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Seasonality of vertical flux and sinking particle characteristics in an ice-free high arctic fjord—Different from subarctic fjords?

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ABSTRACT

The arctic Adventfjorden (78°N, 15°E, Svalbard) used to be seasonally ice-covered but has mostly been ice-free since 2007. We used this ice-free arctic fjord as a model area to investigate (1) how the vertical flux of biomass (chlorophyll *a* and particulate organic carbon, POC) follows the seasonality of suspended material, (2) how sinking particle characteristics change seasonally and affect the vertical flux, and (3) if the vertical flux in the ice-free arctic fjord with glacial runoff resembles the flux in subarctic ice-free fjords. During seven field investigations (December 2011–September 2012), suspended biomass was determined (5, 15, 25, and 60 m), and short-term sediment traps were deployed (20, 30, 40, and 60 m), partly modified with gel-filled jars to study the size and frequency distribution of sinking particles. During winter, resuspension from the seafloor resulted in large, detrital sinking particles. Intense sedimentation of fresh biomass occurred during the spring bloom. The highest POC flux was found during autumn (770–1530 mg POC m^{-2} d^{-1}), associated with sediment-loaded glacial runoff and high pteropod abundances. The vertical biomass flux in the ice-free arctic Adventfjorden thus resembled that in subarctic fjords during winter and spring, but a higher POC sedimentation was observed during autumn.

1. Introduction

Fjords have recently been identified to sequester a high amount of organic carbon (Smith et al., 2015), but global warming affects these high latitude marine ecosystems. Hitherto, seasonally ice-covered fjords may turn into year-round ice-free fjords, and it is largely unknown how ecological processes and glacial runoff may change and impact the downward flux of particulate organic carbon (POC) in these fjords.

The POC flux at high latitudes is generally characterized by a strong seasonality. Nutrient availability, phytoplankton concentration, and zooplankton biomass oscillate throughout the year (Leu et al., 2011; Rat'kova and Wassmann, 2002; Węsławski et al., 1991), resulting in a variable abundance of the most prominent vehicles of the vertical POC flux, i.e., algal aggregates, fecal pellets, and marine snow (Turner, 2002, 2015). Ice algae, which tend to form blooms in seasonally ice-covered seas and fjords during spring (Ji et al., 2013; Leu et al., 2011), are utilized by zooplankton (Søreide et al., 2010; Weydmann et al., 2013), but they also contribute to the vertical export, when the algal cells are released into the water column during melting and ice break-up (Arrigo, 2014; Tremblay et al., 1989). Phytoplankton spring blooms, dominated by diatoms, occur in April–May in ice-free waters or subsequent to ice break-up in seasonally ice-covered regions (Eilertsen and Frantzen, 2007; Leu et al., 2011) and may cause major biomass sedimentation events (Thompson et al., 2008; Wassmann et al., 1991). Senescent diatom cells and diatom resting stages have high sinking velocities (Rynearson et al., 2013; Smayda, 1971), and some taxa release sticky exopolymeric substances, which contribute to the formation of algal aggregates (Kiørboe et al., 1994; Thornton, 2002) and marine snow, i.e., conglomerates (>0.5 mm) of diverse composition and structure (Alldredge and Silver, 1988; Lampitt, 2001). These coagulation processes increase the particle size, which, in turn, can enhance the sinking velocity and the vertical POC export. However, the phytoplankton bloom in the Barents Sea as well as in fjords in northern Norway and around Svalbard may also be dominated by the prymnesiophyte *Phaeocystis pouchetii* (Degerlund and Eilertsen, 2010). This small flagellate has a single cell stage and a mucous colonial stage, but it tends not to promote aggregate formation (Passow and Wassmann, 1994), and its contribution to the vertical carbon flux below 60 m is low, despite sometimes high cell abundances in the water column (Reigstad and Wassmann, 2007; Reigstad et al., 2000).

Irrespective of the phytoplankton composition, strong vertical carbon flux can only occur when the top-down regulation is weak, i.e., when sinking biomass is not substantially grazed by zooplankton (Reigstad et al., 2000). In this scenario, large sinking particles may be

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less frequently fragmented into small, slowly sinking material by sloppy feeding (Noji et al., 1991; Svensen et al., 2012), which results in an higher biomass flux. Conversely, weak top-down regulation also reduces the re-packaging of small particles into fast-sinking zooplankton fecal pellets (Turner, 2002, 2015; Wexels Riser et al., 2008), contributing to a weak vertical biomass flux.

Apart from the biological processes, the surrounding environment, such as, e.g., terrestrial runoff, impacts the vertical carbon flux in fjords. Glacial runoff entrains lithogenic material with a high specific weight. When sinking particles "scavenge" this material, the sinking velocity of the organic material increases and results in an enhanced vertical biomass flux (Passow and De La Rocha, 2006).

It is largely unclear how these interacting seasonal processes of the plankton community and the environment will translate into vertical biomass flux in future arctic fjords. To address this question, we conducted a 9-month field study in the arctic Adventfjorden (78°N, 15°E, Fig. 1), western Svalbard. The fjord was previously seasonally ice-covered but has mostly been ice-free since 2007 (www.met.no) and may thus serve as a model area to study the mechanisms of vertical flux in an ice-free but glacially influenced arctic fjord. Our aim was to investigate the following: (1) how the vertical flux of organic matter follows the seasonal pattern of suspended material, (2) how sinking particle characteristics change with season and are linked to the vertical flux, and (3) if the vertical flux in an ice-free arctic fjord with major glacial runoff during autumn differs from the vertical flux in boreal and subarctic ice-free fjords.

2. Materials and methods

2.1. Study site and sampling program

The present study was conducted at station IsA (Isfjorden-Adventfjorden, 78°15.67′N, 15°32.10′E, Fig. 1) at the mouth of the arctic Adventfjorden. Adventfjorden is an approximately 8 km long, 3.5 km wide, and less than 100 m deep side branch of Isfjorden, a large fjord system on the western coast of Svalbard. Neither Isfjorden nor Adventfjorden has a sill at the fjord mouth, and they are therefore exposed to advection from the Atlantic-influenced West Spitsbergen Current. Warmer and more saline water from this current reached the study site (approximately 50 km from the open coast) and allowed year-round ship-based sampling in ice-free waters. Glacial runoff (Advent River, Longyear River, Fig. 1) affected IsA during the summer and autumn, bringing substantial amounts of sediment-loaded melt water (e.g., $9 \times 10^6\ \mathrm{m}^{-3}$ during September, Węsławski et al., 1999).

Field investigations were conducted throughout 9 months, starting December 14, 2011, and ending September 19, 2012. We refer to the winter sampling days in December, mid-January, and late January as Winter I, Winter II, and Winter III (Table 1). Spring sampling days in late April, mid-May, and late May are denoted Spring I, Spring II, and Spring III, and the mid-September sampling is referred to as Autumn I (Table 1).

2.2. Hydrographic, light, and wind data

Hydrographical data included temperature and salinity measurements by a CTD (SD204, SAIV A/S, Bergen, Norway) and subsequent computation of the potential density. The seasonal light cycle at 78°N includes the polar night from mid-November to late January. The sun is below the horizon from early October to early March, and the midnight sun appears between mid-April and late August. Underwater irradiance was quantified using a handheld LI-1000 Data Logger (LI-COR, Nebraska, USA), and the euphotic zone was defined as the layer of >1% surface irradiance. Boat drift due to strong wind events made vertical deployment of the irradiance logger difficult, and an overestimation of the euphotic zone may be assumed. Wind data from Longyearbyen airport (78°14′N, 15°28′E, Fig. 1) are considered to be

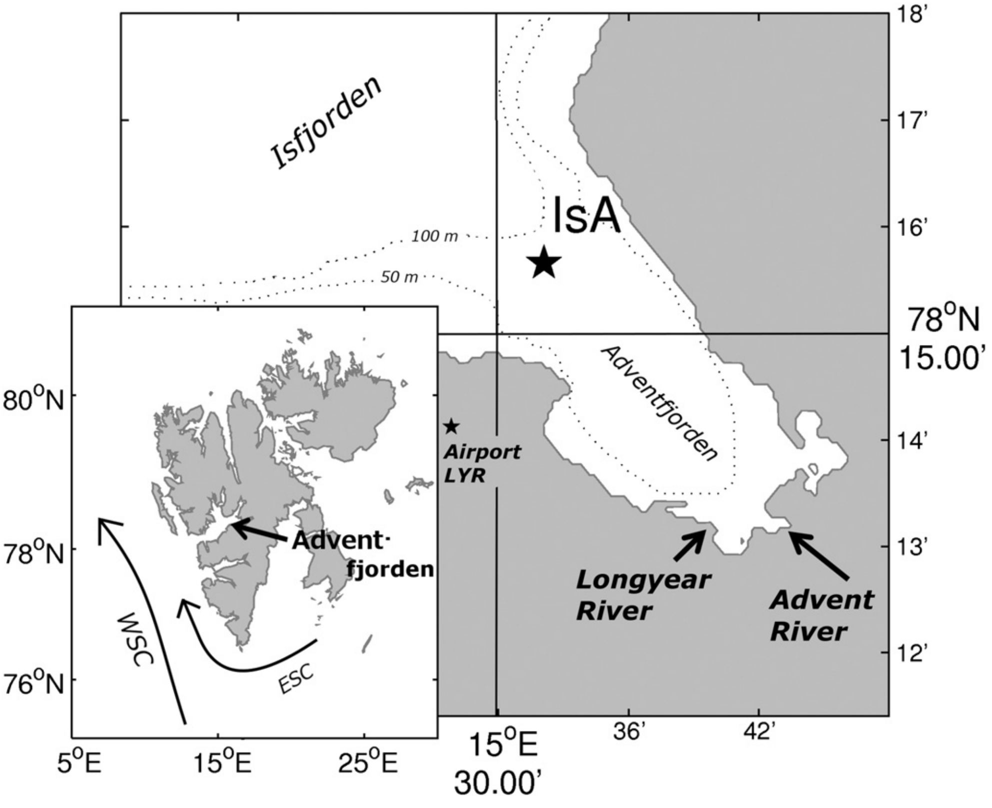

Fig. 1. IsA station was located in the mouth of Adventfjorden, a side branch of the Isfjorden system, western Svalbard (main map, depth contour according to Zajączkowski et al., 2010). Adventfjorden is influenced by the Atlantic-derived, warm West Spitsbergen Current (WSC) and the Arctic-derived, cold East Spitsbergen Current (ESC, small map), as well as glacial runoff from Longyear River and Advent River (during the ice melt period in summer and autumn).