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Unusual phytoplankton bloom phenology in the northern Greenland Sea during 2010☆

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ABSTRACT

Arctic marine ecosystems are disproportionately impacted by global warming. Sea ice plays an important role in the regional climate system and the loss of perennial sea ice has diverse ecological implications. Here we investigate the causes of an unusually early and strong phytoplankton bloom in the northern Greenland Sea (20°W–10°E, 75°N–80°N) during the 2010 season. In order to better understand the anomalous bloom in 2010, we examine the correlation between satellite-derived biomass and several possible environmental factors for the period 2003–2012. Results show that the timing of sea ice melt played an important role in promoting the growth of phytoplankton. Multivariate lagged regression analysis shows that phytoplankton biomass (CHL) is correlated with ice concentration (ICE) and ice melting, as well as sea surface temperature (SST) and photosynthetically active radiation (PAR). During 2010, the spring peak in biomass came much earlier and achieved a higher value than most other years in the satellite archive record, which was due to earlier and more extensive sea ice melt in that year. Relative lower SST and PAR in spring and early summer in year 2010 associated with a persistent negative North Atlantic Oscillation (NAO) index were possible drivers of the bloom. Wind direction changed from the southeast to southwest direction in spring, possibly transporting nutrient enriched melt runoff from glaciers on Greenland and other sources from the south to northern coastal regions.

1. Introduction

The Greenland Sea (GS) is one of the most productive regions in the Arctic (Arrigo and van Dijken, 2011) and adjacent to the world's second largest glacier in Greenland. Glaciers in the northeast of Greenland are melting faster than expected (Glasser et al., 2011). The GS is an important area for water mass exchange between the North Atlantic Ocean and the Arctic Ocean. It is also the area to where most Arctic drifting ice is advected (Cherkasheva et al., 2014). Hence, the GS is an appropriate region for studying the relationship between sea ice and phytoplankton dynamics and where an extensive archive of in situ and satellite-derived chlorophyll data is available (Arrigo et al., 2011).

1.1. Surface currents

The surface currents in the GS are shown in Fig. 1, within our study region is highlighted by the red box. The East Greenland Current (EGC) moves from north to south along Greenland's eastern coastline bringing colder less saline Arctic water to the south. From south-east of Iceland, warmer more saline Atlantic water flows to north merging with the Norwegian current and flowing into Arctic ocean. In this area, the vertical stability of the water column increases to the north due to the input of melt water and solar heating, causing phytoplankton biomass to increase and nutrient concentration to decrease (Lara et al., 1994). Between 70°N and 80°N, there is an anti-clockwise gyre, affecting our study region, and at around 70°N, the EGC branches into two parts, one flowing along the west coast of Norway and east into the Barents Sea, and the other northwards to the Spitsbergen region. The Polar front is located to the east of EGC and the Arctic front is located west of the Norwegian Current.

1.2. Sea ice melt, runoff, iron and phytoplankton dynamics

The decline of Arctic sea ice (and concomitant decrease in surface albedo) in recent decades has resulted in a regional temperature increase in the Arctic, where sea surface temperatures have increased at twice the global average rate and could continue to increase throughout this century (Chalecki, 2007). Melting of Greenland's ice sheet has increased six-fold over the last decade ago, according to a draft of the UN's most comprehensive study on climate change (Stroeve et al., 2011). Greenland may add a total of 4–21 cm to global sea levels by the end of the 21st C (Schuenemann and Cassano, 2010). The indirect effect of melting

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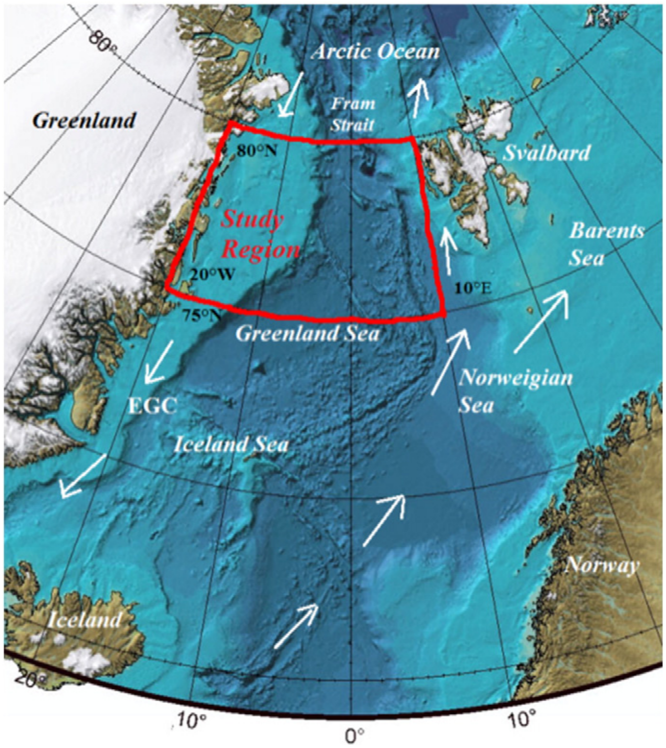

Fig. 1. Map of Study region in Greenland Sea (highlighted box is for 20°W–10°E, 75°N–80°N). White arrows indicate the surface flow directions.

sea ice is an increase in regional average temperatures, which may accelerate the melting of the Greenland ice sheet and lead to global sea level rise. Arctic sea ice concentration has retreated extensively and first-year ice is thinning, making it more vulnerable to summer melting and sea level rising. Summer sea ice could be totally gone by 2030 (Stroeve et al., 2011).

Several studies have examined the impact of sea ice melt on regional phytoplankton biomass (Matrai and Vernet, 1997; Wassmann et al., 1999; Olli et al., 2002; Qu et al., 2006; Pabi et al., 2008; Leu et al., 2011). It is suggested that decreasing sea ice extent and thickness and a concomitant increase in water column illumination, leads to an increase in phytoplankton biomass. Moline et al. (2008) point out that the less saline surface water during ice melt can stimulate primary production. The melting ice increases the area of open water, increases the absorption of solar radiation and could enhance the melt process. In July 2012, the NASA ICESCAPE project discovered large under ice blooms appeared in Arctic water due to thinning ice and proliferation of melt ponds (Arrigo et al., 2012). Phytoplankton was extremely active and growth rates were the highest ever measured in polar waters. Arrigo et al. (2012) suggest that satellite-based estimates of annual primary production in Arctic waters may be underestimated up to 10-fold due to under ice blooms. In contrast to the Southern Ocean where primary production is iron limited, the Arctic Ocean is generally land-locked, with higher levels of atmospheric deposition of micro-nutrients such as iron, which can stimulate primary production during and after ice melting (Moline et al., 2008).

It is suggested that glacial runoff serves as a significant source of bioavailable iron to the surrounding oceans (Bhatia et al., 2013). The Greenland ice sheets are also likely a significant source of iron to the adjacent ocean (Hawkings et al., 2014). The availability of iron (Fe) is said to be the main factor controlling primary production in high nutrient (N, P, Si) and low CHL (HNLC) systems (Martin and Fitzwater, 1988). An alternative source of Fe to the ocean from glacial runoff is associated with glacial particles (Smith et al., 2007). These glacial melt waters provide an important supply of Fe and other micronutrients to surface Arctic waters (Diersson et al., 2002; Statham et al., 2008).

Primary production is high in the coastal zone of Greenland, due to the impact of melting sea ice (Rysgaard and Nielsen, 2006). Macronutrients (N, Si, and P) appear to control primary production (Nielsen and Hansen, 1999), although Fe could be a limiting nutrient (Blain et al., 2004). During winter storms, vertical mixing of high Fe content deep water, together with the lateral entrainment of high Fe surface water from Greenland coast could contribute to relatively high Fe concentrations at the beginning of the phytoplankton bloom period. The melt water input from Greenland glacier inputs is around 10% of sea ice melt water, although sea ice melt would occur earlier in the season (Statham et al., 2008).

Following on a previous analysis of the spike of phytoplankton biomass in the GS during 2009 (Qu et al., 2014), more recent satellite data indicated elevated phytoplankton biomass in the northern Greenland Sea during 2010 when compared to data for the ten year period 2003–2012. Here we examine the factors that may be responsible for higher phytoplankton biomass in 2010. Apart from the effect of melting ice on phytoplankton biomass, other factors such as sea surface temperature (SST), wind speed (WIND), photosynthetically active radiation (PAR), and climate variability as indicated by the North Atlantic Oscillation (NAO) are also considered.

2. Material and methods

2.1. Data sources

Our study region is the northern Greenland Sea (20°W–10°E, 75°N–80°N) (Fig. 1), for the period 2003–2012. Due to the Arctic sunset, satellite data are only available between March and September. MODIS (Aqua) satellite, 8-day, 4-km, level 3, mapped data Aerosol Optical Depth (AOD), Chlorophyll-*a* (CHL) and Photosynthetically Active Radiation (PAR) global data were archived (modis.gsfc.nasa.gov/). Sea ice concentration (ICE) is from the following archive iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.EMC/.CMB/.GLOBAL/.Reyn_SmithOIv2/. Wind speed and direction, and sea surface temperature (SST) were obtained from www.remss.com/windsat.

The image analysis package data analysis system SeaDAS 6.4 (seadas.gsfc.nasa.gov/) is used to subset data for our study region. Mean values for each (1° × 1°) grid cell are calculated first, with missing values excluded. Regional mean values of the CHL, AOD and PAR are calculated by averaging the 150 (1° × 1°) grid cells.

Mean values of the wind and direction of each (1° × 1°) grid are calculated from the 0.25° × 0.25° grid. The weekly data windAW is chosen for wind speed data. windAW is 10 m surface wind for all weather conditions made using 3 algorithms (Meissner and Wentz, 2009) with rainy condition included. The missing values are excluded again in the mean value calculations.

The CHL, AOD and PAR could be slightly over predicted due to the exclusion of missing values. However, the higher CHL spots obviously occurred in early summer in the study region as indicated in the satellite images (Fig. 2). Fig. 2 shows the CHL satellite images in early June (day 184) 2010 and May (day 160) 2011.

EViews statistical software is used for correlation and lagged regression analysis. R software is used to do the partial correlation analysis and multivariate regression analysis among mean time series of CHL, SST, WIND, ICE and PAR in the study region.

2.2. Accuracy of the satellite data

Due to the remoteness of the Arctic Ocean, the satellite data is the only means of obtaining synoptic coverage. However, the accuracy of these data directly relate to the reliability of this study. Surface chlorophyll concentration (CHL) is from the MODIS AQUA sensor with data available from 2002. NASA carried a polarization correction for MODIS