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Physical and ecological processes at a moving ice edge in the Fram Strait as observed with an AUV

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ABSTRACT

Small-scale investigations of physical and biogeochemical parameters have been carried out with an autonomous underwater vehicle (AUV) at a moving ice edge in the Fram Strait. The AUV was equipped with various sensors to study the complex interactions between physical and ecological processes along the ice edge and the associated meltwater front. The AUV covered two cross-front sections of 9 km and recorded high resolution vertical profiles of the physical and biogeochemical properties between 0 and 50 m water depth at a horizontal station spacing of 800–1000 m.

In both physical and biogeochemical terms, the measurements revealed a complex structure of the water column. The distribution of phytoplankton biomass (chlorophyll *a*) and nutrients was highly inhomogeneous. Chlorophyll *a* concentrations of 5 $\mu g\, l^{-1}$ were detected at the frontal interface in a small corridor just 2–4 km wide and only 5 m deep. Nutrients at the surface were depleted, yet, compared to previous studies of this region, were still present in the euphotic zone. Below the euphotic zone, nitrate concentrations of 8 $\mu mol\, l^{-1}$ and oxygen saturation values of 100% resulted in a “dome-like” pattern – suggestive of vertical transport processes. Based on these measurements, three different zones featuring individual biogeochemical characteristics were identified in the cross-front sections. Atmospheric forcing and the presence of the melt water front are assumed to be mainly responsible for the complexity of the water column. Localized vertical transport events seem to have occurred before our investigations. Furthermore, wind driven frontogenesis likely contributed to vertical water movements. All processes had an effect on the biological processes along the observed meltwater front.

1. Introduction

It is well known that ice plays a key role in shaping Polar marine ecological systems and that the Marginal Ice Zone (MIZ) in particular promotes phytoplankton blooms and enhanced biological productivity (e.g. Smith et al., 1985; Perrette et al., 2011). The pronounced stratification, caused by fresh water from melting sea ice, prevents deep mixing, keeping phytoplankton in the euphotic zone (Niebauer and Alexander, 1985; Doney, 2006) and leading to prolonged phytoplankton blooms that are only terminated by nutrient depletion. However, filaments, eddies or other dynamic transport and mixing processes are common features in the water column of MIZs (Engelsen et al., 2002). Atmospheric forcing adds further complexity and the interaction between ocean, ice and atmosphere creates an extremely dynamic environment in both physical and ecological terms (Wassmann and Reigstad, 2011; Cherkasheva et al., 2014). Apart from these regional effects, the world´s Polar ice coverage is rapidly changing due to climate change – with consequences for the ecological system which are only partly understood. Against this background, understanding physical processes in the MIZ and bridging the gap to the associated ecological response is crucial to predict the conditions of the Polar Oceans in the future.

In the Arctic, the Fram Strait is a region that exhibits particularly dynamic interactions between the ocean and sea-ice. The Fram Strait features bathymetric anomalies, such as the Molloy Deep (5607 m, Thiede et al., 1990), and complex hydrography. The hydrographic regime is dominated by the warm, northward flowing West Spitsbergen Current (WSC) in the east (Beszczynska-Möller et al., 2012) and the cold, southward flowing East Greenland Current (EGC) in the western Fram Strait (de Steur et al., 2009). The Fram Strait is also the major route for Arctic sea-ice export. Roughly 10% of the Arctic sea-ice cover leaves the central Arctic via this strait every year (Kwok et al., 2009). Due to the close proximity to the warm WSC, the sea-ice transported by the EGC encounters year-round melting processes sustaining a meltwater front.

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Frontal systems can comprise complex hydrographic structures such as Kelvin-Helmholtz instabilities and geostrophic and ageostrophic circulations. Atmospheric forcing can stimulate front related transport processes. For example, as a result of wind driven ageostrophic secondary circulations (ASC), Thomas and Lee (2005) were able to simulate and detect strong up- and downwelling along frontal systems associated with symmetric instability (SI, Haine and Marshall, 1998; Thomas et al., 2013).

Phytoplankton growth is stimulated by upper water column processes at the MIZ as it is dependent on the availability of sunlight. However, the remoteness of MIZs, harsh environmental conditions and fluctuating dynamics make it difficult to achieve on-site observations in surface waters. "Traditional" shipboard measurements might not necessarily represent true environmental conditions as the presence of a research vessel disturbs the delicate stratification of the upper water column. As a consequence, in order to better understand the interaction between physics and phytoplankton ecology in the MIZ, new technologies need to be applied. Modern instruments such as gliders and autonomous underwater vehicles (AUVs) represent suitable platforms to meet the requirement of conducting high resolution synoptic measurements with minimal disturbance (Lee et al., 2012; Zhang et al., 2013, 2015). Recently, for example, gliders were used to study the MIZ in the Beaufort Sea as part of the Marginal Ice Zone Program of the Office of Naval Research (ONR) (Lee et al., 2012).

In the framework of the project "HAUSGARTEN", the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven, Germany, has conducted year-round investigations on the pelagic-benthic coupling in seasonal ice covered areas of the Fram Strait by means of moored instruments since 1999 (e.g. Bauerfeind et al., 2009). As part of this project AWI ´s AUV "*PAUL*", which is equipped with physical and biogeochemical sensors, has been deployed several times. *PAUL´s* operations are specifically designed to study the near-surface part of the water column. The study presented here focuses on one of *PAUL´s* dives which took place at the periphery of a large ice tongue in the Fram Strait in summer 2013. The vehicle´s deployment particularly focused on investigating physical processes along the ice tongue´s meltwater front in high spatial resolution and to understand the ecological response. The dive was intended to resolve the water column structure of the euphotic zone. Simultaneous measurements of the wind conditions support the interpretation of the AUV data within the context of a meltwater front under atmospheric forcing. To our knowledge this is the first study presenting results from such an environment at high spatial resolution.

2. Methods and data

2.1. AUV "PAUL"

PAUL is based on a type 21 vehicle of the American manufacturer Bluefin Robotics (Quincy, Massachusetts, USA). The torpedo-shaped vehicle is 4.3 m long, weighs approx. 400 kg and has an operational range of 70 km. Considering its intended mission types, namely shallow missions, the original depth rating of 3000 m was limited to 600 m. Since 2009, *PAUL* has regularly operated in the MIZ of the Fram Strait (Wulff et al., 2013). During the 2013 Arctic campaign, *PAUL's* scientific payload consisted of different sensors and a water sample collector (Table 1).

For this particular campaign, the water samples were only used to calibrate the nitrate sensor and to convert the analog signals of the C7-c fluorometer to chlorophyll *a* concentrations (Wulff et al., 2013). To determine nitrate concentrations, 8 ml of each water sample was stored at −20 °C and later measured colorimetrically using a QuAAtro SFA Analyzer (Seal Analytical, Southampton, UK). After the subsample was taken for nitrate analysis, the rest of each sample (~180 ml) was filtered onto Whatman GF/F filters (25 mm diameter, 0.7 μm nominal pore size) to determine chlorophyll *a* concentrations. The filters were stored at −20 °C, until treatment by an ultrasonic device and chlorophyll *a* extraction into 90% acetone. Chlorophyll *a* content of this solution was measured with a calibrated TD-700 Laboratory Fluorometer (Turner Designs, Sunnyvale, California, USA) (Edler, 1979; Evans et al., 1987).

Table 1
Scientific instruments of *PAUL* in the 2013 Arctic campaign.

Parameter	Type of device	Manufacturer
Conductivity, Temperature, Pressure	SBE 49 FastCAT	Sea Bird Electronics (Bellevue, Washington, USA)
Dissolved Oxygen	SBE 43	Sea Bird Electronics (Bellevue, Washington, USA)
Nitrate	Deep SUNA	Satlantic (Halifax, Canada)
Irradiance (PAR)	PAR-log-s	Satlantic (Halifax, Canada)
Chlorophyll a	C7-c	Turner Designs (Sunnyvale, California, USA)
CDOM	C7-u	Turner Designs (Sunnyvale, California, USA)
pCO_2	HydroC CO2	Contros (Kiel, Germany)
Sample Collector	*Prototype*	AWI