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Influence of the physical environment on polar phytoplankton blooms: A case study in the Fram Strait

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ABSTRACT

The Fram Strait is the main gateway for water, heat and sea-ice exchanges between the Arctic Ocean and the North Atlantic. The complex physical environment results in a highly variable primary production in space and time. Previous regional studies have defined key bottom-up (ice cover and stratification from melt water controlling the light availability, and wind mixing and water transport affecting the supply of nutrients) and top-down processes (heterotrophic grazing). In this study, in situ field data, remote sensing and modeling techniques were combined to investigate in detail the influence of melting sea-ice and ocean properties on the development of phytoplankton blooms in the Fram Strait region for the years 1998–2009. Satellite-retrieved chlorophyll-a concentrations from temporarily ice-free zones were validated with contextual field data. These were then integrated per month on a grid size of 20 × 20 km, resulting in 10 grids/fields. Factors tested for their influence on spatial and temporal variation of chlorophyll-a were: sea-ice concentration from satellite and sea-ice thickness, ocean stratification, water temperature and salinity time-series simulated by the ice-ocean model NAOSIM. The time series analysis for those ten ice-free fields showed a regional separation according to different physical processes affecting phytoplankton distribution. At the marginal ice zone the melting sea-ice was promoting phytoplankton growth by stratifying the water column and potentially seeding phytoplankton communities. In this zone, the highest mean chlorophyll concentration averaged for the productive season (April–August) of 0.8 mgC/m^3 was observed. In the open ocean the phytoplankton variability was correlated highest to stratification formed by solar heating of the upper ocean layers. Coastal zone around Svalbard showed processes associated with the presence of coastal ice were rather suppressing than promoting the phytoplankton growth. During the twelve years of observations, chlorophyll concentrations significantly increased in the southern part of the Fram Strait, associated with an increase in sea surface temperature and a decrease in Svalbard coastal ice.

1. Introduction

The rapid decrease in sea-ice extent and thickness in the Arctic (Comiso et al., 2008; NSIDC, 2012), and the freshening of the Arctic Ocean surface waters (Proshutinsky et al., 2010) are likely to impact primary productivity and carbon export of the Arctic Ocean by altering solar irradiation, nutrient transport and plankton seasonality (Arrigo et al., 2012; Boetius et al., 2013; Vaquer-Sunyer et al., 2013; Wassmann, 2011).

Previous satellite-based phytoplankton studies showed that the variability in ice cover affects phytoplankton density in most geographical sectors of the Arctic Ocean except for the Greenland and Baffin Seas (Arrigo and Van Dijken, 2011; Pabi et al., 2008). Time series studies showed that in some regions phytoplankton blooms occur earlier because of the Arctic-wide seasonal sea-ice decrease (Wassmann and Reigstad, 2011), whereas at Fram Strait only a minor change or even delay in phytoplankton bloom timing was recorded (Harrison et al., 2013; Kahru et al., 2011). Generally, sea-ice cover can influence phytoplankton blooms in a variety of ways: Firstly, sea-ice reduces light penetration into the water column, which negatively affects the growth of algae in and under the sea ice (Rysgaard et al., 1999; Smetacek and Nicol, 2005). Secondly, during the ice melt, sea-ice plankton, nutrients and trace elements are released into the upper ocean layer. This process can accelerate the spring bloom (Schandelmeier and Alexander, 1981; Smetacek and Nicol, 2005). Furthermore, melting of sea-ice increases the upper ocean stability

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since freshwater is released into the upper ocean layer. This can either promote blooms by keeping plankton closer to the surface where light levels are favorable (Doney, 2006; Gradinger and Baumann, 1991; Lancelot et al., 1993; Smith et al., 1987), or suppress them by increasing grazing pressure from zooplankton (Banse, 1992; Behrenfeld, 2010). Stratification can also limit nutrient supply from deeper layers and thus constrain phytoplankton growth. The complex spatial, seasonal and interannual variations in these biophysical factors suggest that a considerable spatial resolution is needed to decipher the interaction between key environmental factors governing photosynthetic production, in order to better understand the future of Arctic ocean productivity (Cavalieri and Parkinson, 2012; Rabe et al., 2013; Sakshaug, 2004; Wassmann and Reigstad, 2011). Simulations with sea-ice ocean models provide an important tool to test hypotheses related to the key mechanisms that determine phytoplankton growth on interannual to decadal scales. For the Greenland Sea and Fram Strait, this includes ice cover, stratification, wind, surface water transport and the activity of grazers (Skogen et al., 2007; Slagstad et al., 2011). Generally, interannual variability in this region can be linked to the transport of Arctic water through the Fram Strait, and the presence of sea-ice in spring (Skogen et al., 2007). An effect of atmospheric warming on phyto- and zooplankton growth was detected in the simulations, suggesting that phytoplankton productivity in the Greenland Sea and western Fram Strait may increase in the future (Slagstad et al., 2011).

Two main ocean currents influence the exchange of water masses in Fram Strait (Forest et al., 2010). The current flowing along the Greenland coast is the East Greenland Current which carries cold and low salinity Arctic waters southward. In the eastern Fram Strait, the West Spitsbergen Current transports relatively warm and salty Atlantic waters northward (see Fig. 1). Smith et al. (1987) reported that the pycnocline in the Fram Strait is established by these large-scale water movements and is a year-round feature of this region. However, the Fram Strait is a spatially dynamic area in terms of water mass exchange and sea-ice transport (Rudels and Quadfasel, 1991), with strong North to South and East to West gradients, as well as substantial mixing by eddies (Johannessen et al., 1987). The effects on phytoplankton growth via nutrient and light availability are hence also likely to differ significantly on the scale of a few tens to hundreds of kilometers within the Fram Strait region, rendering the detectability of interannual to decadal trends challenging. Previous field studies reported that in the northeastern Fram Strait (78–81°N, June–July 1984) phytoplankton density is higher in the marginal ice zone, where physical processes such as enhanced water-column stability and upwelling result in favorable conditions for phytoplankton growth (Gradinger and Baumann, 1991; Smith et al., 1987). In the southern Fram Strait (75°N transect, May of 1993 and 1995), phytoplankton biomass was shown to follow hydrographical patterns, with elevated phytoplankton in the areas of low salinities and, hence, higher stratification (Rey et al., 2000). It has been shown that empirical algorithms for estimating CHL from satellite information do not perform well in this environment even if they were developed explicitly for Arctic waters (Cota et al., 2004; Matsuoka et al., 2007). Generally the bio-optical properties of polar waters may differ significantly from those of waters at lower latitudes (e.g. Matsuoka et al., 2007; Mitchell and Holm-Hansen, 1991; Sathyendranah et al., 2001).

Since 1998 sections across the Fram Strait were run repeatedly since 1998 (e.g. Budeus and Ronski, 2009; Schauer et al., 2008). During these cruises the measurements of in situ chlorophyll-a (CHL) are carried out regularly. This time series phytoplankton data can be used for a thorough validation of ocean color products.

In our study, we combine both satellite-derived and simulated physical data for the analysis of spatial (7×10^5 km^2) and temporal (1998–2009) variations in phytoplankton distribution in the Greenland Sea. The satellite phytoplankton biomass data (given as chlorophyll-a (CHL) concentration) were first validated with in situ CHL data within

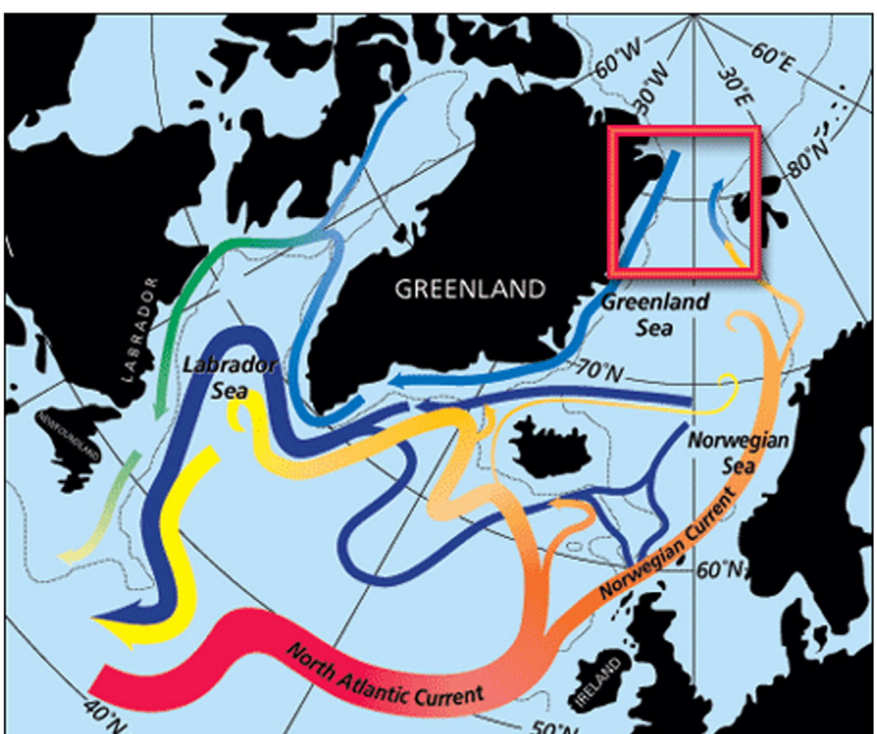

Fig. 1. The scheme of the transformation of warm subtropical waters into colder subpolar and polar waters in the northern North Atlantic. The color of the arrows indicates the temperature of the current; red: 15 °C, yellow: 4 °C, blue: 0 °C, shadings of oranges or greens indicate intermediate temperatures. The small curled or spiraling lines denote sinking. Red square indicates the location of Fram Strait. Image courtesy of Michael McCartney and Ruth Curry, Woods Hole Oceanographic Institution.