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Nutrient and phytoplankton dynamics driven by the Beaufort Gyre in the western Arctic Ocean during the period 2008–2014

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A B S T R A C T

Nutrient and phytoplankton pigment data were collected during summer cruises in 2008–2014 to examine how the Beaufort Gyre (BG) affected regional differences in nutrient stocks and the phytoplankton community. The results showed a gradual decrease in nutrient concentrations and increasing depth of the chlorophyll maxima toward the center of the gyre. A horizontal map of nitrate at a depth of 50 m indicated nitrogen deficiency in the gyre compared with that in the surroundings. Biogeochemical model simulations suggested that an increased freshwater convergence, driven by the strengthened BG and sea ice retreat, was primarily responsible for the decrease in nutrient stocks. In the BG zone, the contribution of diatoms to the phytoplankton community decreased, accompanied by the increased contribution of small flagellates. The current state of the BG under anticyclonic winds negatively affected the diatom biomass and biological carbon pump. The possible rotation of wind regimes from anticyclonic to cyclonic might relieve the nitrogen deficiency for phytoplankton growth in the western Arctic Ocean.

1. Introduction

The anticyclonic Beaufort Gyre (BG) in the western Arctic Ocean accumulates much freshwater, which is involved in oceanic freshwater cycling and global climate systems (Carmack et al., 2008; Morison et al., 2012; Proshutinsky et al., 2009a; Steele et al., 2001). The strength of the BG is controlled primarily by the wind regime (cyclonic vs. anticyclonic) associated with the atmospheric Beaufort High (Proshutinsky et al., 2002; Proshutinsky and Johnson, 1997). Model outputs and satellite data suggest that anticyclonic winds spin up the BG, resulting in freshwater accumulation (Giles et al., 2012; Proshutinsky et al., 2009b). The atmospheric circulation regime characterized by anticyclonic winds has dominated in the Arctic Ocean since 1997 (Proshutinsky et al., 2015). The strong BG under anticyclonic winds makes the Canada Basin where the most freshening is observed in the Arctic Ocean (Davis et al., 2014; Rabe et al., 2011).

In the last decade, sea ice retreat has been identified as a major driver of marine ecological and biogeochemical processes in the Arctic Ocean (Post et al., 2013). The freshening may also have important consequences for ecosystems, perhaps as significant as those caused by sea ice loss (McLaughlin et al., 2011). The BG has gathered much fresh water, resulting in biogeochemical changes in the western Arctic Ocean. Therefore, the BG influences biological production (Arrigo and van Dijken, 2011; Coupel et al., 2015), air-sea CO_2 exchanges and carbon sink (Bates and Mathis, 2009; Cai et al., 2010), aragonite saturation and ocean acidification (Qi et al., 2017; Yamamoto-Kawai et al., 2011). Nutrient and phytoplankton dynamics are also strongly altered by freshwater convergence of the BG. Previous studies reported that the trend of freshening in the Arctic Ocean would favor picophytoplankton growth and larger cells would decline (He et al., 2012; Li et al., 2009). McLaughlin and Carmack (2010) reported that increased stratification caused by freshening constrains upward nutrient flux, causing a deepening of the nitracline and the chlorophyll maximum in the Canada Basin. The deepening of the chlorophyll maximum is further support by the numerical model simulations (Steiner et al., 2016). Additionally, Coupel et al. (2015) reported that freshening might be the cause of low primary production in the Canada Basin.

The changes of the BG will negatively affect primary productivity as

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long as the Arctic Oscillation remains anticyclonic (McLaughlin and Carmack, 2010). The anticyclonic winds have dominated this region since 1997 (Proshutinsky et al., 2015). Satellite records show that Arctic sea ice cover reached a record low in 2007 (Stroeve et al., 2008). Freshwater accumulation in the BG zone showed a marked increase in 2007 (Krishfield et al., 2014; Yamamoto-Kawai et al., 2009). Therefore, 2007 had an abrupt decline in the Arctic sea ice cover and a marked increase in freshwater accumulation in the BG zone. Since 2007, the annual variation of the liquid freshwater content appears to fluctuate compared with the rapid increase from 1997 to 2007 (Rabe et al., 2014). This observation suggests our data collected in the period 2008–2014 were under a strong phase of the BG (Proshutinsky et al., 2015). Here, we evaluate salinity, nutrient and pigment data collected in summer in 2008–2014 in the upper waters of the western Arctic Ocean. The horizontal distributions of salinity, nutrients and pigments during the period 2008–2014 are used to examine the regional effect of the strong BG on nutrient and phytoplankton dynamics. The biogeochemical feedback under different atmospheric circulation (cyclonicvs. anticyclonic) is discussed along with the potential impact of the BG on diatom biomass and biological carbon pump.

2. Materials and methods

2.1. Study sites and sampling

Sampling stations in the BG zone and adjacent waters (72–80°N, 146–170°W) were conducted in summer during Chinese National Arctic Expedition (CHINARE) cruises during the period 2008–2014 (Fig. 1). Water samples were collected from 40 stations in 2008 between August 6 and 16, from 19 stations in 2010 between July 25 and August 1, from 4 stations in 2012 between September 5 and 7, and from 28 stations in 2014 between August 3 and 12 (Table 1S). Nutrients and pigments were measured during all sampling years. Seawater was collected using a Rosette sampler with Niskin bottles. Hydrological parameters (e.g., salinity and temperature) were recorded in situ using an SBE 911 plus CTD (Sea-bird, Bellevue, Washington, USA), which was pre-calibrated. The depth of subsurface chlorophyll maximum (SCM) was determined based on a Seapoint chlorophyll fluorometer (Sea-bird, Bellevue, Washington, USA) attached to the CTD profiler.

2.2. Nutrient analysis

Nutrient samples were filtered through acid-cleaned cellulose acetate membranes (0.45 μm). Nutrient samples were collected at depths of 3, 30, 50, SCM depth, 75, and 100 m. Nitrate plus nitrite, phosphate and silicate were measured on board using a continuous flow analyzer (Skalar San+ +, Breda, Netherlands). Nitrite was measured using spectrometric method. The nutrients were analyzed according to *Specification for Oceanographic Survey* (State Bureau of Quality and Technical Supervision, 2007) and Grasshoff et al. (2009). Analytical precision was ± 1% for nitrite, ± 2% for both nitrate and phosphate and ± 2.5% for silicate.

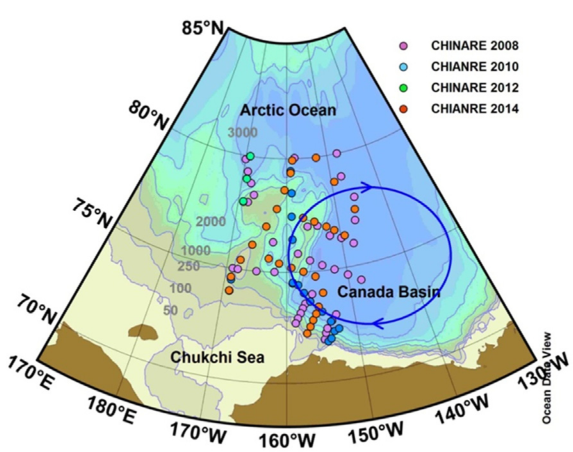

Fig. 1. Bathymetric map (water depth in m) of the Pacific Arctic Ocean showing the sites of samples collected during CHINARE 2008–2014. The center of the BG zone (bounded by blue cycle) is defined based on climatologically salinity minimum (Proshutinsky et al., 2009a) and sea ice motion (Qi et al., 2017).

2.3. Pigment analysis

To collect pigment samples, 4–8 L of seawater was filtered through GF/F filters under a gentle vacuum (< 0.5 atm) and dim light conditions. Samples were collected at 3 m and SCM depth. Filters were stored in liquid nitrogen (–196 °C) until analysis (within 3 months after the cruises). Pigment samples were extracted with 3 mL of 100% HPLC-grade methanol at − 20 °C. The extracts were filtered through a 0.22 μm microporous membrane and premixed with 28 mmol/L tetrabutyl ammonium acetate (TBAA, 1:1 v/v) before injection. The analysis work was conducted on an HPLC (Waters 600) system equipped with an Eclipse SDB C8 column (150 × 4.6 mm, 3.5 μm) and a photodiode array detector (Waters 2998). Detailed information for pigment analysis methods is provided in Zhuang et al. (2014). Pigment standards were purchased from DHI lab (DHI, Denmark). Pigments measured included the following: chlorophyll *a* (Chl *a*), divinyl chlorophyll *a* (DV Chl *a*), chlorophyll *b* (Chl *b*), pheophytin *a* (Phytin *a*), pheophoride *a* (Phide *a*), alloxanthin (Allo), 19′-butanoyloxyfucoxanthin (But-fuco), diadinoxanthin (Diadino), neoxanthin (Neo), fucoxanthin (Fuco), 19′-hexanoyloxyfucoxanthin (Hex-fuco), lutein (Lut), peridinin (Peri), prasinoxanthin (Prasino), diatoxanthin (Diato), violaxanthin (Viola), zeaxanthin (Zea), and β-carotene (β-car).

2.4. Pigment ratio

The pigment ratio was used to assess differencesin phytoplankton composition among samples. The pigment But-fuco can be used as an indicator of chrysophytes and haptophytes, and Chl *b* is an indicator of chlorophytes and prasinophytes (Jeffrey et al., 1997). A confounding problem is that Fuco is found not only in diatoms but also in haptophytes, chrysophytes and some dinoflagellates. Chrysophytes and haptophytes contain Fuco and But-fuco at a ratio of approximately 1 in the Arctic Ocean (Zhuang et al., 2016), and Peri, the diagnostic pigment of dinoflagellates, was generally in low concentration in the study area (Fig. 1S). Thus, the pigment ratio (Chl *b*+But-Fuco)/(Fuco– But-fuco) was used to reveal the relative contribution of small flagellates versus that of diatoms in the phytoplankton community.

3. Results

3.1. Nutrient distribution

Nutrient and salinity observations from the BG showed a clear decrease toward the center of the gyre (Fig. 2). Between 73° − 78°N and 146° − 156°W in the Canada Basin, the water was relatively fresh and low in nutrients, which were characteristics of the center of the BG zone. Salinity and nitrate distributions of 2008 and 2014 were compared (Fig. 2S). The horizontal distribution of salinity and nitrate showed slight annual changes but downwelling of the BG primarily dominated. The horizontal distribution of nitrate at the 50 m water depth indicated that nitrogen deficiency (< 1 μM) occurred in the center of the BG zone compared with that in the surrounding water (Fig. 2b). The influence of freshwater was observed as deep as 75 m in the center of the gyre (Fig. 2c, d). The average N/P and N/Si ratios at 50 m were 2.7 and 0.3, respectively (Fig. 3S), which are lower than the ratios of Redfield et al. (1963) and Brzezinski et al. (2002), indicating an excess of phosphate and silicate relative to nitrate. Phosphate and