset of the spring bloom seem to favor the *M. rubrum* rather than diatoms.

1. Introduction

The Baltic Sea is a shallow intracontinental sea with a limited water exchange with the North Sea (e.g. Lehmann et al., 2002; Leppäranta and Myrberg, 2009). The water mass of the Baltic Sea is brackish, a mixture of saline seawater originating from the North Sea and freshwater from terrestrial runoff. Another characteristic of the Baltic Sea is the seasonal sea ice cover which varies substantially in duration, timing and extent (Leppäranta and Myrberg, 2009) depending on the large-scale atmospheric circulation and the following weather conditions during winter (Uotila et al., 2015). Ice cover hinders the wind-driven mixing, affects the heat exchange between the sea and the atmosphere, and reduces the sunlight penetrating into the sea - especially when snow has fallen onto the ice (Warren, 1982; Leppäranta, 2003; Uusikivi et al., 2006; Granskog et al., 2006; Leppäranta and Myrberg, 2009; Vihma and Haapala, 2009; Thomas and Dieckmann, 2010; Lei et al., 2011; Merkouriadi and Leppäranta, 2015). In the landfast ice zone, wind-driven mixing is notably reduced, providing conditions for under-ice stratification patterns to develop. Due to the high buoyancy of freshwater from terrestrial runoff, distinct freshwater plumes can form just below the ice cover, the so-called under-ice plumes (Granskog et al., 2005). These under-ice plumes are a common coastal phenomenon in water basins with seasonal sea ice cover and inflow from rivers and streams (Granskog et al., 2005; Merkouriadi and Leppäranta, 2014, 2015). The development and physical characteristics of under-ice plumes are fairly well understood (Granskog et al., 2005; Merkouriadi and Leppäranta, 2015). However, there are only few studies about their effects on coastal ecology, and specifically on the development of the phytoplankton spring bloom (Eilola and Stigebrandt, 1998; Spilling, 2007; Kremp et al., 2008).

The length of the ice season in the Baltic Sea varies usually between 4 and 7 months. Despite the high natural variability of the ice seasons, time series studies show a decrease in both the maximum ice extent and the length of the ice season (Jevrejeva et al., 2004; Vihma and Haapala, 2009; Haapala et al., 2015). Merkouriadi and Leppäranta (2014) showed a significant decrease of the ice season length, by 30 days

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during the last century in the western Gulf of Finland. Warming climate shortens the ice seasons in the Baltic Sea, therefore reducing the probability of under-ice plumes. As the ice conditions are undergoing such dramatic changes, it is important to understand the current role of sea ice for the Baltic Sea ecosystem. In this study, we investigate the preconditions for under-ice plume development in a Baltic Sea coastal bay, as well as the spatial and temporal dimensions of the stratification pattern. The freshwater runoff transports high contents of humic substances and suspended matter increasing concentrations of coloured dissolved organic matter (CDOM) and suspended particulate matter (SPM) in Baltic Sea coastal waters (Kratzer and Tett, 2009; Harvey et al., 2015; Kari et al., 2016). The under-ice plume enhances the horizontal transport of terrestrial runoff, including nutrients, CDOM, and other substances, further towards the open sea, due to reduced mixing (Granskog et al., 2005). Here, we develop a new empirical model to estimate CDOM absorption from surface salinity, in order to discuss the role of CDOM for the timing of the spring bloom onset during under-ice plumes.

Phytoplankton spring blooms are annual phenomena in the Baltic Sea (e.g. Höglander et al., 2004; Fleming and Kaitala, 2006; Kremp et al., 2008; Kahru et al., 2016). The onset, intensity, and duration of the blooms depend on the light and nutrient availability – factors interacting with the water column stratification (e.g. Kahru and Nômmann, 1990; Wasmund et al., 1998; Kratzer et al., 2003; Höglander et al., 2004; Fleming and Kaitala, 2006; Winder et al., 2012; Klais et al., 2013). During winter, nutrients are abundant in Baltic Sea coastal waters and thus the onset of the phytoplankton spring bloom is controlled by the light availability and the water column stratification (Wasmund et al., 1998; Fleming and Kaitala, 2006; Klais et al., 2013). The light availability under snow-covered ice is insufficient for primary production, but changes drastically when the snow melts and more light can penetrate through the ice (e.g. Leppäranta, 2003). As soon as the light availability is sufficient within the mixing depth, the spring bloom is expected to initiate (Kahru and Nômmann, 1990; Eilola and Stigebrandt, 1998; Wasmund et al., 1998). The significance and role of the under-ice plumes on the onset and composition of the phytoplankton spring bloom is yet to be studied. Under-ice plumes stabilize the stratification, offering a calm, but cold, environment for the phytoplankton within the euphotic zone.

During the spring bloom, the phytoplankton species of our study area (coastal north-western Baltic proper) mainly belong to the diatom and dinoflagellate groups, but the photosynthetic ciliate *Mesodinium rubrum* can also be abundant (Fleming and Kaitala, 2006; Spilling, 2007; Klais et al., 2011). Kremp et al. (2008) suggest that long-term climatic trends may affect the phytoplankton composition more than the actual nutrient conditions at the time of bloom onset. Phytoplankton species are generally very sensitive to hydrographic conditions, which in turn are often governed by the climate. There are indications that the phytoplankton composition during the spring bloom may shift from diatom to dinoflagellate dominance (Wasmund and Uhlig, 2003; Kremp et al., 2008; Klais et al., 2011). A possible shift in the species composition and dominance can have ecosystem-wide consequences by affecting the nutrient cycling in pelagic ecosystem (Kremp et al., 2008). In this study, we compare spring seasons with and without under-ice plumes. The aim is to describe and discuss the impact of ice cover on the stratification in a bay with relatively low freshwater input and to investigate if under-ice plumes influence the timing and phytoplankton composition of the spring bloom in the Baltic Sea.

2. Materials and methods

The study site, Himmerfjärden, is a frequently monitored bay, located in the southern Stockholm archipelago in the north-western Baltic proper (Fig. 1). Himmerfjärden is about 30 km long and rather shallow with a mean depth of about 17 m. The bay is affected by the effluents of a sewage treatment plant serving southern Stockholm, with the outlet located close to station H5. The water circulation within the bay is estuarine with a relatively low freshwater input from streams and from Lake Mälaren (Engqvist and Omstedt, 1992; Engqvist and Stenström, 2009). There are also several sills, restricting the water exchange with the open Baltic Sea. The surface water (0–10 m) retention time is about 20 days based on a mass-balance model for salt (Khalili, 2007; Håkanson and Stenström-Khalili, 2010), for the deep water the retention time is up to 140 days (Engqvist, 1996). The monitoring stations H6-H2 (Fig. 1), located within Himmerfjärden, are used here for studying the extent and effects of the under-ice plume and station B1, located outside Himmerfjärden, is used as a reference station.

Meteorological and hydrological data were provided by the Swedish Meteorological and Hydrological Institute (SMHI) open data portal. These included daily air temperature, precipitation, and wind speed from Landsort A and runoff at the Södertälje lock (see map, Fig. 1). These meteorological and hydrological quantities were studied from 1st January to 30th April in 1997–2015. Modeled accumulated global irradiance ($W\,h\,m^{-2}$) data are available since January 1999, provided by the STRÅNG model system and validated by SMHI (STRÅNG, 2017). We used the daily data for the time period 1999–2015, focusing on the spring season from 1st January to 30th April. The irradiance data was retrieved for station H4 to represent Himmerfjärden bay. The spatial resolution of the STRÅNG model was about 22 × 22 km in 1999–2006 and 11 km × 11 km in 2007–2015.

Sea ice data were retrieved from two data sources: ice charts from the Finnish Meteorological Institute (FMI) and Baltic Sea ice codes from the SMHI. The ice charts are compiled daily by ice analysts, based on multiple data sources: remote sensing data, model results, and in situ measurements. The SMHI Ice service provided the 'Baltic Sea Ice codes', which are also based on ice charts, for the period 1997 to 2015. This ice code is a four-digit code, describing the ice conditions, where the first digit represents the ice concentration, i.e. ice cover area in percent. The other digits describe the stage of ice development, topography of ice and navigation conditions in ice along the fairway. Here, we used the first digit for the fairway from Södertälje at the head of Himmerfjärden to Landsort in the open sea (see map, Fig. 1). The days with ice concentration greater than zero were summed up in order to calculate the number of ice days. The Baltic Sea ice code data was used in this study to determine the ice conditions at the monitoring stations.

Most water quality data were obtained from the research and environmental control program of the Himmerfjärden sewage treatment plant (H6-H2) and the Swedish national marine monitoring program (station B1). Here, the time period from January to May each year 1997–2015 was investigated with a focus on Conductivity-Temperature-Depth (CTD) -profiler data, chlorophyll-a concentration (Chl-a), and Secchi depth. These parameters are measured once a month from November to February, every second week in early March, and weekly from the end of March to mid-May at stations H6-H3 and B1. CTD-profiling data were used to evaluate the stratification conditions. Water density (unit: $kg\,m^{-3}$) was calculated from the conservative temperature and absolute salinity values (unit: $g\,kg^{-1}$, ppt, parts per thousand, in the following), based on the Thermodynamic Equation of Seawater 2010 (TEOS-10) (McDougall and Barker, 2011). Here, sigma-t values were used, i.e. 1000 $kg\,m^{-3}$ was subtracted from the water density. The vertical sigma-t profiles were interpolated along a transect in order to visualize the spatial stratification patterns and identify the under-ice plumes. The under-ice plume is a distinct layer of less dense water, reaching out from the head of the bay. Chl-a was sampled as vertically integrated samples of the upper 0–14 m at H6-H3 and 0–20 m at B1 using a plastic hose (2.5 cm inner diameter) equipped with a weight at the lower end and a valve at the upper end. Water from the hose was mixed in a bucket and 1–2 l filtered on 47 mm GF/F glass fiber filters and stored frozen until extraction with acetone and absorbance measurement on a Hitachi U-2000 spectrophotometer (Swedish standard method SS028146). During ice cover, the Secchi depth was measured on board ship in the channel that was broken by the ship into