Field-obtained carbon and nitrogen uptake rates of phytoplankton in the Laptev and East Siberian seas

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Abstract

The Laptev and East Siberian seas are the least biologically studied region in the Arctic Ocean, although they are highly dynamic in terms of active processing of organic matter impacting the transport to the deep Arctic Ocean. Field~~-measured~~ measurements of carbon and nitrogen uptake rates of phytoplankton were conducted in the Laptev and East Siberian seas from August 21 to September 22, 2013 as part of the NABOS (Nansen and Amundsen Basins Observational System) program. Major inorganic nutrients were mostly depleted at 100-50% light depths but were not depleted within the euphotic depths in the Laptev and East Siberian seas. The water column-integrated chl-*a* concentration in this study was significantly higher than that in the western Arctic Ocean (t-test, p ~~$>$~~$\leq$ 0.01). ~~Unexpectedly,~~ ~~t~~The daily carbon and nitrogen uptake rates in this study (average ± S.D. = 110.3 ± 88.3 mg C m^{-2} d^{-1} and 37.0 ± 25.8 mg N m^{-2} d^{-1}, respectively) are within previously reported ranges. Surprisingly, the annual primary production (13.2 g C m^{-2}) measured in the field during the vegetative season is approximately one order of magnitude lower than the primary production reported from a satellite–based estimation. Further validation using field-measured observations is necessary for a better projection of the ecosystem in the Laptev and East Siberian seas responding to ongoing climate change.

Keywords

Laptev and East Siberian seas, NABOS, carbon and nitrogen uptake rates of phytoplankton

1. Introduction

The most dramatic environmental change in the Arctic Ocean has been the rapid and extensive decrease in sea ice extent and thickness over the recent decades (Comiso 2006; Overland and Wang, 2013; Overland et al., 2014). Sea ice is a major controlling factor for primary production of pelagic phytoplankton by modulating water column stratification and light fields (Hill et al. 2005; Gradinger 2009; Bélanger et al., 2013), although nutrient supply to the surface water have been proposed as the main controlling factor in seasonally ice-free open waters (Tremblay and Gagnon, 2009). Consequently, these sea ice changes will affect primary productivity as well as physiological status of primary producers (Lee et al. 2008, 2010; more refs) and thus carbon cycling in the Arctic Ocean (Arrigo et al. 2008; Bates and Mathis 2009; Cai et al. 2010). Some evidence for the impacts of environmental changes on phytoplankton have been already reported in various regions in the Arctic Ocean (Arrigo et al., 2008; Li et al., 2009; Wassmann et al., 2011; Ardyna et al., 2014). Several studies have reported increasing signs of annual primary production due to enhanced light availability to phytoplankton as a main consequence of recent increasing open area and longer open period in the Pan-Arctic regions from 1998 to 2009 (Arrigo et al. 2008; Arrigo and Dijken, 2011). In contrast, a restrained primary production was reported as a result of increasing cloudiness in the Arctic Ocean (Bélanger et al., 2013) due to warmer temperature and moisture fluxes in newly open waters during summer and early fall (Eastman and Warren, 2010; Vavrus et al., 2010). To date increasing or decreasing in the primary production~~ of primary producers~~ as a consequence of ongoing environmental changes is still being debated in the Arctic Ocean (Lee and Whitledge, 2005; Coupel et al., 2015). However, it is clear that these environmental changes will have great effects on the ecosystem from altering the patterns of primary production to changing the trophic structure and the elemental cycling pathways (Grebmeier et al. 2006).

The Laptev and East Siberian seas are situated on the widest and shallowest continental shelf in the world (Semiletov et al., 2005). Both seas are highly dynamic in terms of organic matter production and processing, impacting the atmospheric exchange and the transport of organic matter to the deep Arctic Ocean (Semiletov et al., 2005; Anderson et al., 2009). However, the Laptev and East Siberian seas are among the least biologically studied regions in the Arctic Ocean (Semiletov et al., 2005; Arrigo and Dijken, 2011; Hill et al., 2017). Especially, primary production measurements are chronically scarce in this region based on the ARCSS-PP (Arctic System Science Primary Production) database 1950 to 2007 (Hill et al., 2017). Although various physical data on hydrography and ocean circulation have been reported by the continuous NABOS (Nansen and Amundsen Basins Observational System) program (Dmitrenko et al., 2006~~; Bauch et al., 2014; Aksenov et al., 2011;~~ Polyakov et al., 2007; Aksenov et al., 2011; Bauch et al., 2014), no *in situ* measurements of recent phytoplankton productivity or nutrient concentrations have been conducted in the Laptev or East Siberian seas during the program.

In this study, *in situ* carbon and nitrogen uptake rates of phytoplankton were measured to quantify the primary productivity and evaluate nitrogen uptake in the Laptev and East Siberian seas as part of the NABOS program. These data will provide the basic groundwork for future monitoring of the marine ecosystems as it responds to ongoing climate change in the Laptev and East Siberian seas and will provide valuable *in situ* measurements for validating the ranges of phytoplankton primary production estimated from satellite ocean color data.

2. Materials and Methods

~~Field measured c~~Carbon and nitrogen uptake rates of phytoplankton were measured at 19 monitoring stations selected from a total of 116 NABOS stations (Fig. 1; Table 1) in the Laptev and East Siberian seas from August 21 to September 22, 2013 onboard the Russian vessel "*Akademik Fedorov*". After samples for concentrations of major inorganic nutrient and chlorophyll-*a* (chl-*a*) were collected at 19 productivity stations, they were analyzed onboard during the cruise. Nutrient concentrations (nitrate, nitrite, ammonia, phosphate, and silicate) were analyzed using an Alpkem Model 300 Rapid Flow Nutrient Analyzer (5 channels) based on the method of Whitledge et al. (1981). Total and size-fractionated chl-*a* samples were obtained from 6 light depths (100, 50, 30, 12, 5, and 1 %) and 3 light depths (100, 30, and 1%), respectively. The chl-*a* samples were prepared based on the same procedure reported from previous studies in the Arctic Ocean (Lee et al., 2005; Lee et al., 2012). Water samples for chl-*a* concentrations were filtered onto Whatman GF/F (24 mm) and samples for size-fractionated chl-*a* were passed sequentially through 20 μm and 5 μm pore-sized Nucleopore filters (47 mm) and 0.7 μm pore-sized Whatman GF/F filters (47 mm). The filters were kept frozen in a freezer (-80 °C) before further analysis. The frozen chl-*a* samples were extracted in 90% acetone at –5°C for 24 hours, and the concentrations were measured on board using a pre-calibrated Turner Designs model 10-AU fluorometer.

On-deck incubations for carbon and nitrogen uptake rates of phytoplankton were conducted using a ^{13}C-^{15}N-dual tracer technique previously performed in various regions of the Arctic Ocean (Lee and Whitledge 2005; Lee et al., 2007;~~ &~~ 2012, Yun et al., 2015). Six *in situ* photic depths (100, 50, 30, 12, 5, and 1%) were determined at each station by converting Secchi disc depth to light ~~intensity~~depth according to Lambert-Beer's law. It would be better to have radiance or optical measurements for more accurate estimation of euphotic depths or diffuse attenuation coefficients for PAR, K_d(PAR). Since we do not have underwater PAR sensor (and/or optical instruments) due to logistic problems, the light depths were determined by Secchi disc which has been widely and commonly used in various oceans as well as the Arctic Ocean to derive euphotic depth and K_d(PAR) (Son et al., 2005; Tremblay et al., 2000; Lee et al. 2012; Lee et al., 2017a; Lee et al., 2017b). From several previous studies in the Arctic Ocean, we compared the light depths between the two methods of Secchi disc and underwater PAR sensor and found that they were matched quite well (unpublished data).

Seawater samples at each light depth were transferred from the Niskin bottles to acid-cleaned polycarbonate incubation bottles (approximately 1 L) matched each light depth. Then, heavy isotope-enriched (98−99 %) solutions of $NaH^{13}CO_3$, $K^{15}NO_3$, or $^{15}NH_4Cl$ were added to the polycarbonate incubation bottles at concentrations of ~0.3 mM, ~0.8 µM, and ~0.1 µM for $^{13}CO_2$, $^{15}NO_3$, and $^{15}NH_4$, respectively. The carbon isotope enrichment was 5–10% of the total inorganic carbon in the ambient water determined during the cruise. In contrast, the concentrations of $^{15}NO_3$ and $^{15}NH_4$ additions were greater than 10 % of the ambient nitrate and ammonium concentrations at several stations with very low concentrations. The waters injected with isotopes were incubated in big incubators on deck under natural light conditions with cooled with surface seawater for 4 to 6 hours. So, the light conditions were not constant during the incubation hours among the productivity stations. After ~~4 to 6 hour~~the incubation~~s on deck~~ done, the filters used for the isotopic measurements as well as particulate organic carbon (POC) and particulate nitrogen (~~PON~~PN) were immediately preserved at –20°C for further mass spectrometric analysis (Finnigan Delta+XL) in the stable isotope laboratory of University of Alaska Fairbanks, US. The uncertainties for δ^{13}C and δ^{15}N measurements were ± 0.1‰ and ± 0.3 ‰, respectively. Calculations of the carbon and nitrogen uptake rates of phytoplankton were based on the methods from Hama et al. (1983) and Dugdale and Goering (1967). Carbon uptake rates were obtained as follows:

$$\text{Carbon uptake rate} = \text{POC}_{\text{incubation}} \times [{}^{13}\text{C}_{\text{excess}} / ({}^{13}\text{C}_{\text{enriched}} * t)],$$

where $\text{POC}_{\text{incubation}}$ is the concentration of particulate organic carbon after incubation, ${}^{13}\text{C}_{\text{excess}}$ is the excess ^{13}C [concentration of ^{13}C in the particulate phase after incubation – natural abundance of ^{13}C in the particulate phase], ${}^{13}\text{C}_{\text{enriched}}$ is the ^{13}C enrichment in the dissolved fraction, and t is the time duration of incubation in hours. Since the discrimination factor for ^{13}C/^{12}C (1.025; Hama et al., 1984) was not considered, the production rate calculated in this study could be somewhat underestimated. Nitrogen uptake rate was obtained same as carbon uptake rate. Dark carbon uptake values were subtracted from light carbon uptake values since the measured dark uptake rates were assumed from bacterial processes (Gosselin et al. 1997). Integrated values of the carbon and nitrogen uptake rates of phytoplankton were calculated from surface (100 %) to 1 % light depths based on the trapezoidal rule. The *f* ratio was calculated as a fraction of nitrate uptake rate to the sum of nitrate and ammonium uptake rates in this study (Eppley and Peterson, 1979).

3. Results and Discussion

The sea surface temperature and salinity values ranged from –1.76 °C to 1.62 °C and 28.29 to 33.44, respectively (Table 1). Sea ice concentration averaged during the cruise period in 2013 retrieved from National Snow & Ice Data Center ranged from 0 % to 100 % (Table 1).

The vertical concentrations of major inorganic nutrients except nitrite+nitrate shown in Fig. 2 were generally consistent from surface to 1 % light depth at each station although they were largely variable among the productivity stations. In comparison, the concentrations of nitrite+nitrate were homogeneous within 20 m water depth (approximately 30 % light depth) at the most stations and then increased rapidly below the depth. The concentration of nitrite+nitrate (mostly nitrate) at surface ranged from 0 µM to 2.11 µM (average ± S.D. = 0.53 ± 0.65 µM). The concentrations of major inorganic nutrients ~~(nitrite+nitrate,~~

~~ammonium, phosphate, and silicate)~~ were integrated from surface to 50 m water depth because the average euphotic water column was 49.6 m (S.D. = ± 10.6 m) during our cruise period in 2013 (Fig. ~~2~~3a-d). The concentrations of nitrite+nitrate and ammonium were 19.3-189.3 mmol m^{-2} and 2.5-39.7 mmol m^{-2}, respectively (Fig. ~~2~~3a & b). The concentration of DIN (nitrite+nitrate+ammonium) was 25.8-213.7 mmol m^{-2}. The concentrations of phosphate and silicate were 7.6-39.7 mmol m^{-2} and 19.5-329.7 mmol m^{-2}, respectively (Fig. ~~2~~3c & d). Generally, high concentrations of nitrite+nitrate and phosphate were found at AF005, AF068, AF071, and AF100 and they were relatively higher in the ~~Laptev Sea~~western part than in the ~~East Siberian Sea~~eastern part of the studied region (Fig. ~~2~~3a & c). In contrast, the pattern of silicate concentration ~~is appeared~~ showed opposite as those of nitrite+nitrate and phosphate. The silicate concentration was higher in the ~~East Siberian Sea~~eastern side than in the ~~Laptev Sea~~western part (Fig. 3~~2~~d). Generally, the integrated nutrient concentrations were not depleted within the euphotic depths. Rather, they (except silicate) were nearly depleted in the upper layers (< 10 m), which represented approximately 50 % light depth in this study (Fig. 2). Our findings are consistent with the previous results in the Laptev and East Siberian seas obtained by Codispoti and Richards (1968) who observed that the concentrations of phosphate and nitrate ~~are~~were so low as to indicate nutrient limitation for phytoplankton production in the upper layers. ~~However, our stations~~

~~were substantially deeper (> 200 m bottom depth; Table 1) than those in Codispoti and Richards (1968) which were generally located in shallow shelf regions (< 50 m).~~

The vertical patterns of chl-*a* concentrations were largely variable from surface to 1 % light depth among the productivity stations but the chl-*a* concentrations generally decreased with depth except several stations with strong sub-surface chl-*a* maximum layers (Fig. 4). Surface chl-*a* concentrations ranged from 0.23 mg chl-*a* m^{-3} at AF049 to 2.05 mg chl-*a* m^{-3} at AF019 with an average of 0.64 mg chl-*a* m^{-3} (S.D. = ± 0.51 mg chl-*a* m^{-3}) which are significantly (t-test, $p < 0.01$) higher than those (< 0.1 mg chl-*a* m^{-3}) in previous studies (Lee and Whitledge, 2005; Lee et al., 2012; Yun et al., 2015) from different regions in the Western Arctic Ocean. Water column-integrated chl-*a* concentrations from surface to ~~50 m water~~1 % light depth ranged from 9.9 mg chl-*a* m^{-2} at AF036 to 59.8 mg chl-*a* m^{-2} at AF091 (average ± S.D. = 25.7 ± 14.2 mg chl-*a* m^{-2}) in this study (Fig. ~~3~~5). In comparison to other deep waters in the western Arctic Ocean, this range is significantly higher (t-test, p ~~>~~≤ 0.01) than those in the ice-free deep waters (6.4-24.8 mg chl-*a* m^{-2}) and the newly opened deep waters (7.1-15.1 mg chl-*a* m^{-2}) in the northern Chukchi Sea from mid-August to early September in 2008 (Lee et al., 2012) and in the Canada Basin from mid-August to early September in 2002 (1.6-16.7 mg chl-*a* m^{-2}; Lee and Whitledge, 2005). Furthermore, the recent study in the northeast Chukchi Sea and the western Canada Basin showed a similar lower range of euphotic-integrated chl-*a* concentration (8.3-9.7 mg chl-*a* m^{-2}) during the early summer period with mostly sea ice cover from mid-July to mid-August, 2010 (Yun et al., 2015). Generally, small sized-cells (0.7-5 µm) of phytoplankton appear to be dominant in the euphotic water columns of the Laptev and East Siberian seas based on the size-fractionated chl-*a* data in this study (Fig. ~~4~~6). The contributions of small sized-cells averaged from all the stations were 63.3 (S.D. = ± 17.5 %), 61.4 (S.D. = ± 19.9 %), and 59.0 % (S.D. = ± 18.4 %) at 100, 30, and 1 % light depths, respectively. These ranges are similar to that (64.3 %) in the western Canada Basin (Yun et al., 2015). However, the contributions of small-sized cells in the Canada Basin reported by Lee and Whitledge (2005) are somewhat higher (69.3 %) at the surface but lower (44.4 %) at chl-*a* maximum layer at 50-60 m than those in this study although they were not statistically significant (t-test, $p > 0.05$).

The water column-integrated hourly carbon uptake rates ~~was~~were 0.89-16.60 mg C m^{-2} h^{-1} (average ± S.D. = 4.83 ± 3.52 mg C m^{-2} h^{-1}) in this study (Fig. ~~5~~7). The highest rate was observed at AF019 and the lowest rate was at AF005. The remarkably high uptake rate at AF019 among other productivity stations were mainly due to relatively higher particulate organic carbon (POC) concentrations and specific carbon uptake rates at upper light depths (> 30 % light level). Vertically, the hourly carbon uptake rates were generally highest at the

100-50% light levels among the six different light depths (data not shown). The water column-integrated hourly nitrate and ammonium uptake rate ranges were 0.05-1.96 mg N m^{-2} h^{-1} (average ± S.D. = 0.48 ± 0.52 mg N m^{-2} h^{-1}) and 0.19-3.37 mg N m^{-2} h^{-1} (average ± S.D. = 1.06 ± 0.76 mg N m^{-2} h^{-1}), respectively (Fig. ~~6~~8). Generally, the ammonium uptake rates were relatively higher than the nitrate uptake rates during our cruise period. The total nitrogen (nitrate + ammonium) uptake rate ranged from 0.25 mg N m^{-2} h^{-1} at AF044 to 4.49 mg N m^{-2} h^{-1} at AF019. No specific pattern was observed in the spatial distribution of the carbon and nitrogen uptake rates of phytoplankton in this study.

Assuming a 24-h photoperiod per day during the summer period in the Arctic Ocean (Subba Rao and Platt 1984; Lee and Whitledge 2005; Lee et al., 2010) for a comparison purpose, the daily carbon and nitrogen (nitrate + ammonium) uptake rates of phytoplankton varied substantially, with ranges of 9.9-398.3 mg C m^{-2} d^{-1} (average ± S.D. = 110.3 ± 88.3 mg C m^{-2} d^{-1}) and 6.0-107.7 mg N m^{-2} d^{-1} (average ± S.D. = 37.0 ± 25.8 mg N m^{-2} d^{-1}), respectively. Although the water column-integrated chl-*a* concentration is significantly higher (approximately five-fold) in this study than in other deep waters in the western Arctic Ocean, as previously mentioned above, our mean daily carbon uptake rate (110.9 mg C m^{-2} d^{-1}) are relatively equivalent to previously reported rates (Cota et al., 1996; Lee and Whitledge, 2005; Hill et al., 2017). Cota et al. (1996) and Lee and Whitledge (2005) obtained rate of 123.5 mg C m^{-2} d^{-1} and 106 mg C m^{-2} d^{-1} in the Canada Basin, respectively. However, the mean daily carbon rates in the northeast Chukchi Sea (29.8 mg C m^{-2} d^{-1}) and western Canada Basin (20.6 mg C m^{-2} d^{-1}) reported by Yun et al. (2015) were substantially lower than those in other measurements. These lower values are mainly due to their measurements conducted in the early ice-opening season with a considerably heavy sea ice concentration over 70 % (Yun et al., 2015). The sea ice concentration in this study ranged widely from 0 % to 100 %, mostly ice free conditions with an average of 20 % during the cruise period (Table 1).

The mean daily nitrogen uptake rate (average ± S.D. = 37.0 ± 25.8 mg N m^{-2} d^{-1}) is comparable to the rates previously reported in the western Arctic Ocean (Lee and Whitledge, 2005; Lee et al., 2012). Lee and Whitledge (2005) measured 30.5 mg N m^{-2} d^{-1} (S.D. = ± 16.2 mg N m^{-2} d^{-1}) in the Canada Basin, and Lee et al. (2012) observed 33.4 mg N m^{-2} d^{-1} (S.D. = ± 18.4 mg N m^{-2} d^{-1}) in the deep, ice-free northern Chukchi Sea. Based on the nitrate and ammonium uptakes rates, the *f*-ratio averaged from all the productivity stations in this study was 0.28 (S.D. = ± 0.17; Fig. ~~7~~9), which is comparable to the average *f*-ratios (0.22-0.34) previously reported in the western Arctic Ocean (Lee and Whitledge, 2005; Lee et al., 2012; Yun et al., 2012; Codispoti et al., 2013). The low *f*-ratio estimated in this study indicates that the predominant nitrogen source for phytoplankton growth was ammonium at that time of sampling. There are two possible explanations for that result: the low amount of nitrate available for phytoplankton growth (Kim et al., 2015) and the existence of low light growth conditions (Lee and Whitledge, 2005; Yun et al., 2012). The nitrate uptakes of phytoplankton are reported to be more strongly coupled with light than ammonium uptakes (Dortch and Postel 1981). Relatively low *f*-ratios were observed overall in the Laptev and East Siberian seas even though there were some nitrate concentrations available within the euphotic water depths (Fig. 3). In fact, no strong relationship between *f*-ratio and euphotic water depth-integrated concentration of nitrite+nitrate was found in this study ($R^2 = 0.02$). This provides indirect evidence for potential light-limited conditions for phytoplankton growth in the Laptev and East Siberian seas during the study period. However, we need to be cautious for the conclusion of light-limited phytoplankton growth in this study. Based on the size-fractionated chl-*a* concentrations, major contributors to the phytoplankton community in this region were small sized-cells throughout the euphotic water columns in this study (Fig. 6). Generally, these small sized-cells prefer ammonium than nitrate as a nitrogen source for their growth (Tremblay et al., 2002; Lee et al., 2012). In fact, Lee et al. (2012) observed significantly lower *f*-ratios for small sized-cells in the Western Arctic Ocean. Therefore, the low *f*-ratios in this study could be caused by relative ammonium preference of the small cells-dominant phytoplankton community in in the Laptev and East

Siberian seas during the study period.

Codispoti et al. (2013) suggests that a nutrient-limited condition of phytoplankton production exists in the Laptev and East Siberian seas because of limited inorganic nutrient availability (phosphate and nitrate) at the surface (Codispoti and Richards, 1968). Generally, carbon/nitrogen (C/N) ratios have been used to an indicator of nutrient condition of phytoplankton (Smith and Sakshaug 1990; Lee and Whitledge, 2005; Yun et al., 2012). For example, high C/N ratios are often indicative of nitrogen deficiency for phytoplankton growth (Smith and Sakshaug 1990). The C/N ratio of particulate organic matters and assimilated C/N ratio averaged from all the productivity stations were 7.23 (± 5.51) and 7.03 (± 5.14), respectively in this study. These C/N ratios similar to the Redfield ratio (6.6) indicate no strong nutrient-limited condition of phytoplankton production during the cruise period in 2013. In this study, the relatively lower daily carbon uptake rate despite of significantly higher chl-*a* concentration could be caused by a potential light-limited growth condition of phytoplankton in the Laptev and East Siberian seas. In fact, there was no strong relationship between water column-integrated POC and chl-*a* concentrations as representative biomass for phytoplankton and daily carbon uptake rate in this study (R^2 = 0.001), which indicates that phytoplankton biomass itself is not a main factor for the different carbon uptake rates from the productivity stations during this cruise period.

However, no relationship between POC and chl-*a* concentrations in this study could be caused by natural characteristics of POC samples since it normally includes all suspended organic carbon (detritus, bacteria, microzooplankton, etc.) as well as phytoplankton carbon. In general, the ratio of C/chl-*a* is lower for phytoplankton under low light conditions than under high light conditions, although it is highly variable depending on all other environmental conditions that affect the growth rate of phytoplankton (Smith and Sakshaug, 1990). Based on cultures of polar or subpolar phytoplankton, the ratio ranges from 20-50 in low light conditions to 100-200 in high light conditions (Smith and Sakshaug, 1990). In fact, Lee and Whitledge (2005) found that ratios in the Canada Basin (16.8 at approximately 2% light level of surface irradiance to 314 at surface water) were comparable to the laboratory-measured ratios. In this study, the C/chl-*a* ratio averaged from all the productivity stations was 290.8 (S.D. = ± 164.4), which indicates no light-limited condition. Since POC contains not only phytoplankton carbon but also all suspended organic carbon, the C/chl-*a* ratio might not be a good indicator in the Laptev and East Siberian seas with large terrestrial inputs during the ice-free summer season (Macdonald et al., 2010; Anderson et al., 2011).

At this point, we do not have a good explanation for the lower carbon uptake rate despite of substantially high chl-*a* concentration of phytoplankton in the Laptev and East Siberian seas during our observation period. Based on various indicators in this study, the growth of phytoplankton in the Laptev and East Siberian seas may have experienced a light-limited condition as well as the nutrient-limited condition, both of which are generally considered to occur in the Arctic Ocean during the summer periods (Codispoti and Richards, 1968; Codispoti et al., 2013).

For a comparison purpose, same assumptions used previously in the Arctic Ocean were applied for estimating the annual primary production in this study. ~~Assuming~~ Based on a 120-day growing season and the ~~same~~constant daily productivity over the growing season in the Arctic Ocean (Subba Rao and Platt, 1984; Gosselin et al. 1997; Lee and Whitledge 2005; Lee et al. 2012; Yun et al., 2015), the annual primary production (13.2 g C m^{-2}) during the arctic vegetative season roughly estimated in this study is comparable to the indirect estimation (9.6 g C m^{-2}) from drawdown measurements of dissolved inorganic carbon in the East Siberian Sea (Anderson et al., 2011). In addition, Hill et al. (2017) confirmed the annual primary production of 8 g C m^{-2} in the East Siberian Sea which is consistent with other estimates (Codispoti et al., 2013; Popova et al., 2010), based on the seasonal *in situ* primary production data from the ARCSS-PP database. However, these production~~s~~ levels are substantially (approximately one order magnitude) lower than the mean production~~s~~ estimates (101-121 g C m^{-2}) in the Laptev and Siberian seas for 1998-2009 estimated from satellite-based measurements (Arrigo and Dijken 2011). Unfortunately, no annual primary production estimated in 2013 by Arrigo and Dijken (2011) makes difficult for a direct comparison of annual productions in 2013 between our measured rates and their satellite-based rates. In fact, uncertainties associated with each productivity-derived method specifically versus *in situ* measurements versus satellite-based methods are complicated (Grebmeier et al. 2015). *In situ* measurements could be open to various incubation artifacts whereas satellite imagery could be biased low and high in the Arctic Ocean (Grebmeier et al. 2015). An overestimation of satellite-derived primary production in the Arctic Ocean is generally caused by an overestimation of chl-*a* concentration from massive colored dissolved organic matter (CDOM) of terrestrial origin and degraded phytoplankton (Guéguen et al., 2007; Matsuoka et al., 2011; Lewis et al., 2016). Indeed, large terrestrial inputs of dissolved and particulate organic matter are transported from substantial inputs of river runoff such as from the Lena, Indigirka, and Kolyma rivers to the shelves of the Laptev and East Siberian seas during the ice-free summer season (Macdonald et al., 2010; Anderson et al., 2011). Arrigo and Dijken (2011) also discussed a potential overestimation by the CDOM which causes some overestimation in surface chl-*a* and thus net primary production from satellite-based approaches. However, they argued that the overestimation of net primary production as high as 6.1 % is nearly equivalent to the underestimated portion (7.6 %) by missing subsurface chl-*a* maximum (SCM) layer in the Arctic Ocean. In this study, the SCM layers were also detected ~~but not~~ common in overall productivity stations ~~(6 stations out of 19 productivity stations)~~ during the cruise period (~~data not shown~~Fig. 4). ~~However~~Regional coverages could cause the difference in the annual primary productions between this and their studies. The geographic sectors defined by Arrigo and Dijken (2011) include a large part of coastal regions which have generally high primary productivities (Arrigo et al., 2008). By comparison, our productivity stations were located in deep waters (> 200 m bottom depth; Table 1) which have relatively lower primary productivities (Arrigo et al., 2008).

In spite of the considerations for potential difference between the two methods, our filed-measured annual production is surprisingly lower compared to the satellite-derived production in the Laptev and East Siberian seas~~, although our productivity in this study were executed at one time period in 2013~~. At this stage, our simple comparison of the primary production between this study and the satellite based-study is preliminary since our productivity measurements in this study are very limited for one time period in 2013. Based on more field measurements from different seasons and years as well as coastal regions, ~~F~~further careful validation between the two different methods (field measurement vs. satellite-derived approach) is needed for a better understanding of the least biologically studied region undergoing severe and ongoing environmental changes in the Arctic Ocean.

4. Summary and Conclusion

Field-measured phytoplankton productivity and nutrient concentrations were obtained in the Laptev and East Siberian seas, one of the least biologically studied regions in the Arctic Ocean (Semiletov et al., 2005; Arrigo and Dijken, 2011), during the NABOS (Nansen and Amundsen Basins Observational System) cruise from August 21 to September 22, 2013 (Fig. 1).

During the cruise period, the nutrient concentrations within the euphotic depths were not depleted although they were depleted in the upper layers which are consistent with the previous results (Fig. 2). The euphotic water column-integrated chl-*a* concentration (25.7 ± 14.2 mg chl-*a* m^{-2}; Fig. 3) was significantly higher in this study than those previously reported in the other parts of the Arctic Ocean (Lee and Whitledge, 2005; Lee et al., 2012). Among the different cell sizes of phytoplankton, small phytoplankton were dominant (approximately 60 %) in the Laptev and East Siberian seas (Fig. 4). Based on the low *f*-ratio (0.28 ± 0.17; Fig. 7) observed in this study, ammonium appears to be the predominant nitrogen source for phytoplankton growth in the Laptev and East Siberian seas during our sampling period although there were some nitrate concentrations available within the euphotic depths.

The daily carbon uptake rate (110.3 ± 88.3 mg C m^{-2} d^{-1}) and nitrogen uptake rate (37.0 ± 25.8 mg N m^{-2} d^{-1}) in this study were somewhat comparable to the rates previously reported in the Arctic Ocean (Cota et al., 1996; Lee and Whitledge, 2005; Lee et al., 2012). This is a surprising result since the water column-integrated chl-*a* concentration in this study is significantly higher (approximately five-fold) compared to the previous results. Various indicators determining light or nutrient-limited conditions were suggested for the mismatch between the higher chl-*a* concentration and relatively lower carbon and nitrogen uptake rates. However, no consistent results were obtained because of some inherent problems of POC including all suspended organic carbon in addition to phytoplankton carbon.

The annual primary production (13.2 g C m^{-2}) estimated in this study is somewhat equivalent to the indirect measurements (9.6 g C m^{-2}) from dissolved inorganic carbon ~~in the East Siberian Sea~~ (Anderson et al., 2011) and 8 g C m^{-2} based on the ARCSS-PP database (Hill et al., 2017) in the East Siberian Sea. However, the satellite-based estimations (101-121 g C m^{-2}) reported by Arrigo and Dijken (2011) were substantially higher in the Laptev and Siberian seas. This large discrepancy between the field-measured and satellite-derived primary productions ~~might be caused by the overestimated chl-*a* concentration and primary production from CDOM of degraded phytoplankton and terrestrial origin (Guéguen et al., 2007; Matsuoka et al., 2011)~~ was discussed~~.~~ but our simple comparison is preliminary at this stage. More field-measured data are needed to understand the mismatch between the chl-*a* concentration and primary production and will be valuable for further validation of satellite-derived primary productions in the Laptev and East Siberian seas.

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Table caption

Table 1. Geographical and physical information ~~of~~at the productivity measurement stations in the Laptev and East Siberian seas. Sea ice concentration was retrieved from National Snow & Ice Data Center during the cruise period in 2013.

Figure captions

Figure 1. Hydrographic stations and sea ice concentration in NABOS 2013. Red dots represent productivity-measured stations. Sea ice concentration data provided from National Snow & Ice Data Center were averaged during the cruise period in 2013.

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Figure 4. Vertical distribution of chl-*a* concentration (mg chl-*a* m^{-3}) from surface to 1 % light depth at the productivity stations in the Laptev and East Siberian seas during the cruise period in 2013.

Figure ~~3~~5. Spatial distribution of chl-*a* concentration (mg chl-*a*~~mmol~~ m^{-2}) integrated from surface to 50 m water depth in the Laptev and East Siberian seas during the cruise period in 2013.

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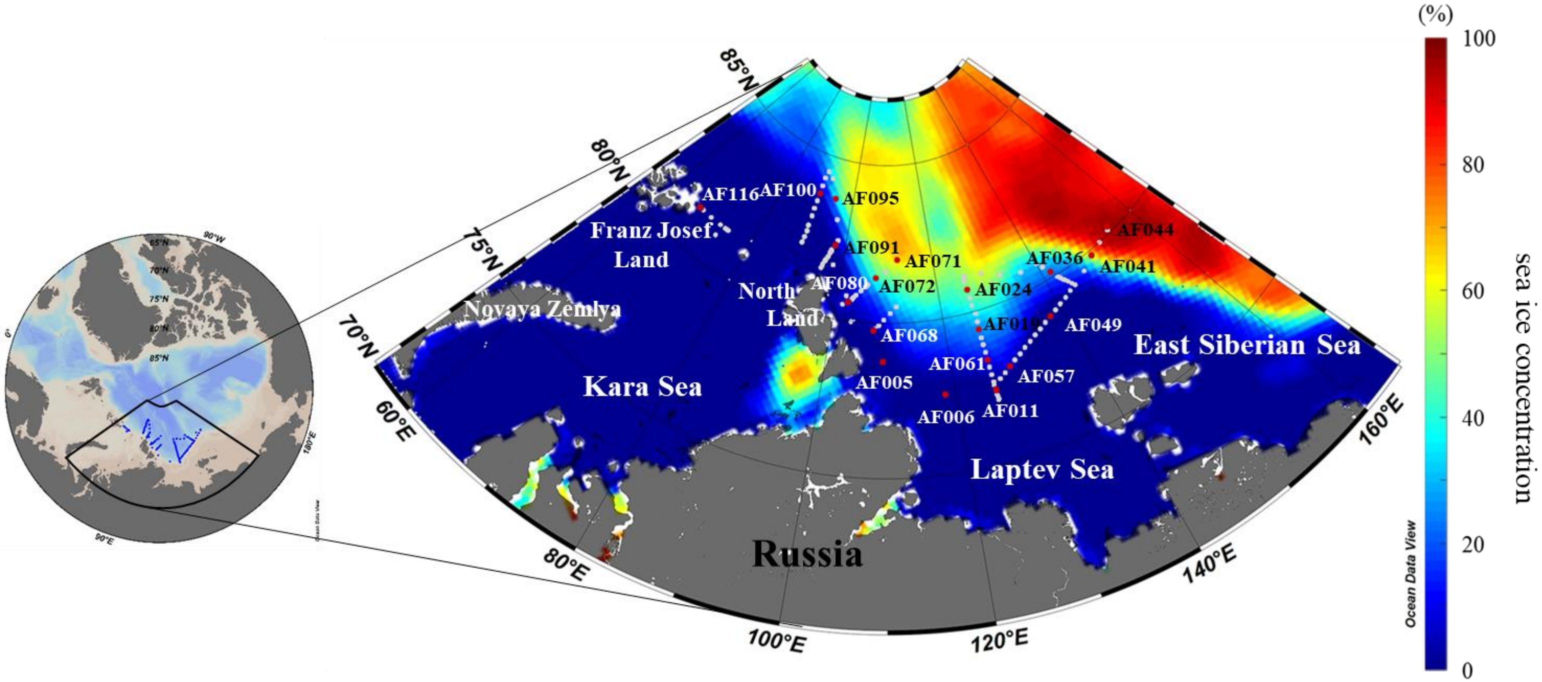
Table 1. Geographical and physical information of the productivity stations in the Laptev and East Siberian seas. Sea ice concentration was retrieved from National Snow & Ice Data Center during the cruise period in 2013.

Station	Location		Date (mm/dd/yyyy)	Depth (m)	Sea surface temperature (℃)	Sea surface salinity (psu)	Sea ice concentration (%)
	Longitude (ºE)	Latitude (ºN)					
AF005	109.2031	78.7811	8/25/2013	283	-0.08	31.42	0
AF006	118.4494	77.5925	8/26/2013	1244	0.75	31.36	0
AF011	125.8045	77.4005	8/27/2013	1543	1.62	30.01	0
AF019	125.7401	79.4156	8/28/2013	3196	-1.6	32.44	25
AF024	125.6861	80.7248	8/29/2013	3730	-1.48	30.96	45
AF036	141.5607	80.1791	9/1/2013	1480	-1.22	28.29	25
AF041	149.3758	79.8456	9/2/2013	561	-1.57	29.86	60
AF044	154.9831	80.2246	9/3/2013	1904	-1.67	30.91	100
AF049	137.7743	78.9502	9/5/2013	1552	1.57	29.09	0
AF057	128.8313	77.9848	9/5/2013	2325	1.49	30.25	0
AF061	125.825	78.399	9/6/2013	2700	-0.07	31.39	10
AF068	107.3858	79.7628	9/10/2013	1200	-0.35	32.57	0
AF071	112.0952	82.0163	9/11/2013	3530	-1.73	31.86	65
AF072	107.4838	81.4388	9/12/2013	3349	-1.75	32.37	40
AF080	102.3065	80.6008	9/13/2013	315	-1.14	32.81	0
AF091	97.5466	82.3014	9/14/2013	2959	-1.32	33.3	0
AF095	94.7876	83.7409	9/15/2013	3668	-1.76	32.36	40
AF100	90.0078	83.7489	9/16/2013	3410	-1.49	33.29	0
AF116	66.8714	81.3366	9/19/2013	530	0.47	33.44	0



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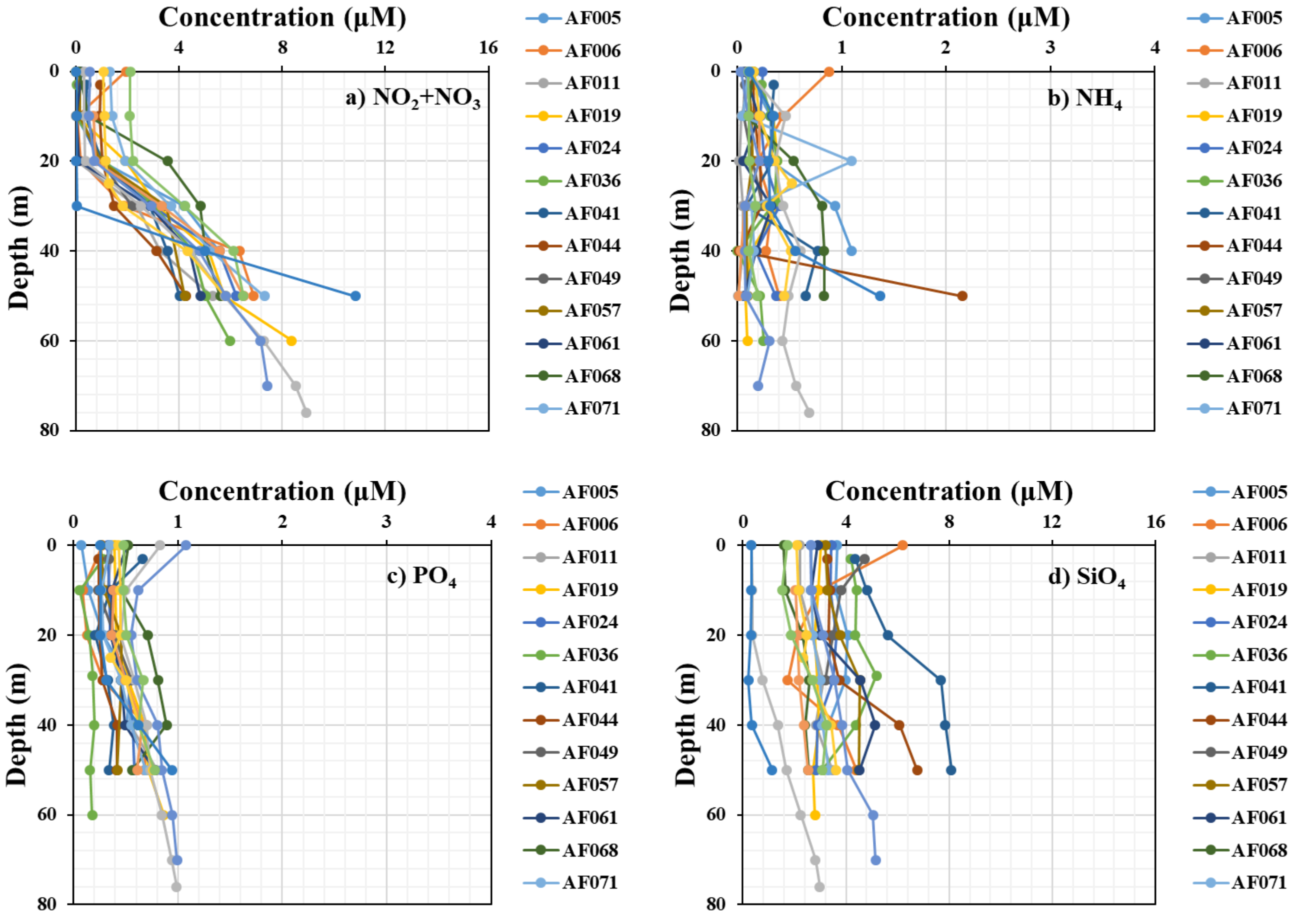

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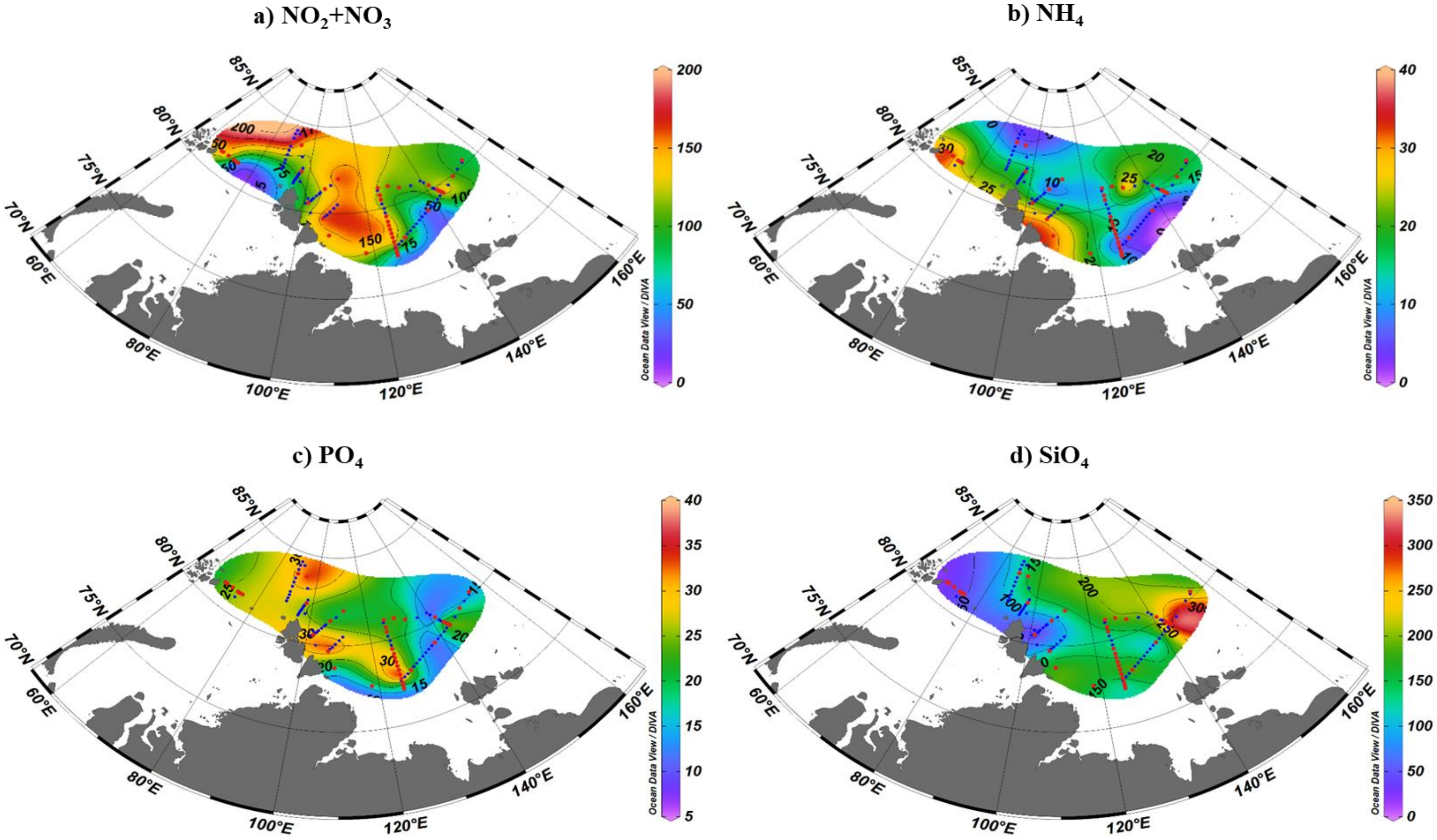

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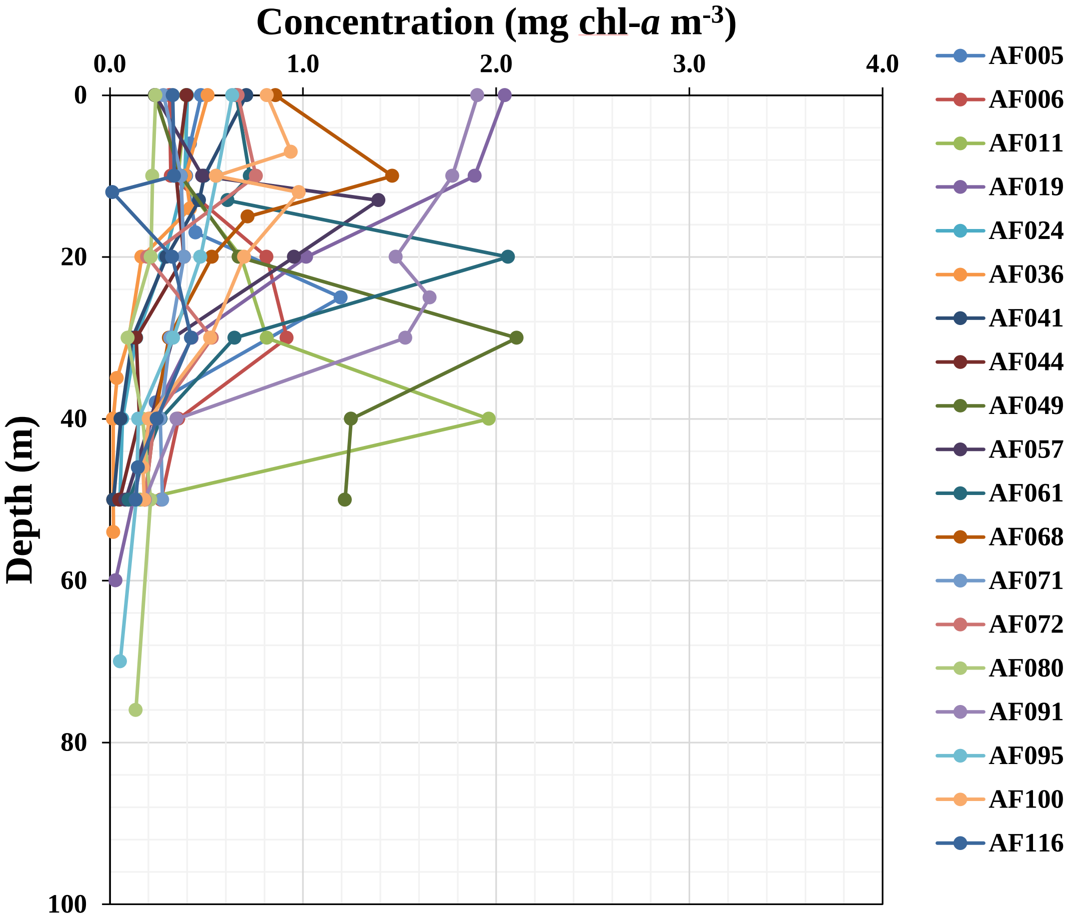

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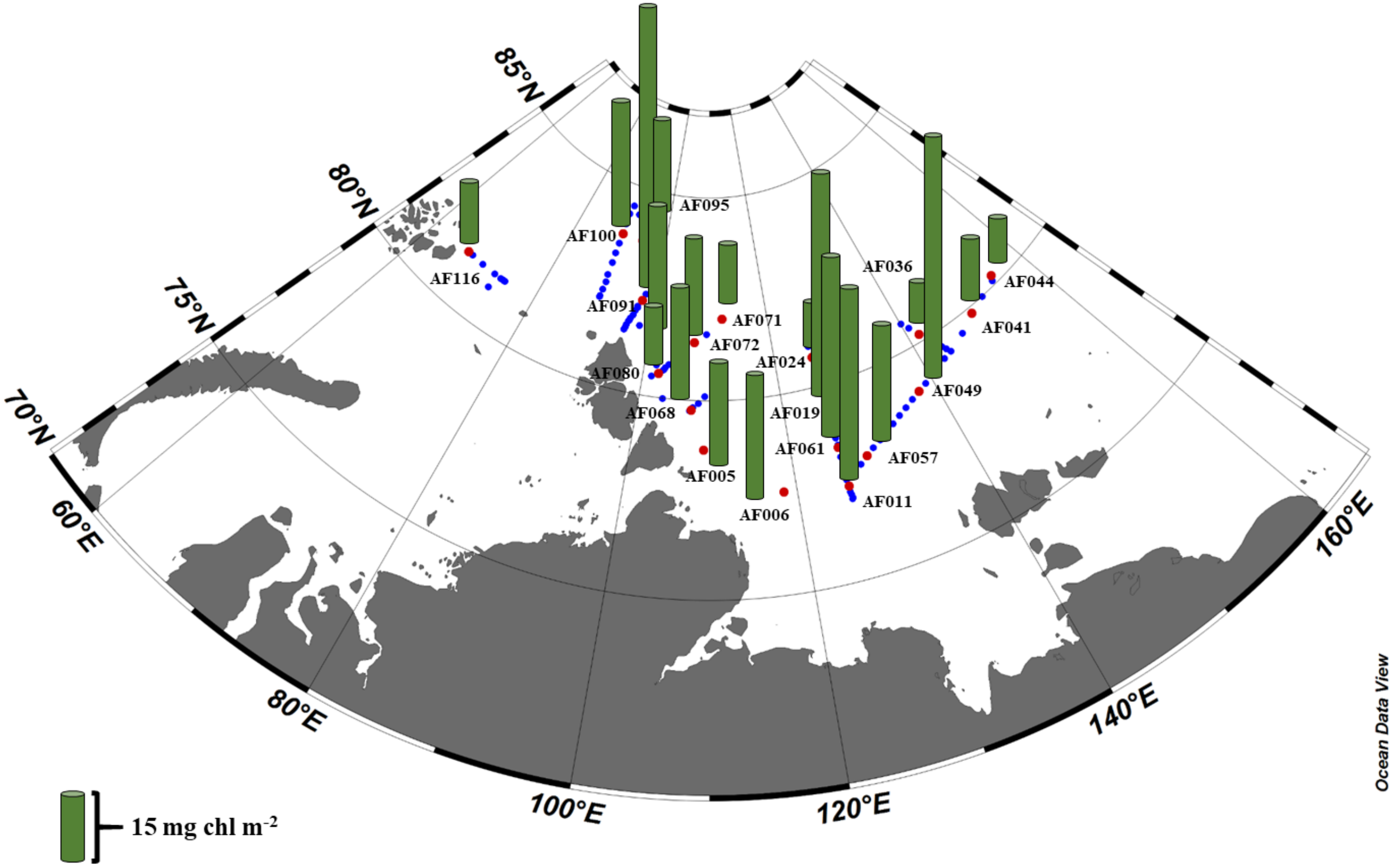

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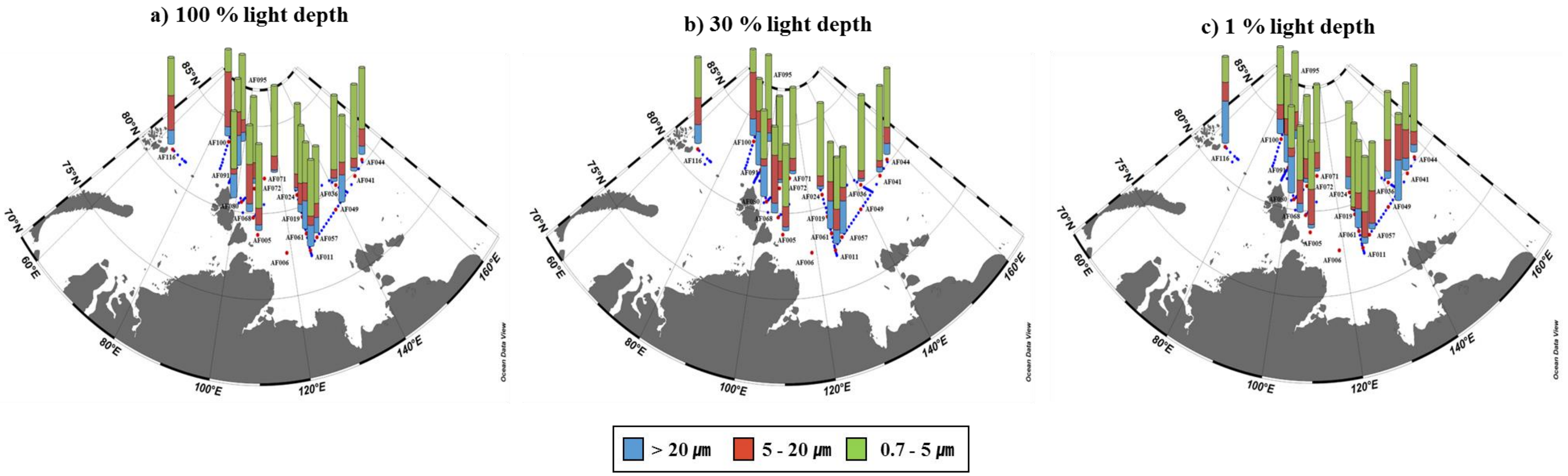

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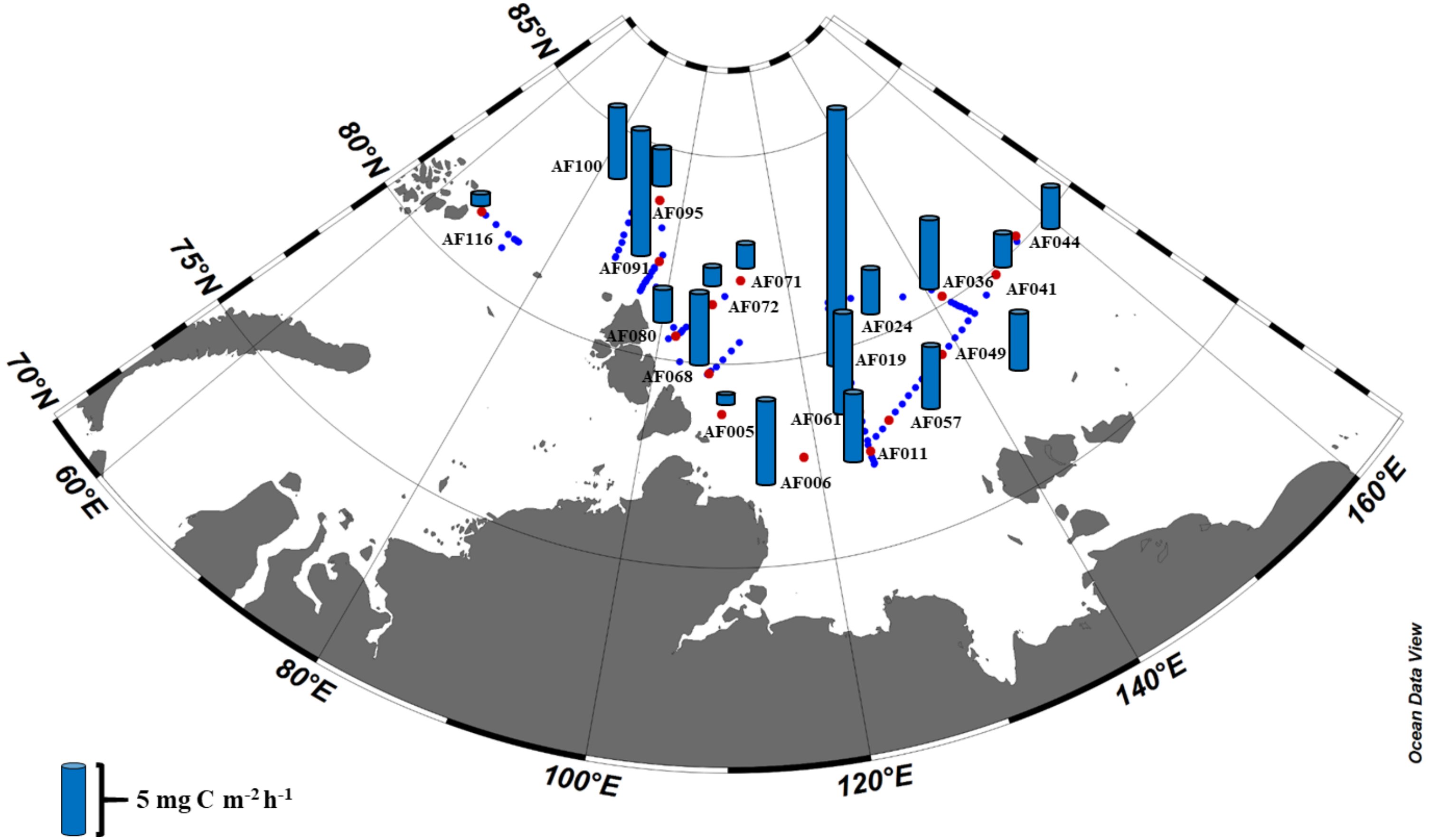

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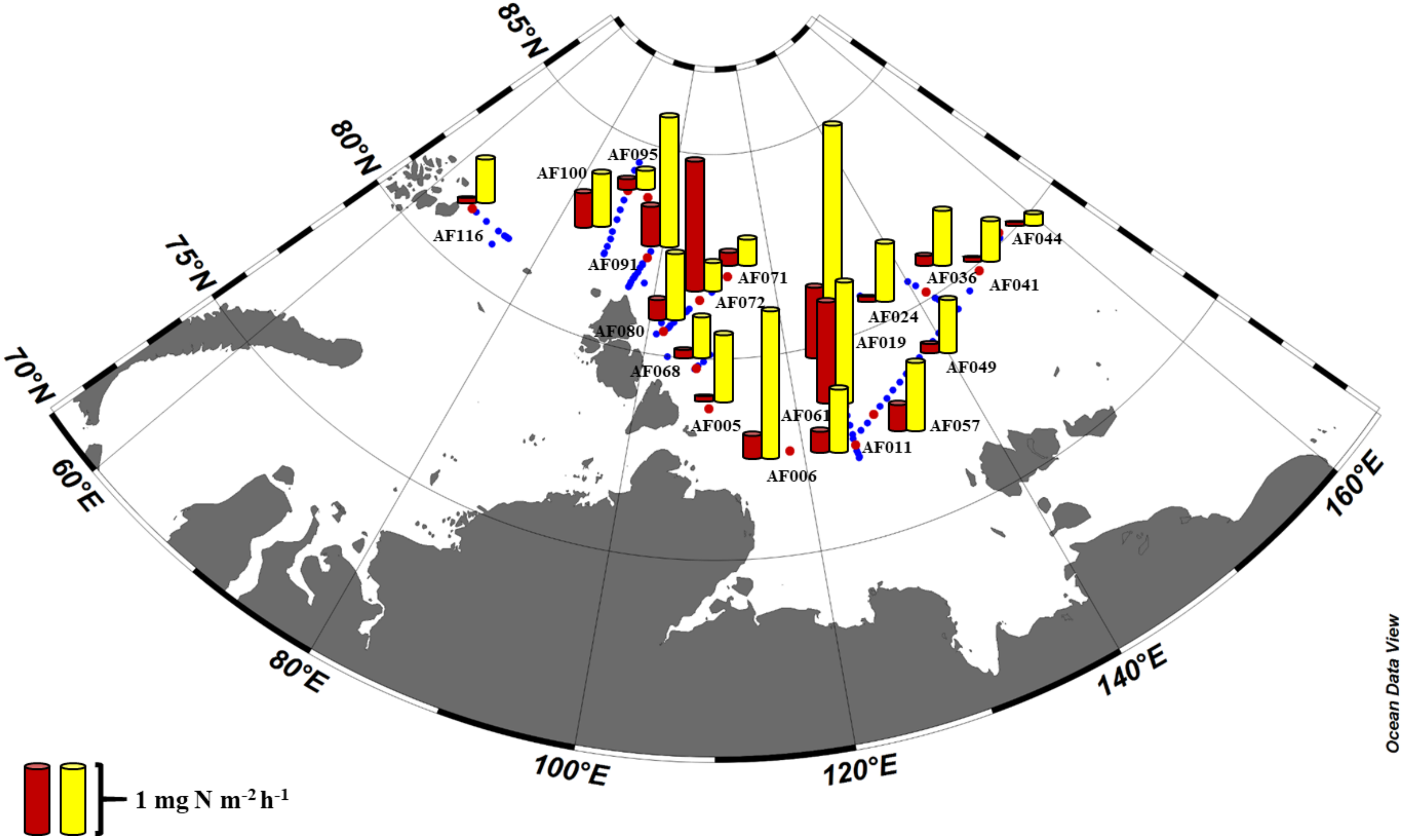

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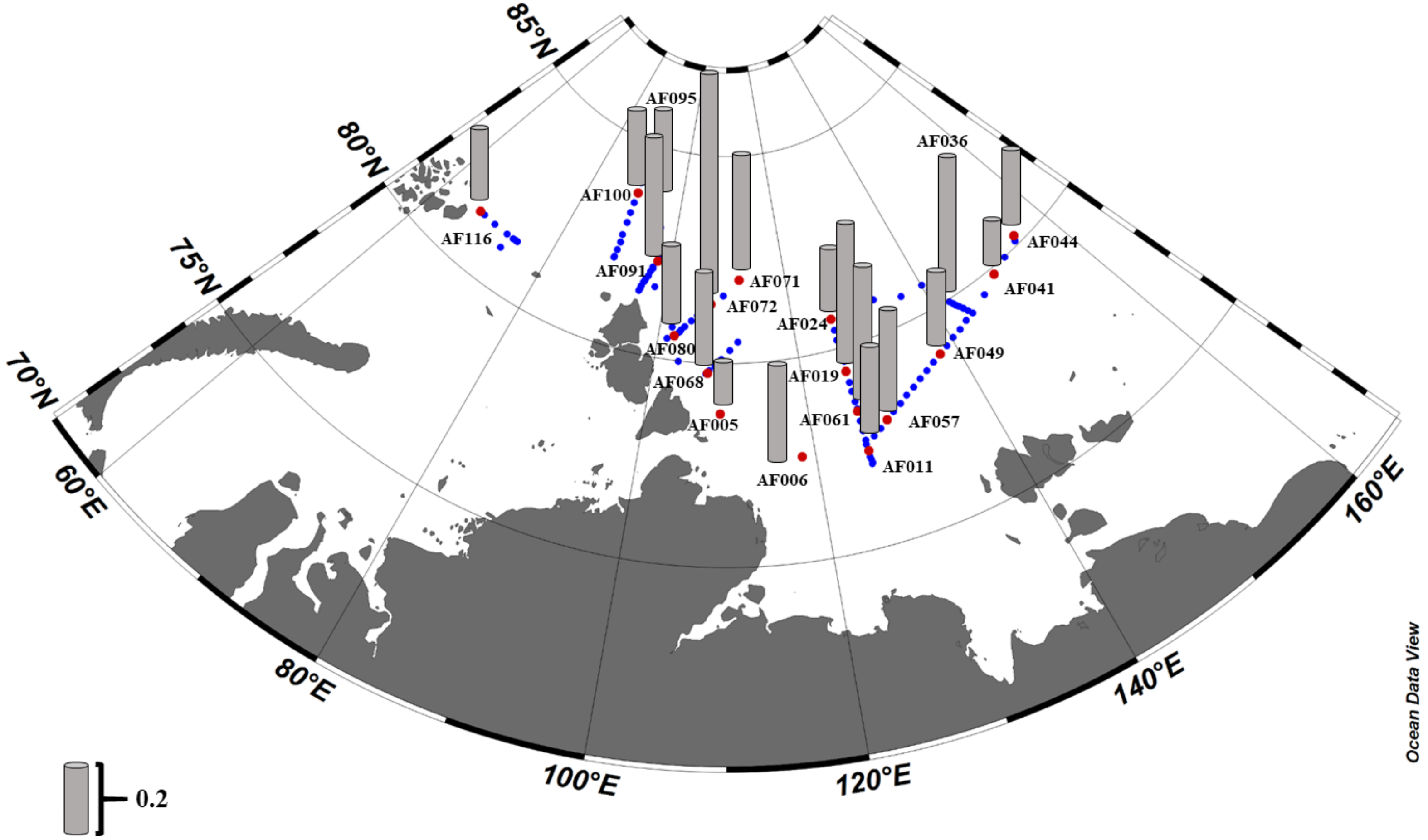

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