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## **RESEARCH ARTICLE**

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#### **Kev Points:**

- In the seasonal ice zone, significant phytoplankton activity occurs under ice earlier in the season
- · At the ice edge, a high phytoplankton biomass is present around a subsurface chlorophyll maximum feature that persists into summer
- Half of the annual Net Community Production occurs under ice and the other half at the ice edge

**Supporting Information:** 

• Supporting Information S1

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# Assessing Phytoplankton Activities in the Seasonal Ice Zone of the Greenland Sea Over an Annual Cycle

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Abstract In seasonal ice zones (SIZs), such as the one of the Greenland Sea, the sea ice growth in winter and subsequent melting in summer influence the phytoplankton activity. However, studies assessing phytoplankton activities over complete annual cycles and at a fine temporal resolution are lacking in this environment. Biogeochemical-Argo floats, which are able to sample under the ice, were used to collect physical and biogeochemical data along vertical profiles and at 5-day resolution during two complete annual cycles in the Greenland Sea SIZ. Three phytoplankton activity phases were distinct within an annual cycle: one under ice, a second at the ice edge, and a third one around an open-water subsurface chlorophyll maximum. As expected, the light and nitrate availabilities controlled the phytoplankton activity and the establishment of these phases. On average, most of the annual net community production occurred equally under ice and at the ice edge. The open-water subsurface chlorophyll maximum phase contribution, on the other hand, was much smaller. Phytoplankton biomass accumulation and production thus occur over a longer period than might be assumed if under ice blooms were neglected. This also means that satellite-based estimates of phytoplankton biomass and production in this SIZ are likely underestimated. Simulations with the Arctic-based physical-biologically coupled SINMOD model suggest that most of the annual net community production in this SIZ results from local processes rather than due to advection of nitrate from the East Greenland and Jan Mayen Currents.

### 1. Introduction

The timing and the quantity of the phytoplankton production are already changing in the pan-Arctic area (Arrigo et al., 2008; Arrigo & van Dijken, 2015; Ji et al., 2013; Kahru et al., 2011, 2016), with consequences for biogeochemical cycles (Tremblay et al., 2015; Wassmann et al., 2006; Wassmann & Reigstad, 2011), the zooplankton production and the production in higher trophic levels (Hunt et al., 2016; Leu et al., 2011; Wassmann, 2011; Wassmann & Reigstad, 2011). The seasonal ice zone (SIZ) of the Greenland Sea basin, an area of the pan-Arctic system, in the future will mainly experience a smaller proportion of sea ice cover (Carmack & Wassmann, 2006; Michel et al., 2015). A reduced sea ice concentration in the SIZ, with thinning ice and a strengthening of the vertical stratification of the water column, will, for example, influence the light regime experienced by the microalgae (ice algae and phytoplankton, e.g., Wassmann, 2011) and the nutrient limitation may become more prominent (Hunt et al., 2016; Michel et al., 2015; Tremblay et al., 2015).

The biological production occurring in the SIZ is linked to the sea ice where microalgae within brine channels become productive as soon as there is enough light available (Leu et al., 2015). The atmospheric conditions, the snow cover, and sea ice properties influence this light availability (e.g., Assmy et al., 2017; Frey et al., 2011). At the interface with the water column, microalgal cells attached to the bottom of the ice can also be present and productive (Leu et al., 2015). These primary production events inside sea ice or at the interface with the water column are the first important productive events in the SIZ ecosystem (Leu et al., 2011, 2015). Later, in summer, the melting of sea ice induces a strong stratification of the water column at the marginal ice zone (MIZ). The increase in vertical stratification allows phytoplankton cells to remain within surface layers and to experience a better light regime in comparison to the previous dark winter period (e.g., Wassmann, 2011). Phytoplankton accumulation at the ocean surface then increases remarkably and forms the ice edge bloom. Past in situ oceanographic cruises conducted in the Subartic Atlantic areas (i.e., Greenland and Barents Seas mainly) have described the ice edge bloom as a high but short productive biological event (Gradinger & Baumann, 1991; S. L. Smith et al., 1985; W. O. Smith et al., 1987; W. O. Smith & Sakshaug, 1993;

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Wassmann et al., 2006). At the conclusion of the ice edge bloom event, when surface nutrient concentrations become low, the development of a subsurface chlorophyll *a* maximum (SCM) occurs (Gradinger & Baumann, 1991; W. O. Smith et al., 1987; Strass & Nöthig, 1996; Tremblay et al., 2015). This winter-to-summer transition has been summarized with conceptual models (Carmack & Wassmann, 2006; Leu et al., 2015; W. O. Smith & Niebauer, 1993; W. O. Smith & Sakshaug, 1993; Wassmann et al., 2006); how-ever, most of the available data cover the late spring-summer transition instead. Presently, it is crucial to quantify and understand the importance of each phase occurring in the SIZ (from the dark under-ice period to the summer ice edge bloom at the MIZ and the SCM feature) in order to better represent them in models and predict the potential consequences of climate change on the SIZ ecosystem and related biogeochemical cycles.

In terms of phytoplankton activity, Arrigo et al. (2012) have reported a high and extensive microalgal biomass under sea ice in the Chukchi Sea. Multiple field experiments confirm the presence of significant phytoplankton biomass under sea ice at different locations in the Arctic (e.g., Fram Strait, Canadian Archipelago, and Arctic Ocean) (Assmy et al., 2017; Laney et al., 2014; Mundy et al., 2009, 2014). Historically, the seeding of this under-ice phytoplankton community has been ascribed to a release of ice algae (e.g., Schandelmeier & Alexander, 1981), although differences in community composition between sea ice algae and under-ice phytoplankton challenge this seeding hypothesis (Assmy et al., 2017; Mundy et al., 2014; Selz et al., 2018; W. O. Smith & Nelson, 1985). Its effect on the annual production was suggested by observations of significant nitrate depletion prior to sea ice melting (Matrai & Apollonio, 2013; Tremblay et al., 2008). For example, Matrai and Apollonio (2013) suggested that more than half of the annual net community production (NCP) could occur under sea ice in the Canadian Arctic Archipelago. In situ simultaneous physical and biogeochemical observations over an annual cycle in this hard-to-reach environment of the SIZ will allow verification and quantification of the importance of the pre-ice edge and post ice edge bloom periods in the annual budget of community production in the SIZ.

Ocean color investigations provide a good opportunity to study the open-water phytoplankton production over the pan-Artic area and, to a certain extent, in the MIZ (Arrigo et al., 2014; Perrette et al., 2011). Focusing on the ice-edge bloom, Perrette et al. (2011) found that satellite observations can only provide ocean color information when sea ice concentration is below 10%, although they also suggested that the bloom may start at concentration >10%. In fact, the presence of sea ice prevents accurate observation of phytoplankton activity, due to optical signal interference and resulting low performance of current ocean color algorithms in MIZ areas (e.g., Bélanger et al., 2007). In addition, satellite observations hardly detect the subsequent SCM feature, which appears after the ice edge bloom and lasts into summer (Ardyna et al., 2013; Arrigo et al., 2011; V. Hill et al., 2013). While much of the discussion has occurred on the relative input of the SCM on a pan-Arctic scale, at regional and local scales, the importance of SCM to the annual primary production can be very high (Ardyna et al., 2013). Until these proved limitations of the ocean color observations are overcome, it is necessary to continue to obtain high frequency and long-term in situ observations in the SIZ, especially with concurrent in situ physical and biogeochemical observations.

In the study herein, data from biogeochemical-Argo floats (hereafter BGC-Argo floats) deployed in the Greenland Sea will be analyzed. The miniaturization of biogeochemical sensors allow their implementation on autonomous underwater vehicles (AUVs, e.g., ice-tethered profilers, gliders and Argo floats). Successful deployments of AUVs in the pan-Arctic area provide new physical and biogeochemical insights, even in the presence of sea ice (e.g., Laney et al., 2014; Wulff et al., 2016). Nowadays, BGC-Argo floats are largely used to evaluate the NCP in different ocean basins (e.g., Bushinsky & Emerson, 2015; Hennon et al., 2016; Plant et al., 2016; Riser et al., 2018; Yang et al., 2017). Here invaluable observations over multiple years from BGC-Argo floats that sampled the SIZ of the Greenland Sea, mainly under the sea ice in winter and at the MIZ in summer, are discussed. These observations represent one of the first physical and biogeochemical data sets collected at a fine temporal resolution (5 days) in a SIZ over several annual cycles.

The challenge is to analyze the annual phytoplankton activity in the SIZ and quantify its influence on the annual budget of the NCP. More specifically, the presence of possible under-ice phytoplankton activity is first assessed. Next, the transition in summer of the phytoplankton activity from the ice edge to the open-ocean environments is investigated. Some potential mechanisms regulating the phytoplankton



activity in the SIZ are proposed. The observed phytoplankton biomass in the SIZ that may be missed by satellite observations is also specifically addressed. Finally, the temporal evolution of the NCP over the annual cycle is assessed, as well as the mechanisms that affect its variability in relation to phytoplankton activities.

#### 2. Data and Methods

Two BGC-Argo floats were deployed in the north-central Greenland Sea (dots in Figure 1a): a first one in August 2011 followed by a second one in August 2012. Soon after its deployment, the first BGC-Argo float was entrained into the southward flowing East Greenland Current and went east at the northern edge of the Jan Mayen Ridge, where it stayed for a year (Figure 1b—2012; trajectory for August 2011 to January 2012 not shown). The second one spent a year in the central gyre of the Greenland Sea (Figure 1b—2013; trajectory for August 2012 to January 2013 not shown), followed a similar trajectory for a second year as the first BGC-Argo float (Figure 1b—2014), and finally stayed north of the Jan Mayen Island for its third and last sampling year (Figure 1b—2015). Both BGC-Argo floats were equipped with conductivity-temperature-depth (CTD) sensors, an oxygen optode, a nitrate sensor, a chlorophyll *a* measuring fluorometer and a backscatter sensor (details provided below). They collected vertical profiles every 5 days to record data from 1,000 m to the surface. Most of all, during their ascent, floats were programmed to infer the possible presence of sea ice at the ocean surface. If the 10–30 dbar mean temperature was  $<-1^{\circ}$ C, floats assumed that sea ice was present and terminated their ascent at 10 m then saved the vertical profile data collected and descended without surfacing, in order to avoid damage. Floats transmitted their data when they were able to surface again later in the year.

In total, four complete annual cycles (January to December 2012–2015) of vertical profiles of physical and biogeochemical variables are available. According to the BGC-Argo float trajectories (Figure 1b), two of the available annual cycles were observed in open-ocean areas (in 2013 and 2015) and two others in the SIZ area (in 2012 and 2014). For these last two annual cycles, floats activated their ice avoidance algorithm from March to June or July. According to the sea ice cover in the area (Figure 1b, data obtained from the National Snow and Ice Data Center (NSIDC)—see section 2.5), floats effectively profiled under sea ice during these winter periods and in the SIZ most of the year (in 2014, the float probably left the SIZ in early November). Note that when floats activated their ice avoidance algorithm, their positions were unknown, and so their trajectories are assumed linear between the last and next known locations (dotted lines, circled in red, in Figure 1b).

#### 2.1. Salinity, Temperature, and Density

The data quality control of the Argo program (http://doi.org/10.13155/33951) was applied to the salinity (PSS-78) and temperature (in °C) values derived from CTD sensors (Seabird 41CP); only data flagged *good* were retained. Using the international thermodynamic equation of seawater—2010 (McDougall & Barker, 2011), estimates of potential temperature ( $\Theta$  in °C) and density ( $\sigma$  in kg/m<sup>3</sup>) were obtained. Then, for each vertical profile, the mixed layer depth (MLD) was estimated using the potential density profile and was defined as the depth where the potential density exceeds by 0.005 kg/m<sup>3</sup> the potential density measured at 20 m (Latarius & Quadfasel, 2016). This relatively small threshold value gives an indication of the depth of recent mixing (e.g., Brainerd & Gregg, 1995). In addition, water masses were identified by using the water mass definitions proposed by Rudels et al. (2005).

#### 2.2. Particulate Backscattering and Chlorophyll-a Concentration

BGC-Argo floats were equipped with Wetlabs ECO FLbb sensors to obtain optical measurements of backscattering at 700 nm and chlorophyll *a* fluorescence at 470 nm. Using the manufacturer's equations, the particulate backscattering coefficient ( $b_{bp}$ , in m<sup>-1</sup>) and the chlorophyll *a* concentration ([Chl *a*], in mg/m<sup>3</sup>) were estimated. In addition,  $b_{bp}$  values were converted to particulate organic carbon concentration ([POC], in g C/m<sup>3</sup>) using a relationship specific to the Arctic from Reynolds et al. (2016, coefficients from their Tables 2 and 3):





**Figure 1.** Study area map with main currents, average location of sea ice cover during maximum and minimum annual extents, and BGC-Argo floats trajectories. (a) Thick colored arrows represent current location and direction (EGC = East Greenland Current; JMC = Jan Mayen Current; EIC = East Iceland Current; WSC = West Spitsbergen Current; RAC = Return Atlantic Current). The black line and the light blue area show the mean sea ice extent, defined as a sea ice concentration of 10%, in April (annual maximum extent) and in September (annual minimum extent), respectively (i.e., averaged from 2012 to 2015). The box shows the study area, and the black and white dots indicate the deployment locations for each BGC-Argo floats. Depth contours shown for 1,000 and 2,000 m. (b) For each year (from 2012 to 2015), the annual location of the sea ice cover is represented, as well as the BGC-Argo float trajectory (the colored line). Dotted line sections, circled in red, in the BGC-Argo floats trajectories correspond to the periods when BGC-Argo floats activated their ice avoidance algorithm. For the 2012 and 2014 maps, the black dashed line shows the mean sea ice extent at the start of the ice edge phase (defined in section 3.2).

$$[POC] = 57 \times \left[ \left( b_{bp} \times \frac{700}{550} \right)^{-1.254} \right]^{1.02}$$
(1)

For the [Chl *a*], and according to the Argo data management protocol (http://doi.org/10.13155/35385), an in situ measured dark count correction was calculated for each profile by assuming that the [Chl *a*] should be equal to zero at depth (i.e., here between 750 and 1,000 m) in an unmixed water column. Therefore, if the MLD was shallower than 750 m, a dark value was calculated as the median value of [Chl *a*] between 750 and 1,000 m and subtracted from the whole profile. On the contrary, if the MLD was deeper than 750 m (i.e., well-mixed water column), the last available estimated dark value was used and subtracted from the whole profile. For the two BCG-Argo floats discussed here, dark values were generally low (median values over the two float sampling times were 0.051 mg/m<sup>3</sup> and 0.047 mg/m<sup>3</sup>). For both BGC-Argo floats, the *b*<sub>bp</sub> and [Chl *a*] values in surface covary (Spearman's rank correlation,  $\rho = 0.84$ , *p* value < 0.01, and  $\rho = 0.69$ , *p* value < 0.01; see section 3.2 for the surface layer definition), therefore, chlorophyll *a* fluorescence profiles were not corrected for nonphotochemical quenching. We note that the [Chl *a*] correction is still under discussion in the literature (e.g., Roesler et al., 2017) and subject to change.

#### 2.3. Oxygen Concentration

Oxygen concentration ( $[O_2]$ , in µmol/kg) was estimated with an Aanderaa 3830 oxygen optode. Using manufacturer's equations and a calibration process, both reviewed by the Argo-BGC team (http://doi.org/ 10.13155/46542), quality controlled and calibrated  $[O_2]$  data were obtained. The data processing includes, in brief, a pressure correction of the measurements, a calibration of the optode phase with temperature dependent coefficients, a salinity correction, and a drift correction with in air measurements (for more details, the procedure has been recently reviewed in Bittig et al., 2018). Note that these quality controlled and calibrated  $[O_2]$  data were previously used in Johnson et al. (2015) to determine an air oxygen calibration.



In addition, the apparent oxygen utilization (AOU, in  $\mu$ mol/kg) was estimated as the difference between the expected [O<sub>2</sub>] at equilibrium with the atmosphere (using the solubility coefficients of Garcia & Gordon, 1992) and the measured [O<sub>2</sub>].

#### 2.4. Nitrate Concentration and Annual Net Community Production Estimations

Ultraviolet spectrophotometer nitrate sensors (Johnson et al., 2013; Johnson & Coletti, 2002) were deployed on the two BGC-Argo floats. Nitrate concentrations ([NO<sub>3</sub>], in µmol/kg) were calculated according to the Argo data management protocol (http://doi.org/10.13155/46121), and data were corrected using the locally interpolated nitrate regression of Carter et al. (2018) (as described in Johnson et al., 2017). A comparison was done between deep [NO<sub>3</sub>] values (average value between 950 and 1,000 m, supposedly stable over years) from floats and from the World Ocean Atlas climatology 2009 (Garcia et al., 2010). For the two BGC-Argo floats, a median difference of less than 1 µmol/k was calculated, which is within the accuracy range expected for this nitrate sensor. From the [NO<sub>3</sub>] profile, the nitracline depth was determined as the depth with the maximal vertical gradient of [NO<sub>3</sub>].

Using the resulting nitrate profiles, estimations of NCP were obtained following the seasonal nitrate drawdown methodology (Codispoti et al., 2013). In theory, the nitrate drawdown near the sea surface between the winter and summer periods, converted into carbon drawdown by using the C:N Redfield Ratio of 106:16 (Redfield et al., 1963), should correspond to the balance between the gross primary production and the community respiration (i.e., algal and heterotrophic respirations). In other words, the difference between depth integrated summer and winter nitrate profiles should correspond to an estimation of the biological uptake of nitrate during the intervening vegetative season,

$$NCP = \int_{0}^{h} \left( \overline{[NO_3]_{winter}} - \overline{[NO_3]_{summer}} \right) dz$$
(2)

where *h* is the integration depth that depends on how deep the net nutrient uptake is able to be observed. The integration depth *h* has been chosen to be the depth where the summer nitrate profile diverges from the winter profile (Codispoti et al., 2013). The use of monthly mean nitrate profiles in winter  $([NO_3]_{winter})$ , i.e., in March for data obtained in the SIZ area and April for data obtained open-ocean areas) and summer  $([NO_3]_{summer})$ , i.e., late July to mid-August) reduced small temporal and spatial scale variations. In addition, by repeatedly using equation (2) with all single nitrate profiles available from April or May (when [NO<sub>3</sub>] began to decrease) through September (when [NO<sub>3</sub>] increased again), time series of cumulative (time-integrated) NCP were generated.

This method assumes the advective fluxes (horizontal and vertical) as negligible, suggesting that biological processes dominate the nitrate changes over a seasonal time scale and a large area (as the one covered by the float over a year). However, to estimate the relative influence of such physical processes on the NCP estimations, two different models were used: the bulk mixed layer model of Glover et al. (2011, named PWP model, originally developed by Price et al., 1986) and a coupled 3-D hydrodynamic-ecological model system named SINMOD (Slagstad et al., 2015), the last one specifically tuned for the Arctic Ocean, particularly its Atlantic side.

Concerning the PWP model (i.e., the bulk, one-dimensional, mixed layer model), atmospheric forcing (i.e., heat fluxes, precipitation and wind stress) applied to the model are from the National Centers for Environmental Prediction-Department of Energy Reanalysis 2 (Kanamitsu et al., 2002), which provided data at a four times daily resolution over a T62 Gaussian global grid (192 × 94). The wind stress curl, necessary to derive the Ekman pumping, came from the six-hourly synoptic pressure fields provided by the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (distributed by the Environmental Research Division of the Southwest Fisheries Science Center) on a global 1° latitude–longitude grid (https://data.noaa.gov/dataset/dataset/fnmoc-wind-and-ekman-transport-data-360x181-6-hourly-for-thismonth-lon-180). The model had a vertical resolution of 2 m (between 0 and 500 m) and a time step of 3.5 hr. In order to apply the model along the float trajectories, float locations and model forcing have been interpolated to match the spatiotemporal resolution of the model. No biological processes were represented in the model, and the nitrate was incorporated as a passive tracer. Therefore, the difference between the modeled and observed nitrate profiles can be attributed mainly to biological processes. Note

that the influence of any horizontal physical advection on these results will be inferred from the SINMOD model.

A comprehensive description of SINMOD is available in Slagstad et al. (2015) and a short description is given here. The grid size of the SINMOD model used was 20 × 20 km. The hydrodynamic model is established on a *z* grid and based on the primitive Navier-Stokes equations (Slagstad & McClimans, 2005). The model has two groups of phytoplankton: diatoms and flagellates. Nitrogen is the main currency, with silicate further restricting the growth of diatoms. Microzooplankton (ciliates) graze on both flagellates and diatoms and are preyed upon by mesozooplankton, which also graze on diatoms. The SINMOD model is among the few Arctic models to explicitly include three major mesozooplankton species: *Calanus finmarchicus, Calanus glacialis*, and *Calanus hyperboreus*. SINMOD operates with two boxes for detritus, for fast and slow sinking debris, respectively. Explicit bacterial and dissolved organic carbon components are included.

#### 2.5. Auxiliary Datasets: Sea Ice Concentration and Remotely Sensed Ocean Color Data

Sea ice concentration data were downloaded from NSIDC/NOAA (https://doi.org/10.7265/N59P2ZTG). This product provides a climate data record of passive microwave sea ice concentration (Version 3), at daily temporal resolution and a 25  $\times$  25 km spatial resolution (Peng et al., 2013 – from the Scanning Multi-channel Microwave Radiometer (SMMR) sensor onboard the Nimbus-7 satellite and the Special Sensor Microwave Imager (SSM/I) and the Special Sensor Microwave Imager Sounder (SSMIS) onboard Defense Meteorological Satellite Program (DMSP) satellites). This data set was used to estimate sea ice concentration at the location and time of each float vertical profile.

Spatial and temporal matchups between vertical float profiles and several remotely sensed ocean color variables were carried out. Estimates of surface [Chl *a*] from merged remote sensing products (Moderate Resolution Imaging Spectroradiometer Aqua, MEdium Resolution Imaging Spectrometer, Visible Infrared Imaging Radiometer Suite sensors) at temporal and spatial resolutions of 5 days and 4 km, respectively, were downloaded from Ocean Color Climate Change Initiative (www.esa-oceancolour-cci.org, Version 3.1, https://doi.org/10.5285/9c334fbe6d424a708cf3c4cf0c6a53f5). Daily photosynthetically active radiation values (PAR, in E m<sup>-2</sup>/day) at the ocean surface, also from merged satellite data products (Moderate Resolution Imaging Spectroradiometer Aqua, MEdium Resolution Imaging Spectrometer, Visible Infrared Imaging Radiometer Suite sensors) at temporal and spatial resolutions of 8 days and 4 km, were downloaded from GlobColour (www.globcolour.info).

#### 3. Results

According to the time series of time-integrated NCP (equation (2) and Figure 2), open-ocean areas (years 2013 and 2015) displayed higher values (>3 mol C/m<sup>2</sup>) early in the season (in June) than those obtained in the SIZ (years 2012 and 2014). However, later in summer (in July and August), the time-integrated NCP estimates were similar between years except in 2014 ( $\approx$ 4 mol C/m<sup>2</sup> in 2012, 2013, and 2015; 2.8 mol C/m<sup>2</sup> in 2014). Spatiotemporal variability in physical and biological processes affecting the NCP between open-ocean and SIZ areas in the Greenland Sea should be expected from a conceptual point of view (e.g., Keene et al., 1991; Legendre et al., 1993; Richardson et al., 2005) and may explain the differences between the NCP estimated in 2014 and those estimated in 2013 and 2015. However, in 2012 and 2014, the BGC-Argo floats sampled and remained in the same SIZ area (at a similar latitude, around the Jan Mayen Ridge). Therefore, it might be expected that the spatial variability of the SIZ environment should be reduced for these 2 years, which would not account for the observed differences. Throughout the rest of the paper, the results will mainly focus on these 2 years of data (i.e., 2012 and 2014), in order to explain the observed temporal variability in the NCP and its relationship with the phytoplankton activity in the SIZ.

#### 3.1. Annual Cycles of Physical Variables

In 2012 and 2014, from March to June/July, potential temperatures below  $-1.5^{\circ}$ C were measured to depths of 50–75 m, while the mean surface salinity continuously decreased from 34.65 in March to less than 34.4 in June and July (Figure 3). During this period, missing data between the surface and 20 m were the consequence of the ice avoidance algorithm being activated. According to the water mass definitions of Rudels et al. (2005), these water parcels have the same hydrological characteristics as Polar Surface Water (PSW;  $\sigma \leq 27.7 \text{ kg/m}^3$  and  $\Theta \leq 0^{\circ}$ C). Thus, the surface water freshening likely results from a combination of local



**Figure 2.** Annual time series of cumulative (time-integrated) net community production (NCP) in 2012, 2013, 2014, and 2015, derived from [NO<sub>3</sub>] measurements. Time series were smoothed with a three points (i.e., 15 days) moving boxcar average. The raw data for the growth period are represented by colored dots. BGC-Argo floats trajectories can be seen in Figure 1b.

sea ice melting and advection of PSW. In addition, subsurface maxima (between 50 and 75 m to 200 m) in potential temperature ( $>2^{\circ}C$ ) and salinity (>34.95) were observed (Figure 3) and correspond to the recirculating Atlantic water mass.

For both of these annual cycles, obtained in the SIZ, MLDs were shallow during the sea ice presence and melting periods (black lines in Figures 3a–3d). These observations contrast with the deep winter and shallow summer MLDs measured by the same BGC-Argo float in the open-ocean area of the Greenland Sea (MLD  $\geq$ 1,000 m in winter 2013 and MLD  $\approx$  200 m in winter 2015, Figure S1 in the supporting information).



**Figure 3.** Annual time series of hydrological properties measured by BGC-Argo floats in 2012 and 2014. The top panels represent the sea ice concentration from satellite passive microwave data (NSIDC). (a and b) Potential temperature and (c and d) salinity measured in 2012 (a and c) and 2014 (b and d); white isolines correspond to the potential density (kg/m<sup>3</sup>), and the black lines represent the mixed layer depth. BGC-Argo floats trajectories can be seen in Figure 1b.



In the SIZ, the salinity determined the shallowing of the MLD, with MLDs estimated to be at their minimum (20 m) when the salinity observations were below 34.4 and the surface potential density was less than 27.7 kg/m<sup>3</sup>. MLDs stayed shallow until November, when the surface potential temperature started to decrease. In addition, time series of the Brunt-Vaisala frequency ( $N^2$  in/s<sup>2</sup>, water column is stable when  $N^2 > 0$  s<sup>-2</sup> and unstable if  $N^2 \approx 0$  s<sup>-2</sup>, Figure S1) confirmed an increase of the water column stability in surface in April–May, while in October–November the deepening of the MLD followed the depth at which the  $N^2$  is maximum. This suggests that for both annual cycles, the melting of sea ice or advection of PSW was responsible for the observed strong stratification from spring to the end of the growth season (i.e., from April to September).

#### 3.2. Annual Cycles of Phytoplankton Activity

We define a depth of the chlorophyll layer ( $Z_{CHL}$ ) as the depth where the maximal negative gradient in the vertical [Chl *a*] profile was observed (e.g., Carvalho et al., 2017; Chiswell, 2011). In summer, the temporal variability of  $Z_{CHL}$  and the nitracline depth were similar (Figure S2, from April to November, Pearson correlation, r = 0.76, *p* value <0.001), and a change from negative to positive AOU values occurred at  $Z_{CHL}$  ( $12 \pm 12 \mu$ mol/kg was the average AOU at  $Z_{CHL}$  from July to November, Figures 4g and 4h), supporting the assumption that the community respiration largely surpassed the phytoplankton production below this defined  $Z_{CHL}$ . In autumn,  $Z_{CHL}$ , the MLD and the depth with the maximum  $N^2$  values were close, and in spring,  $Z_{CHL}$  was related with the base of the upper-layer of the water column that presented high  $N^2$  values (Figure S1). This suggests that, in spring and autumn,  $Z_{CHL}$  corresponded to the base of the mixed layer recently mixed, as also suggested by the homogeneous distribution of the phytoplankton biomass from the surface to  $Z_{CHL}$ .

Three phases in phytoplankton activity are also defined: under ice, ice edge, and open ocean. The start of the under-ice phase is defined when [Chl *a*], integrated in  $Z_{CHL}$  ( $\langle Chl a \rangle_{ZCHL}$ ), increased above the highest value measured in winter (December, January, and February, i.e., 10 mg/m<sup>2</sup>) and in the presence of sea ice (sea ice concentration > 0%). The onset of the phytoplankton activity phase at the ice edge is defined when a significant increase in the phytoplankton biomass is observed (date when  $\langle Chl a \rangle_{ZCHL}$  increased above 100 mg/m<sup>2</sup>, the highest value measured in spring—March, April, and May) in the period of the seasonal decrease of the sea ice concentration (between June 2012/May 2014 and July 2012/2014). Finally, the beginning of the openocean phase is defined to start when there is no more sea ice (in July 2012/2014) and a significant decrease in the phytoplankton biomass occurs (date with the minimal annual d $\langle Chl a \rangle_{ZCHL}/dt$ ), and end in September (when [NO<sub>3</sub>] increased again). The dates associated with these phases and describe below are specific to the Greenland Sea SIZ and likely vary within the pan-Arctic area.

#### 3.2.1. Phytoplankton Activity Under Ice

The onset of the phytoplankton activity under ice occurred at the beginning of April and this phase ended in June, both in 2012 and 2014 (Figure 5). During this phase, sea ice concentration averaged above 50% (~57% in 2012 and ~59% in 2014, Figure 4) at the float positions, and the ice avoidance algorithm of the profiling floats was often activated (missing data between the surface and 20 m in Figure 4). This confirmed that BGC-Argo floats profiled in SIZ areas covered by sea ice.

The [Chl *a*] and  $b_{\rm bp}$  values integrated in  $Z_{\rm CHL}$  ((Chl *a*)<sub>ZCHL</sub> and  $\langle b_{\rm bp} \rangle_{\rm ZCHL}$ ) started to increase ((Chl *a*)<sub>ZCHL</sub> > 15 mg/m<sup>2</sup> and some  $\langle b_{\rm bp} \rangle_{\rm ZCHL} > 0.05$ , Figures 4a–4d and 5). During this under-ice phase, decreases in average [NO<sub>3</sub>] in  $Z_{\rm CHL}$  were also observed (Figures 4e and 4f) with a cumulative decrease of  $-2.2 \ \mu$ mol/kg in 2012 and  $-2.8 \ \mu$ mol/kg in 2014 (Figure 6a). Change in vertical profiles of [Chl *a*] and  $b_{\rm bp}$  between the start and the end of the time period considered were unambiguous, from  $\approx 0.1$  to  $>0.5 \ mg/m$  and from  $0.4 \times 10^{-3}$  to  $>1 \times 10^{-3} \ m^{-1}$  (Figures 6b and 6c), respectively. This similar temporal evolution of [Chl *a*] and  $b_{\rm bp}$  suggests that the phytoplankton biomass under ice truly increased at that time, rather than only an increase of the intracellular chlorophyll *a* content. In total, the under-ice phase represented 28% of the annually integrated (Chl *a*)<sub>ZCHL</sub> and between 25% and 35% of the annually integrated ( $b_{\rm bp}$ )<sub>ZCHL</sub>. However, (Chl *a*)<sub>ZCHL</sub> and ( $b_{\rm bp}$ )<sub>ZCHL</sub> increases were not monotonic (Figure 5) and AOU values were still mostly positive (Figures 4g and 4h).

#### 3.2.2. Phytoplankton Activity at the Ice Edge

In 2012, the data (Figure 5) unambiguously suggest that significant phytoplankton activity at the ice edge started on June 30 ( $\langle Chl a \rangle_{ZCHL} > 100 \text{ mg/m}^2$ , and is the date with the maximal annual d $\langle Chl a \rangle_{ZCHL}/dt$ ) and ended on July 31. In 2014,  $\langle Chl a \rangle_{ZCHL}$  exceeds 100 mg/m<sup>2</sup> on June 17, but the maximal annual



**Figure 4.** Annual time series of biogeochemical properties measured by BGC-Argo floats in 2012 and 2014. The top panels represent the sea ice concentration from satellite passive microwave data (NSIDC). (a and b) [Chl *a*], (c and d) *b*<sub>bp</sub>, (d and f) [NO<sub>3</sub>], and (g and h) apparent oxygen utilization measured in 2012 (a, c, e, and g) and 2014 (b, d, f and h); white or black isolines correspond to the potential density. White bands indicate no data available.

d $\langle$ Chl  $a\rangle_{ZCHL}/dt$  occurred 10 days after (27 June). However, 17 June corresponded to the date with the second maximal annual d $\langle$ Chl  $a\rangle_{ZCHL}/dt$ . Therefore, we consider that in 2014 significant phytoplankton activity at the ice edge started on June 17 and ended on July 8. Two weeks after the onset of the ice edge phase, and for both years, the maximal annual  $\langle$ Chl  $a\rangle_{ZCHL}$  (299 mg/m<sup>2</sup> in 2012 and 358 mg/m<sup>2</sup> in 2014) and  $\langle b_{bp}\rangle_{ZCHL}$  (0.18 in 2012 and 0.19 in 2014) were observed. These strong phytoplankton biomass peaks in  $Z_{CHL}$  were associated with observations in this layer of strong decreases in [NO<sub>3</sub>] (from 10.2 to 1.3 µmol/kg in 2012 and from 9.1 to 1.4 µmol/kg in 2014, Figure 6a) and with AOU values that became negative (supersaturated in oxygen, on July 10 in 2012 an on June 23 in 2014, Figures 4g





**Figure 5.** Annual time series of [Chl *a*] and  $b_{bp}$  integrated in  $Z_{CHL}$  in 2012 (a) and 2014 (b).  $Z_{CHL}$  is defined between 0 m and the depth where the maximal negative gradient in the vertical profile of [Chl *a*] was observed. Black lines above figures represent the duration of each phase: under-ice (1), ice-edge (2) and open-water (3).

and 4h). Taken together, these observations demonstrate that a strong increase in the primary production occurred within  $Z_{CHL}$ .

In addition, these important phytoplankton activities coincided with important sea ice concentration decreases (Figures 7a and 7b). When sea ice concentration decreased below 50% in 2012 and 40% in 2014, [Chl *a*] averaged in  $Z_{CHL}$  increased above 2 mg/m<sup>3</sup>. At the beginning of the ice edge phase, near surface data (between 0 and 20 m) are missing because the ice avoidance algorithm of both BGC-Argo floats was still active. Later, vertical profiles of [Chl *a*] and  $b_{bp}$  displayed a SCM feature below 10 m, associated with [Chl *a*] above 5 mg/m<sup>3</sup> and  $b_{bp}$  approximately  $5.10^{-3}$  m<sup>-1</sup> (Figures 7c and 7f). This suggests that the phytoplankton development occurred at the ice edge and at a SCM. Ocean color [Chl *a*] from the same time interval in 2012 decreased from 1.1 to 0.5 mg/m<sup>3</sup> and finally to 0.3 mg/m<sup>3</sup>, following the decrease observed in the averaged [Chl *a*] in the first optical depth, the layer from which most of the upwelling radiance detected by satellite originates (0–10 m in April in the Greenland Sea according to Cherkasheva et al., 2013; black dots and line Figures 7a and 7b); ocean color [Chl *a*] data in 2014 were mostly unavailable.

#### 3.2.3. Phytoplankton Activity in Open-Water and Around a SCM

After the peak in phytoplankton biomass (on July 20 in 2012 and July 3 in 2014),  $Z_{CHL}$  was depleted in nitrate ([NO<sub>3</sub>] < 2 µmol/kg), and SCM features were still observed (Figures 4a–4d), with a second annual peak in August of  $\langle b_{bp} \rangle_{ZCHL}$  (on August 26 in 2012 and on August 9 in 2014, Figure 5). This suggests that the open-water SCMs in 2012 and 2014 corresponded again to subsurface phytoplankton biomass maxima. The vertical distributions of [NO<sub>3</sub>] and AOU show that the nitracline depth (38 m in 2012 and 34 m in 2014) and the depth at which the AOU equaled 0 µmol/kg (37 m in 2012 and 31 m in 2014) were close. These depths (i.e., the nitracline and AOU = 0 µmol/kg) were both deeper than the SCM (35 m in 2012 and at 27 m in 2014; Figure 4). This suggests that the SCM features also corresponded to a productive subsurface phytoplankton maximum. In addition, note that the SCM in summer 2012 was significantly deeper than in summer 2014.

#### 3.3. Estimations of the Annual NCP

Integrated differences between mean winter and summer nitrate profiles were used to estimate annual NCP (equation (2), Codispoti et al., 2013; Figure 8a and 8b). However, in 2012,  $[NO_3]$  in the deep layers (below 200 m) was different between winter and summer profiles (a difference of 0.6  $\mu$ mol/kg; data not shown). This suggests that the nitrate content in deep water masses was probably different at the winter and summer float





**Figure 6.** Annual time series of averaged [NO<sub>3</sub>] in  $Z_{CHL}$  (a), and vertical profiles of [Chl *a*] and  $b_{bp}$  at the start and at the end of the under-ice phase in 2012 (b) and in 2014 (c). (a) The definition of  $Z_{CHL}$  is described in Figure 4. Colored lines above the top panel represent the duration of each phase: under-ice (1), ice edge (2) and open water (3) in 2012 (green) and 2014 (blue).

sampling locations. Therefore, nitrate supplies in the surface layer before the start of the vegetative season, sustained by deep winter mixing, could have been different between the summer and winter locations. In order to avoid overestimations of NCP, an offset between deep summer and winter profiles (median value of  $[NO_3]$  between 200 and 300 m) has been substracted from the mean winter profiles in 2012.

The annual NCP estimate in 2012 was higher  $(3.9 \pm 0.6 \text{ mol C/m}^2)$  than in 2014  $(2.8 \pm 0.2 \text{ mol C/m}^2)$ . These estimates are close to the value of  $2.5 \pm 0.4 \text{ mol C/m}^2$  for the Nordic Seas of Codispoti et al. (2013). Note that the difference in estimated value between the Codispoti's study and the one conducted here is mainly related to a difference in the mean [NO<sub>3</sub>] winter profiles. In fact, BGC-Argo floats reported homogeneous winter profiles ([NO<sub>3</sub>]  $\approx 12 \mu \text{mol/kg}$  from surface to 300 m), while Codispoti's climatology, with scarcest data in winter, reported a depletion in winter nitrate between 0 and 150 m of  $\approx 1-2 \mu \text{mol/kg}$  (Figure 7 in Codispoti et al., 2013), which here would have resulted in a decrease of 0.5–0.75 mol C/m<sup>2</sup>. Our annual NCP estimates are also in the range of the global estimate of  $3 \pm 1 \text{ mol C/m}^2$  from Emerson (2014). However, although there are similitudes with other annual NCP from different ocean basins, seasonal cycles of the NCP, as for the biomass accumulation, should be different (e.g., Westberry et al., 2016).

In order to study the temporal evolution of NCP, the mean summer profile in equation (2) (i.e.,  $[NO_3]_{summer}$ ) has been replaced with each single available summer vertical profile of nitrate (from March to September, Figure 8c), in order to obtain time series of time-integrated NCP. By the end of the under-ice phase,





**Figure 7.** The ice edge phase. (a and b) Time series, during the ice edge phase, of sea ice concentration (blue lines), and of average [Chl *a*] in  $Z_{CHL}$  (green lines) and in the first optical depth (black lines) from BGC-Argo floats, in 2012 (a) and in 2014 (b). Ocean color-[Chl *a*] values are depicted by black dots. (c and f) Vertical profiles of [Chl *a*] and *b*<sub>bp</sub> at the ice-edge in 2012 (c and d) and in 2014 (e and f). The color of each profile represents the sampling date.

the time-integrated NCP was around 1.5 mol C/m<sup>2</sup> for both years (1.5  $\pm$  0.8 mol C/m<sup>2</sup> in 2012, and 1.5  $\pm$  0.1 mol C/m<sup>-2</sup> in 2014). In 2014, the annual NCP value of 2.9  $\pm$  0.4 mol C/m<sup>2</sup> had already been reached by the end of the ice-edge phase (at the end of June 2014, this phase added 1.4  $\pm$  0.4 mol C/m<sup>2</sup>), and the time-integrated NCP did not increase much during the open-water SCM phase. On the other hand, in 2012, the time-integrated NCP was at 3.4  $\pm$  0.4 mol C/m<sup>2</sup> by the end of the ice edge phase (this phase added 1.9  $\pm$  0.4 mol C/m<sup>2</sup>), while the annual NCP maximal of 3.9  $\pm$  0.6 mol C/m<sup>2</sup> was reached later, including the open-water SCM phase.

#### 3.4. Estimations of the Lateral Advection of Nitrate at the BGC-Argo Float Locations

The SINMOD model (Slagstad et al., 2015), a 3-D physical-biogeochemical coupled model was used to test the assumption that horizontal fluxes were not the main factor influencing changes in [NO<sub>3</sub>] between 2012 and 2014. For this, the observed  $[NO_3]$  in the surface layer (0–25 m) in 2012 and 2014 was compared to the simulated surface (0-25 m) [NO<sub>3</sub>] at the mean position of BGC-Argo floats and to the monthly flux of nitrate inside the surface layer (0–25 m) through three sections located near the BGC-Argo float positions (Figure S3): two west-east sections (between 10°W and 20°W, at 73.5°N in 2014, and 72.4°N in 2012) and one north-south section (between 71°N and 75°N, at 15°W). First, [NO<sub>3</sub>] agree between observations and simulation (Figure S4). The model values at the west-east sections (Figures S5a and S5b) show that over a year, the north-to-south flux of nitrate was maximal (>1.75  $10^7$  mmol m<sup>-2</sup> day<sup>-1</sup>) over the 1,000-m bathymetric line (around 17°N). At 73.5°N in 2014 (Figure S5b), the flux of nitrate near the coast was north-to-south and <0.5 mmol m<sup>-2</sup> day<sup>-1</sup>, while south-to-north and < 0.5 mmol m<sup>-2</sup> day<sup>-1</sup> in the eastern part of the section. At 72.4°N in 2012 (Figure S5a), the north-to-south flux of nitrate was also <0.5 mmol m<sup>-2</sup> day<sup>-1</sup> near the coast, but a second maximum in surface nitrate flux ( $\approx$ 1–1.5 mmol m<sup>-2</sup> day<sup>-1</sup>) was simulated at 13.5°W. At the latitude range of the BGC-Argo float locations in spring-summer 2012 and 2014 (between 72°N and 73°N), the simulated surface flux of nitrate from east-to-west at the north-south section was low (<0.5 mmol m<sup>-2</sup> day<sup>-1</sup>, Figures S5c an S5d). These model results suggest that the East Greenland Current flows over the 1,000-m bathymetric line in this area, and that neither float was inside its boundary, especially during the spring-summer transition. On the other hand, the north-to-south surface flux of nitrate simulated



**Figure 8.** The annual NCP estimated in 2012 and 2014. (a and b) Mean vertical profiles (with standard deviation) of winter (i.e., March) and summer (i.e., late July to mid-August, grey area in panel c) nitrate profiles used to estimate the annual net community production (NCP; red profiles) in 2012 (a) and in 2014 (b). (c) Annual time series of cumulative (time-integrated) NCP. Horizontal colored lines represent the duration of each phase: under ice (1), ice edge (2), and open water (3). (d and e) [Chl *a*] profile in summer 2012 (d) and 2014 (e). The color of each profile represents the sampling date.

at 13.5°W might be the signature of the Jan Mayen Current and could have influenced the measured [NO<sub>3</sub>] only in 2012 (Figure S5a). In 2012, most of the measured nitrate decrease occurred in July, with a cumulative decrease of 9  $\mu$ mol/kg (more than 70% of the annual decrease). The nitrate decrease in the model results, evaluated at the mean BGC-Argo float location in 2012 (13°W and 72°N), was also of a similar order of magnitude (9  $\mu$ mol/kg) and accounted for more than 70% of the annual decrease but occurred earlier (in June and ended in July, Figure S4). The simulated horizontal nitrate flux associated with the Jan Mayen Current mainly decreased in April (40% of its annual maximum) and only decreased by 17% between June and July. This suggests that most of the nitrate, and thus of the NCP, variability occurring in the SIZ area of the Greenland Sea was due to the physical and biological processes which occurred within this area. In conclusion, in our area of interest, the lateral advection of nitrate into the productive layer appears to be limited.



#### 4. Discussion

#### 4.1. Pelagic Phytoplankton Is Active Under Ice

In the pan-Arctic area, pelagic phytoplankton biomass has long been observed under sea ice (Arrigo et al., 2012, 2014; Fortier et al., 2002; Laney et al., 2014; Michel et al., 1996; Mundy et al., 2009, 2014; Strass & Nöthig, 1996). Reported surface-integrated values of [Chl a] measured under ice span an order of magnitude, generally between 15 and 170 mg/m<sup>2</sup>, and [POC] ranged between 9 and 30 g C/m<sup>2</sup>, with some very high values when influenced by a shelf break upwelling of nutrients (e.g., Arrigo et al., 2014 with [Chl a] > 1,000 mg/m<sup>2</sup>). In the Greenland Sea SIZ studied here, BGC-Argo floats measured under-ice (Chl a)<sub>ZCHL</sub> between 17 and 100 mg/m<sup>2</sup> (on average, 52 and 42 mg/m<sup>2</sup> in 2012 and 2014, respectively) and [POC] integrated in  $Z_{CHL}$  between 1.2–3.3 g C/m<sup>2</sup> (on average, 2.4 and 1.9 g C/m<sup>2</sup> in 2012 and 2014, respectively). Thus, in situ values reported here are in the range of previous estimations. Simultaneously, a cumulative decrease of ~2.2–2.8  $\mu$ mol/kg in [NO<sub>3</sub>] in the same layer (i.e., Z<sub>CHL</sub>) during this under-ice phase occurred (Figure 6a). These [NO<sub>3</sub>] decreases were associated with increases of the [Chl a] and  $b_{bp}$ , leading to a clear phytoplankton biomass accumulation in surface layers (profiles in Figure 6). Most importantly, the availability of complete annual cycles of in situ measurements (Figure 5) allows the determination that between 25%–35% of the annually integrated phytoplankton biomass (i.e., [Chl a] and  $b_{bp}$  may be considered to be proxies for phytoplankton biomass) can be present during this under-ice phase and can contribute up to half of the annual NCP (later discussed in section 4.3). In addition, these estimates of under-ice phytoplankton biomass in the SIZ area studied were similar between two different years, although obtained from two different BGC-Argo floats. This supports the hypothesis of a recurrent and significant presence of phytoplankton biomass under-ice earlier in the season in this SIZ.

A reduction in snow cover and ice thickness, as well as the appearance of leads and melt ponds, can result in an increase in light availability under ice (Assmy et al., 2017; Frey et al., 2011; Mundy et al., 2014). In the condition of a stratified water column, the light availability for phytoplankton cells present under ice could thus significantly increase and induce a phytoplankton biomass accumulation earlier in the season (e.g., Lowry et al., 2018). Here in both 2012 and 2014, the phytoplankton biomass started to increase under ice in the first week of April. The water column was stratified (shallow MLD, black lines in Figure 3), covered with close to open-drift ice (sea ice cover was around 50% in 2012, and 65% in 2014, Figure 3), and at this time of the year (early April), at this latitude, the surface daily light availability drastically increased. Satellite PAR values are unavailable for this period, but the temporal variation of the daily PAR at the ocean surface can be estimated by using the downward solar radiation flux in 2012 and 2014 (from the National Centers for Environmental Prediction-Department of Energy Reanalysis), which is linearly related with the amount of incident daily PAR (e.g., Olofsson & Eklundh, 2007). The first week of April (in 2012 and 2014) represents the first time of the year when the daily downward solar radiation flux began to be above its annual median value (not considering the polar night period, when solar radiation is null). Therefore, the onset in early-April of the phytoplankton biomass accumulation under ice in this SIZ area is supposed related to the light availability.

These increases in pelagic phytoplankton biomass under ice could also result from the release of ice algal cells during sea ice melting, that subsequently add to the [Chl *a*] value recorded under ice (Laney et al., 2014; Mundy et al., 2014). Some ice algae may have seeded the phytoplankton community growing in the pelagic environment (Schandelmeier & Alexander, 1981). However, ice algae may also directly sink at depth or be grazed (Boetius et al., 2013; Fortier et al., 2002; Leu et al., 2015; Michel et al., 1996). Therefore, it is still necessary to find a way to distinguish the fluorescence signal from ice algae and pelagic phytoplankton (Laney et al., 2014).

#### 4.2. From a Phytoplankton Activity at the Ice Edge to an Open-Water SCM

In the SIZ, one of the main events during the winter-to-summer transition is the development of significant phytoplankton activity during and just after ice edge retreat (generally referred to as ice edge bloom, e.g., Carmack & Wassmann, 2006; W. O. Smith & Sakshaug, 1993; Wassmann, 2011). Relatively high concentrations of nutrients below the ice in winter, and the sea ice melting in summer inducing a stratification of the water column and a higher light availability, have been suggested to explain this ice edge bloom event (W. O. Smith & Niebauer, 1993; W. O. Smith & Sakshaug, 1993). These hypotheses are supported here by the BGC-Argo floats measurements in the SIZ of the Greenland Sea.



One of the remaining challenges is to be able to understand and predict the timing of this seasonally significant phytoplankton biomass accumulation at the ice edge, which influences the coupling with higher pelagic trophic levels and the benthos ecosystem, via its possible rapid export at depth (Carmack & Wassmann, 2006; Hunt et al., 2016; Leu et al., 2011; Wassmann, 2011). In addition, climate change, by influencing the sea ice melting and formation periods, could modify the phytoplankton phenology in the Arctic (e.g., Ji et al., 2013; Kahru et al., 2011, 2016). As its name indicates, the phytoplankton ice edge bloom relies on the definition of the ice edge, the limit between the sea ice and the open ocean, usually determined by a threshold value of sea ice concentration. The relationship between the timing of the ice edge bloom and sea ice concentration has been inferred with satellite observations (e.g., Lowry et al., 2014; Perrette et al., 2011). Perrette et al. (2011) suggested that an ice edge bloom cannot be observed from satellite when sea ice concentration is above 10%, but it certainly could have peaked before. On the other hand, Lowry et al. (2014) used the much higher threshold values of 50% of sea ice concentration to determine the ice edge, based on in situ observations (Arrigo et al., 2014), and were thus able to observe the development of phytoplankton ice edge blooms in the MIZ of the Chukchi Sea. Here BGC-Argo float measurements demonstrated that high phytoplankton biomass was observed (i.e.,  $(Chl a)_{ZCHL}$  above 100 mg/m<sup>2</sup>, higher than  $(Chl a)_{ZCHL}$  observed during the under-ice phase), when sea ice concentration (from passive microwave data) in 2012 was at 50% and at 40% in 2014 (Figure 7). This suggests that the ice edge definition based on sea ice concentration and where phytoplankton biomass accumulation can be observed is around 40%–50% of sea ice concentration (close to the definition proposed by Arrigo et al., 2014).

BGC-Argo float observations also confirmed that the phytoplankton activity at the ice edge occurs around a SCM, whose presence was obvious at the times of the  $\langle Chl a \rangle_{ZCHL}$  maxima, both in 2012 and 2014 (Figure 7). During the ice edge phase, satellite observations of [Chl *a*] (only available in 2012) were in the range of previously published data of ice edge bloom observations in the Greenland Sea (maximum around 1 mg/m<sup>3</sup>, Perrette et al., 2011) but rapidly decreased, even though an increase of the [Chl *a*] at the SCM was ongoing (Figure 7). BGC-Argo float observations of [Chl *a*] averaged within the first optical depth (0–10 m in the Greenland Sea, Cherkasheva et al., 2013) also decreased during this phase (Figure 7). This suggests that satellite [Chl *a*] estimations at the ice edge may miss substantial phytoplankton biomass accumulation at depth (e.g., Hill et al., 2013). However, the ocean color atmospheric correction in (subartic) arctic areas, especially in areas close to sea ice, is known to be inconsistent and could have resulted in this decrease in satellite [Chl *a*] values (Bélanger et al., 2007).

Later, during the open-water phase, in late July–August and both in 2012 and 2014, the stable and ice-free water column (Figure 3) prevented a vertical resupply of nitrate and likely resulted in maintaining the SCM features throughout the open-water phase (until the end of September, Figure 4). These open-water SCMs were closely linked to the nitracline (with highest [NO<sub>3</sub>] values below the SCM), as previously reported for the Greenland Sea (e.g., Gradinger & Baumann, 1991; S. L. Smith et al., 1985; W. O. Smith et al., 1987).

In summary, our observations suggest that under-ice phytoplankton activity can occur early in the vegetative season, that under 40%–50% of sea ice concentration significant phytoplankton biomass accumulation at the ice edge may start at a SCM, and finally that an open-water SCM can be a recurring feature in the SIZ of the Greenland Sea. All these processes can contribute to an underestimation of the net primary production (NPP) inferred from satellite observations done on a pan-Arctic scale (Babin et al., 2015; IOCCG, 2015; Lee et al., 2015, and references therein). In fact, phytoplankton biomass accumulation under and close to the sea ice, as well as around a SCM, is seldom detectable with remotely sensed ocean color. For instance, the presence of SCMs, mainly when located deeper than 30 m, as here, has been shown to induce an underestimation of NPP in the Artic at regional and seasonal scales, though not determinant for pan-Arctic annual NPP (Ardyna et al., 2013; Arrigo et al., 2011; Hill et al., 2013). Therefore, NPP estimations could be significantly different in SIZ areas, mainly at a seasonal and subseasonal time scale.

#### 4.3. NCP Interannual Variability in the SIZ of the Greenland Sea

BGC-Argo floats revealed that in the SIZ of the Greenland Sea, the annual NCP was lower in 2014  $(2.8 \pm 0.2 \text{ mol C/m}^2)$  than in 2012  $(3.9 \pm 0.6 \text{ mol C/m}^2)$ . Understanding the reasons of this observed variability between years 2012 and 2014 reveals the relative roles of environmental factors. More importantly, continuous measurements from these BGC-Argo floats provide information on the influence of each phase (i.e.,





**Figure 9.**  $\theta$ -*S* diagram of the mean summer profiles (i.e., late July to mid-August) in 2012 and 2014, with the colors representing the [NO<sub>3</sub>]. Contour lines represent the isopycnals (kg/m<sup>3</sup>). The location in the diagram of the polar surface water (PSW) and recirculating Atlantic water (RAW) are symbolized by their acronyms (water mass definitions from Rudels et al., 2005). The depth where [NO<sub>3</sub>] start to be >9 µmol/kg are indicated (50 m in 2012 and 40 m in 2014).

under ice, ice edge, and open water) in the annual cycle of NCP. By the end of the under-ice phase in 2012 and 2014, net deficits in [NO<sub>3</sub>] corresponded to a cumulative NCP of  $1.5 \pm 0.8$  mol C/m<sup>2</sup> in 2012 and  $1.5 \pm 0.1$  mol C/m<sup>2</sup> in 2014. Note that these NCP estimates were derived from changes in [NO<sub>3</sub>], which could be influenced by melting of sea ice depleted in nitrate. In fact, the [NO<sub>3</sub>] decrease in Z<sub>CHL</sub> was correlated with a decrease in the surface salinity (Spearman's rank correlation,  $\rho = 0.84$  and p value < 0.001 in 2012;  $\rho = 0.93$  and p value < 0.001 in 2014). However, this influence of sea ice melting on the [NO<sub>3</sub>] in the Z<sub>CHL</sub> could modify the annual NCP only by 3%–6% (Codispoti et al., 2013). Thus, the phytoplankton under-ice activity, while definitely playing an important role in the annual production of organic carbon (Matrai & Apollonio, 2013), presents apparently a low interannual variability. However, more winter nutrient profiles are needed to conclude on the variability of the under-ice phase in the Greenland Sea (e.g., in the climatological database of nitrate profiles from Codispoti et al., 2013; only 3% of the nitrate profiles available from the Greenland Sea have been done in winter).

Most of the annual NCP occurred at the ice edge, as one might expect, with a cumulative NCP of  $3.4 \pm 0.4$  mol C/m<sup>2</sup> in late July 2012 and  $2.9 \pm 0.4$  mol C/m<sup>2</sup> in late June 2014. Later in summer, and for both years, a second phytoplankton biomass peak linked to the open-water SCM occurred in August. In 2014, this increase lead to a cumulative NCP as high as the one previously estimated at the ice edge ( $2.8 \pm 0.2$  mol C/m<sup>2</sup>, Figure 8). Instead, in 2012, the NCP reached its maximal annual cumulative value during this open-water SCM phase ( $3.9 \pm 0.6$  mol C/m<sup>2</sup>, Figure 8).

Biological and physical factors influence the dynamic of the  $[NO_3]$  field in different ways, and consequently the annual NCP. According to the results from the SINMOD model (section 3.4), the variability of the  $[NO_3]$  in the SIZ was due to the physical and biological processes, which occurred within this area, with limited impact of the lateral advection of nitrate into the productive layer.

In this SIZ area of the Greenland Sea, two distinct nitraclines were visible in summer (Figures 8a and 8b): a first one with  $[NO_3]$  changing from 0 to 9 µmol/kg and a second, deeper one with  $[NO_3]$  changing from 9 to 11 µmol/kg. The deepest nitracline appeared during the under-ice phase, when the  $[NO_3]$  decreased from around 12 to 10 µmol/kg between the surface and a depth of 50 m. During the open-water phase, this nitracline was located 20 m deeper in 2012 (75 m) than in 2014 (55 m). The depth of the isopycnals displayed similar temporal and vertical variability (Figures 4e and 4f). A  $\theta$ -S diagram with mean profiles from August 2012 and August 2014 (Figure 9) suggests that the deepest nitracline was situated at the transition



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**Figure 10.** Comparison of nitrate, temperature and salinity profiles in summer 2012 (first half of August) from the PWP model (red) and measurements (black). "exp-1" corresponds to the run with initiations of the nitrate profile at each BGC-Argo float sampling time step, while "exp-2" corresponds to the run with only one initiation of the nitrate profile at the beginning.

between the polar surface water ( $\sigma \le 27.7$  and  $\Theta \le 0$ ) and the recirculating Atlantic water masses (27.70 <  $\sigma \le 27.97$  and  $\Theta > 2$ ; water mass definitions from Table 1 in Rudels et al., 2005). Both of these water masses were deeper in 2012 than in 2014, which could explain the difference in the nitracline depth between these two years (Figures 8a and 8b and 9). Bourke et al. (1992) already demonstrated a similar spatial difference in the depth position of these two water masses in this SIZ of the Greenland Sea and related it to the establishment of the Jan Mayen Current in this area. Therefore, the difference between 2012 and 2014 in the NCP might be due to a density-related variability in the depth of water masses, rather than a biological consequence. By not taking into account this deepest part of the nitrate profile linked to the physics (depth where [NO<sub>3</sub>] > 9 µmol/kg, after 50 m in 2012 and 20 m in 2014), the annual NCP estimates in 2012 and 2014 are reduced to  $3.2 \pm 0.8 \text{ mol C/m}^2$  and  $2.6 \pm 0.2 \text{ mol C/m}^2$ , respectively. This means that for both years almost half (i.e., ≈52%) of the annual NCP would have occurred during the under-ice phase and the other half (i.e., ≈40%) at the ice edge, while the open-water phase would not have a strong influence on the annual NCP (i.e., ≈8%).

Concerning the shallowest nitracline, the use of the PWP model reveals, on one hand, how physical processes influenced the vertical distribution of nitrate, while, on the other hand, it also suggests a potential influence of biological processes. The model was initiated with BGC-Argo floats physical and nitrate profiles after the ice edge phase (i.e., 31 July) and run until the end of August. A first simulation experiment (i.e., *exp-1*) consisted of reinitializing the model with each observed nitrate profile and comparing the modeled and observed nitrate profile at the next observed time. A second simulation experiment (i.e., *exp-2*) involved





**Figure 11.** Comparison between open-ocean and seasonal ice zones areas. (top panels) Annual time series of cumulative (time-integrated) net community production (NCP; a) and *b*<sub>bp</sub> integrated in *Z*<sub>CHL</sub> (b), from 2012 to 2015. Time series were smoothed with a three points (i.e., 15 days) moving boxcar average. (bottom panels) Vertical profiles of [Chl *a*] measured every 5 days in August during each of these 4 years, where the brightness encodes time (the darker, the later). Note that years 2012 and 2014 represent the seasonal ice zones area, while 2013 and 2015 represent the open-ocean area.

initializing the model only with the first nitrate profile and evaluating the difference between the modeled and observed nitrate profiles at the end of the run.

In the exp-1, the model did not reproduce the short temporal variability of the shallowest nitracline in August 2012 (Figure 10), which experienced a deepening from 30 to 50 m between 4 and 9 August 2012. Therefore, this deepening of the shallowest nitracline, mainly responsible for the 0.6  $\pm$  0.35 mol C/m<sup>2</sup> difference in annual NCP (≈19% of difference) between 2012 and 2014 might not be due to one-dimensional physical processes. Instead, the [Chl a] profiles available on 10 and 15 August 2012 (Figure 11, lower panels), displayed a SCM also around 50 m, which suggests the influence of biological processes on a productive open-water SCM. In comparison, the SCM was always near 30 m in August 2014 (Figure 11, lower panels). Considering that the phytoplankton production in the surface layer of the Greenland SIZ is mainly bottom-up regulated (Carmack & Wassmann, 2006), a higher daily average PAR at the ocean surface observed during the first half of August in 2012 (31.3 E m<sup>-2</sup>/day) than in 2014 (28.2 E m<sup>-2</sup>/day) could also have induced a change in the depth of the open-water SCM and in the nitrate consumption and, thus, in NCP. A photoadaptation to low light levels by the phytoplankton community previously located under ice could explain this rapid transition from an under-ice activity to an efficient growing phytoplankton community around the SCM (Tremblay et al., 2008, 2015). However, possible top-down regulation on the open-water SCM development, thus affecting the nitracline depth location, by zooplankton grazing cannot be excluded (Carmack & Wassmann, 2006; Møller et al., 2006) and will be addressed elsewhere.

The exp-2 reveals that without the presence of the SCM,  $[NO_3]$  would have increased by 2.5 µmol/kg in the upper 20 m by the end of August (Figure 10), while observations were  $\approx 0 \ \mu mol/kg$  in both years studied. In addition, these observed open-water SCMs were located above the depth where AOU equalled 0 µmol/kg (Figures 4e–4h), which again suggests that the open-water SCM is a productive feature (i.e., it is not simply a passive accumulation of biomass, or only an increase of the intracellular chlorophyll *a* content). The presence of a productive SCM in other Arctic SIZs has already been proposed from scarce past observations (e.g., Tremblay et al., 2008).



Although the open-water SCM has a relatively small impact on the annual NCP, in order to understand the role of this summer feature, it is important to compare the open-ocean and SIZ NCP. Up to now, we have focused on the annual and subannual variability of NCP at the SIZ, in part because of the consistency of the summer NCP in the Greenland Sea open-ocean region sampled by the BGC-Argo floats. In the SIZ, however, during this open-water phase, a second peak in  $\langle b_{bp} \rangle_{ZCHL}$  was observed, and the NCP remained high (Figures 4e and 4f and 11a and 11b) as nitrate concentration was still exhausted in  $Z_{CHL}$ . Actually, up to  $\approx$ 28% of the annually integrated  $\langle b_{bp} \rangle_{ZCHL}$  occurred during the open-water phase in the SIZ (i.e., 15% before April, 24% during the under-ice phase, 17% at the ice edge, 28% during the open-water phase, and 16% after September). In comparison, in the open-ocean region (defined as the region never covered by sea ice over a year), although NCP was high in August, the  $\langle b_{bp} \rangle_{ZCHL}$  was already decreasing (Figures 11a and 11b), inducing a difference in the [POC] integrated in Z<sub>CHL</sub> of around 2 g C/m<sup>2</sup> in August between the SIZ and the open-ocean regions. The [Chl a] profiles in August also show a SCM more developed in the SIZ than in open-ocean areas (Figure 11, lower panels). Richardson et al. (2005) suggested a difference in the phytoplankton community around the SCM in August in the Greenland Sea with more diatoms along the ice edge than offshore that could ultimately influence the biological carbon pump. Therefore, the higher [POC] accumulation in the SIZ than in the open-ocean region supports a more productive open-water SCM in the SIZ than in the open ocean. This difference, not visible in the NCP time series (Figure 11a), should be taken into account for its influence on any NPP estimation (as already discussed in section 4.2).

#### **5.** Conclusions

Characterizing the phytoplankton activity in a SIZ continuously over an annual cycle remains a challenge. Physical and biogeochemical data obtained at fine temporal resolution (5 days) from two BGC-Argo floats that were capable of sampling under sea ice provide insight into the annual cycles of phytoplankton biomass and NCP in the Greenland Sea SIZ. On average, the early phytoplankton activity under-ice and at the ice edge represent, respectively, 23% and 13% of the annual phytoplankton biomass, and 52% and 40% of the annual NCP.

In the SIZ and from the beginning of the ice edge phase to the end of the open-water phase, the phytoplankton development occurred around a SCM shown to be a productive phytoplankton biomass maximum. This SCM feature seems to be recurrent in the Greenland Sea SIZ and, as with the phytoplankton activity underice, undetectable with ocean color data. Therefore, we anticipate that phytoplankton production annual estimates based on ocean color information may be biased, even when the SIZ becomes ice free. In addition, a higher POC concentration was observed around the open-water SCM in the SIZ than in open-ocean areas, which suggests a high spatial variability within the Greenland Sea. Model simulations suggest that most of the annual NCP results from processes occurring within the SIZ of the Greenland Sea. The spatial variability of the NCP should be considered for subsequent studies on the biological carbon pump, and the ecosystem functioning in this basin.

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#### Erratum

In the originally-published version of this article, the name of coauthor K. Johnson was misspelled as "K. Johnson." The error has been corrected, and this may be considered the official version of record.