Shifts in biological productivity inferred from nutrient drawdown in the southern Beaufort Sea (2003–2011) and northern Baffin Bay (1997–2011), Canadian Arctic

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Abstract This paper reports the first in situ evidence of change in the net biological productivity of high-latitude western Arctic seas. Estimates of seasonal drawdown for major plant nutrients show that net community production (NCP) shifted differently in two contrasted Canadian oceanographic settings. In the stratified southeast Beaufort Sea, seasonal nitrate consumption increased 1.6-fold between 2003–2004 and 2010–2011. The concomitant thickening of the nitrate-depleted layer in summer/fall implies that subsurface chlorophyll maxima now consume nutrients over a larger extent of the water column. Meanwhile, nitrate consumption in the once productive North Water Polynya declined by 65% and is now nearly on par with the oligotrophic coastal Beaufort Sea. This decline is attributed to freshening and increased stratification. Commensurate changes in silicate and phosphate drawdown in the two regions indicate that diatoms drove the spatial and temporal shifts in NCP.

1. Introduction

Drastic reductions in the extent, thickness, and seasonal persistence of sea ice [*Kwok et al.*, 2009; *Markus et al.*, 2009; *Maslanik et al.*, 2011] augment the penetration of sunlight into the Arctic Ocean, setting the stage for a rise in primary production [*Arrigo et al.*, 2011; *Rysgaard et al.*, 1999]. The realization of this potential also depends on nutrient availability, which was shown to explain large-scale differences in productivity across the Arctic [*Tremblay and Gagnon*, 2009]. While recent increases in the freshwater content of the upper ocean augment vertical stratification and reduce the upward flux of nutrients in some sectors [*Rabe et al.*, 2011; *Li et al.*, 2009], the increasing strength and frequency of strong-wind events may also increase nutrient supply and productivity through upwelling, vertical mixing, and eddy generation in specific areas [*Tremblay et al.*, 2011; *Pickart et al.*, 2013; *Rainville and Woodgate*, 2009; *Watanabe et al.*, 2012]. Whether primary production undergoes enduring upward or downward shifts in a given seasonally ice-free region thus depends on a combination of factors, including light availability and altered nutrient loading resulting from changes in the freshwater balance (stratification), horizontal transport and atmospheric forcing of the upper ocean [*Tremblay and Gagnon*, 2009].

Synoptic assessments of variability and change in productivity can only be achieved from remotely sensed properties of the sea surface, with the caveat that satellite-based estimations of primary production require cloud-free conditions and do not formally include production under the ice [*Fortier et al.*, 2002; *Arrigo et al.*, 2012] and in subsurface chlorophyll maxima (SCM), where a variable and sometimes large portion of water column PP and/or phytoplankton biomass occurs [*Martin et al.*, 2012, 2013]. The size of resulting uncertainties depends on season, region, and estimation method [*Ardyna et al.*, 2013; *Hill et al.*, 2013; *Arrigo and van Dijken*, 2011] and can be larger than the estimates of change. *Arrigo et al.* [2011] estimated a Pan-Arctic increase of 20% in net primary production between 1998 and 2009 (+8.1 Tg C yr^{-1}). Using a different algorithm, *Bélanger et al.* [2013] reached qualitatively similar conclusions for the period 1998–2010. At the regional scale, however, trends can be either positive or negative and depart substantially from the overall mean.

To our knowledge, there are no available time series of in situ annual PP measurements available to assess and compare long-term change across different sectors of the High Arctic. Alternately, a comparison of nutrient inventories between winter and the end of the growth period can provide time-integrated estimates
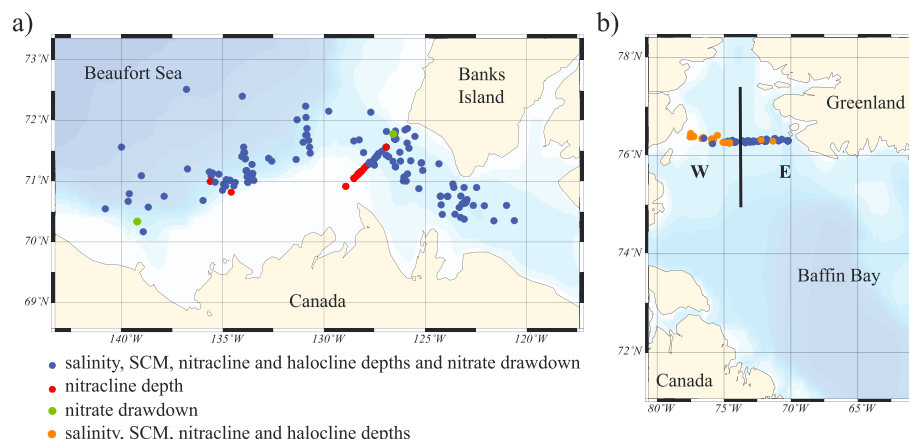
Figure 1. Stations of (a) the southeast Beaufort Sea and Amundsen Gulf and (b) northern Baffin Bay (BB; subregions: western BB (W) and eastern BB (E) on either side of the black line) where detailed vertical profiles of nitrate, silicate, phosphate, chlorophyll *a*, temperature, and salinity were obtained. Symbol colors refer to the variables estimated at a given station.

of productivity that incorporate under ice and SCM components [e.g., *Tremblay et al.*, 2008; *Codispoti et al.*, 2013; *Matrai and Apollonio*, 2013]. The cumulative depletion of phosphate (PO_4^{3-}) and total inorganic nitrogen over a growing season reflects net community production (NCP), which drives net changes in biomass. In areas where nitrogen fixation is low and other forms of labile nitrogen are negligible at the onset of the growth season, nitrate (NO_3^-) depletion simultaneously provides an estimate of NCP and new production [*Dugdale and Goering*, 1967], which sets an upper limit to the amount of carbon that can be exported (or harvested) [*Eppley and Peterson*, 1979]. Moreover, changes in the relative drawdown of different nutrients provide coarse indications of change in the contribution of diatoms to NCP, since these organisms have distinct requirements for silicon and phosphorus. Diatoms need silicon to synthesize their frustules [*Brzezinski*, 1985] and have a high requirement for phosphorus, which has been linked to their investment in cellular components that support fast growth [*Geider and La Roche*, 2002; *Deutsch and Weber*, 2012].

Here we report changes in the magnitude and ratios of nutrient drawdown in the High Canadian Arctic, comparing two regions with historically contrasted mixing regimes and exposure to the advection of Atlantic versus Pacific-derived waters (Figure 1). The Canadian Beaufort Shelf in the southeast Beaufort Sea (BS) is a perennially stratified interior shelf influenced by Pacific-derived waters supplied via the Beaufort Gyre and the Alaskan coastal current. Northern Baffin Bay (BB), the site of the secular North Water Polynya, has been a seasonally well-mixed and productive region through which Pacific-derived water from the High Arctic exits in the west and Atlantic-derived water moves north in the east [*Tremblay et al.*, 2002a].

2. Calculation of Nutrient Drawdown

Two methods can be used to estimate seasonal nutrient drawdown. The simplest one relies on the difference in nutrient inventory between winter and the moment of sampling, which *Codispoti et al.* [2013] used extensively to characterize spatial patterns of NCP from historical data. Here we expand on the salinity-nutrient procedure introduced by *Tremblay et al.* [2008], which accounts for the horizontal and vertical displacement of water masses and freshwater dilution (see supporting information). Since salinity is a conservative property, seasonal and interannual changes reflect strictly physical processes such as dilution (from sea ice melt, rivers, and glaciers), evaporation, vertical mixing, or shifts in the vertical position of layered water masses (e.g., upwelling). This approach allows to isolate the biologically driven component of change in the nutrient field and to attribute it to differences in nutrient supply to the euphotic zone or in the extent to which phytoplankton mostly are able to exploit what is available in this zone. To do so, we exploited a database assembled under the auspices of ArcticNet (2004–2011), the IPY-Circumpolar Flaw Lead Systems Study (2007–2008), the Canadian Shelf-Exchange Study (2003–2004), and the International North Water Polynya Program (1997–1998).

During the different expeditions (see Figure 1 for the position of summer/fall stations; see supporting information for winter data), detailed vertical sampling was performed at standard depths with a rosette equipped with a conductivity-temperature-depth sensor (Sea-Bird SBE-911plus), an in vivo fluorescence sensor (SeaTech), a sensor for photosynthetically available radiation (Biospherical) and 12-L Niskin sampling bottles (see *Tremblay et al.* [2002a, 2008] and *Forest et al.* [2011] for details on sensors and bottles). Concentrations of nitrate, phosphate, and silicate were determined with colorimetric methods (details in *Martin et al.* [2010]). The depths of the nitracline and halocline were identified as those where the vertical gradients in nitrate concentration (dNO_3/dz) and salinity ($dsalinity/dz$) were the highest, respectively. The so-called surface salinity values reported here are weighted averages for the 0–50 m layer, based on stations deeper than 100 m and with no direct river influence. The position of the SCM was determined as the depth of maximum fluorescence.

Net nutrient consumption or drawdown was obtained by difference between observed concentrations (N_{obs}) and those that would be expected in the absence of biological activity (N_{exp}). Values of N_{exp} were estimated by combining the salinity profile at the time of sampling with previously established nutrient-salinity (N-S) relationships during the winter nutrient maximum (see supporting information). In order to minimize the influence of seasonal fluctuations (e.g., recycling) in deep nutrient inventories on drawdown estimates, integration depth was determined for each station as the point where N_{obs} and N_{exp} profiles intersected. Ratios of nutrient drawdown were estimated in two ways by (1) calculating nitrate, silicate, and phosphate drawdowns separately and then dividing one by the other (so-called "deficit" ratios) and (2) calculating the slopes of nutrient-nutrient regressions (geometric mean or model II) using data from the upper 100 m at the time of sampling (so called "residual" ratios). The rationale for using the two methods is that each has its advantages and limitations. While the residual ratios rely on measured values, the deepest data points anchor the regressions and potentially minimize differences over time and space. Deficit ratios are not sensitive to this effect but propagate the uncertainties attached to the estimation of N_{exp} (see supporting information).

3. Interpreting Estimates of Nutrient Drawdown: Caveats and Possibilities

For the BS, the lack of change in nitrate-salinity relationships at the winter maximum between 2004 and 2008 confirms temporal stability in the processes that lead to the biogeochemical "reset" (e.g., decomposition) of inorganic nitrogen during winter (see Figure S1). Such direct validation was not possible for BB, for which prebloom data were available only for spring 1998. Nevertheless, we surmise that prebloom nutrient-salinity relationships remained stable there as well since the Arctic outflow though western BB draws Pacific-derived waters from the BS [*Tremblay et al.*, 2002a].

Our analyses of inter-annual trends were based on different temporal windows of sampling for some years, which would introduce biases if data from the bloom period in some years (i.e. when cumulative nutrient consumption increases rapidly with time) were compared with post-bloom data for other years. These biases must be minor here since nearly all the nitrate drawdown observed in seasonal time-course studies of BB during 1998 [*Tremblay et al.*, 2006] and of BS during 2004 [*Simpson et al.*, 2013; *Tremblay et al.*, 2008] and 2008 [*Forest et al.*, 2011] occurred prior to August. No relationship was found between sampling date and nitracline depth (*p* values > 0.7) or nitrate drawdown (*p* values > 0.07) in the present data set (Figures 2c and 2d).

Interannual changes in productivity can result from differences in mixing, which affects the quantity of nutrients injected in the euphotic zone, and/or by a greater realized consumption of available nutrients by phytoplankton. All other things being equal, greater mixing will result in higher salinities in the upper water column and translate into a higher N_{exp} estimate. The second mechanism relies on the SCM, a widespread and active feature associated to the nitracline in the High Arctic [*Ardyna et al.*, 2013; *Hill et al.*, 2013; *Arrigo et al.*, 2011; *Martin et al.*, 2010, 2012; *Mclaughlin and Carmack*, 2010]. Since phytoplankton have to compose with low temperature and light limitation at the SCM [*Martin et al.*, 2012], it is plausible that an increase in light availability caused by greater ice transparency or a longer ice-free season would increase nutrient drawdown within the upper halocline. This would result in lower nutrient inventories at the time of sampling and widen the gap between N_{obs} and estimated N_{exp} values.

While rivers (e.g., the Mackenzie River in the BS) supply nutrients to the coastal domain, there is mounting evidence that phosphate and inorganic nitrogen are readily consumed in the most neritic (e.g., 2–5 m deep)
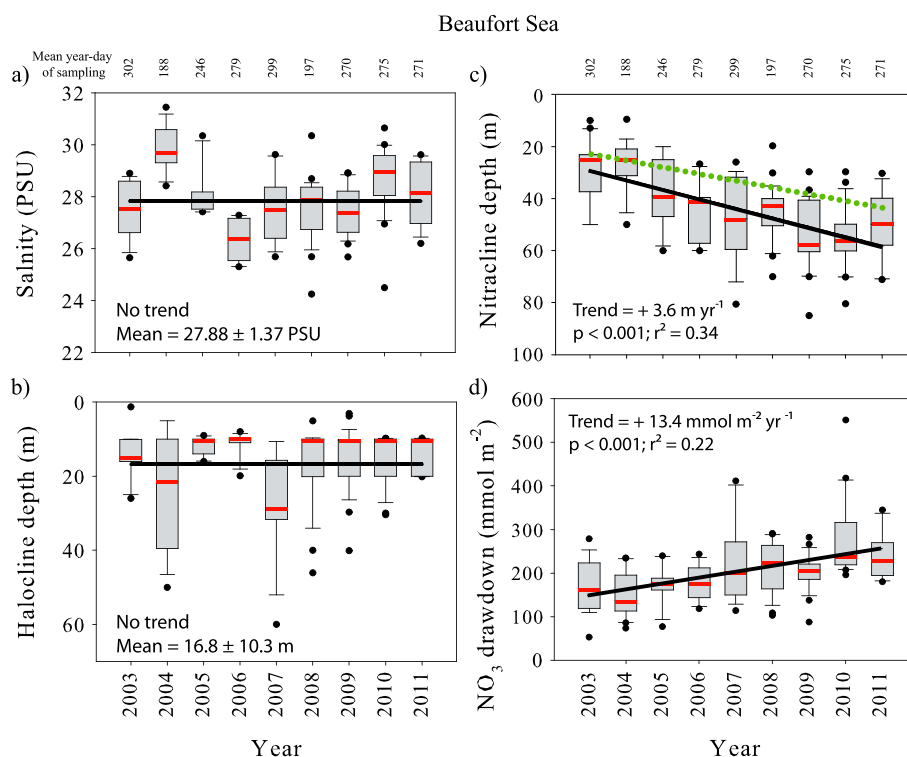
Figure 2. Box plots of the (a) weighted mean salinity in the first 50 m of the water column, (b) vertical position of the halocline, (c) nitracline depth, and (d) seasonal nitrate (NO_3^-) drawdown for the Beaufort Sea. Each box represents 50% of the observations, and the red mark gives the median value. Whiskers provide ranges for the upper and lower quartiles, and circles indicate extreme values. The black linear regression lines (trends) were fitted using all individual data points (not plotted). The green line in Figure 2c gives the trend in the mean vertical position of the subsurface chlorophyll maximum (SCM) ($p < 0.001$; $r^2 = 0.09$). Note the different vertical scales. The mean year-day of sampling is noted on the upper axis.

portion of inner estuarine transition zones [*Emmerton et al.*, 2008; *Tank et al.* 2012] and that the labile fraction of riverine, dissolved organic nitrogen is very small [*Shen et al.*, 2012]. In this context, the main potential influence of rivers at our sampling stations is freshening, which our estimation method would adequately capture as dilution with no net input of inorganic nutrients (see supporting information).

4. Nitrate Drawdown in the Beaufort Sea

Figure 2 clearly shows that the position of the nitracline and the extent of nitrate drawdown did not covary with the physical properties of the upper water column. Results showed no significant trends in halocline depth and weighted mean salinity in the upper 50 m (Figures 2a and 2b), consistent with prior observations by *Comeau et al.* [2011]. While these authors detected a small drop in salinity at specific depths between 25 and 150 m, those were not sufficient to skew the weighted mean salt content in the upper 50 m. This suggests that our sampling region maintained relatively high surface salinities despite some influence from the freshening Beaufort Gyre and/or Alaskan Coastal Current [*Woodgate et al.*, 2006; *Chan et al.*, 2011].

From 2003 to 2011, the median depth of the nitracline increased by 3.6 m yr^{-1}, while median nitrate drawdown rose by +13.4 mmol m^{-2} yr^{-1} (Figures 2c and 2d). While the box plots reveal considerable spatial variability within years, the low and high quartiles (whiskers) and extreme outliers (circles) generally covaried with the median values. Since the increase in nitrate drawdown resulted primarily from declining N_{obs} instead of rising N_{exp} in the upper euphotic zone (i.e., no increase in salt content in Figure 2a and no change in winter nitrate-salinity relationships in Figure S1), it can be attributed to a greater vertical extent of biological consumption by SCM layers. The mean position of the SCM incidentally deepened by 2.2 m yr^{-1} in the interval ($p < 0.001$; $r^2 = 0.09$; Figure 2c), consistent with increases of 9.4, 8.0, and 3.3% yr^{-1} in the irradiance penetrating the upper water column for the months of June, July, and August for the period 1998–2009 [*Bélanger et al.*, 2013, Table 2]. Lesser deepening of the SCM relative to the nitracline is possibly due to the

late sampling date. When incident light rapidly declines during fall, SCM communities rely mostly on recycled ammonium [*Martin et al.*, 2012] and may then grow better above the nitracline.

The contribution of the SCM layer to annual new production in the area during 2008 was estimated at 80% in a recent model simulation [*Martin et al.*, 2013]. Orbiting sensors do not detect the associated chlorophyll *a*, which is consistent with the lack of a clear, overall satellite-based trend in primary production at the scale of the southeast Beaufort Sea [*Arrigo et al.*, 2011; *Bélanger et al.*, 2013] despite what we report here. The contribution of SCM layers to annual water column production in other sectors of the Arctic Ocean is a matter of debate [*Ardyna et al.*, 2013; *Hill et al.*, 2013; *Arrigo et al.*, 2011] and has yet to be assessed from contemporary measurements for the reasons discussed in *Martin et al.* [2012].

Although we adjusted a linear relationship to the data in Figures 2c and 2d, nitrate drawdown and nitracline depth appear to be stabilizing, hinting that the SCM shifted to a depth below which irradiance is no longer sufficient to support net growth (i.e., the algae reached their compensation light intensity). It is therefore plausible that NCP in the BS has reached a new stable state that would only be perturbed by the additional provision of nutrients to the upper euphotic zone. Irradiance levels at 70 m during July in central Amundsen Gulf (~0.04 mol quanta $m^{-2} d^{-1}$) match those observed in the deepest SCM of oligotrophic subtropical gyres, suggesting that light is now limiting SCM deepening in the coastal Beaufort Sea.

Our coastal observations contrast with those made offshore in the Beaufort Gyre, where a physically driven deepening of the nutricline and SCM was attributed to the accumulation of freshwater in the surface layer caused by ice melt, river discharge, and a strong anticyclonic circulation [*McLaughlin and Carmack*, 2010]. The contrast suggests that seasonality in surface nutrient concentrations offshore is much lower than in the coastal domain, where nitrate accumulates at the surface throughout the winter. Ice concentration and thickness are usually much lower there, where winds create a polynya and foster modest but significant turbulent resupply of nutrients during late fall and early winter [*Bourgeault et al.*, 2011; *Forest et al.*, 2011], resulting in surface nitrate concentrations of 4–5 μM at the winter maximum and high salinities relative to the Beaufort Gyre. *Codispoti et al.* [2013] reported winter nitrate concentrations ranging from 0.1 to 1.0 μM for the deep Canada Basin, which would tend to confine SCM layers to the permanent halocline and dampen seasonal productivity cycles offshore.

5. Nitrate Drawdown in Baffin Bay

Nitrate drawdown in Baffin Bay decreased at the mean rate of 26.3 mmol $m^{-2} yr^{-1}$, with a maximum of 802 mmol m^{-2} in 1998 and a minimum of 214 mmol m^{-2} in 2009 (Figure 3). The decreasing trend was more pronounced in western BB (-28.6 mmol $m^{-2} yr^{-1}$, $p = 0.018$, $r^2 = 0.39$) than in eastern BB (-19.9 mmol $m^{-2} yr^{-1}$, $p = 0.002$, $r^2 = 0.28$) (Figure 3d).

The analysis of salinity and nutrients, although less conclusive than for the Beaufort Sea, suggests that physical processes influenced nutrient distributions and drawdown in BB. The halocline and nitracline depths stayed relatively constant, but the surface salinity decreased by 0.22 $year^{-1}$ between 1997 and 2011 (Figures 3a–3c). This effect remained significant ($p = 0.027$) when the combined effect of sampling year and sampling date was considered (analysis of variance). *Rail* [2005] documented a seasonal freshening from May to July, but this cannot account for differences in salt content between years for which sampling occurred at similar dates (i.e., 1997 and 2005; 1999 and 2008). Seasonality, however, accounts for the higher salinities observed in 2009–2011, when sampling occurred after mid-October and some mixing had already taken place. Salinity and nitracline depth reached exceptionally low values in 2007 and 2008 (Figures 3a and 3c), mostly associated with western stations and the Arctic outflow (data not shown). The decreasing salinity trend is consistent with the freshening of Canada Basin source waters for the west [*Yamamoto-Kawai et al.*, 2009] and accelerated Greenland glacier melt in the east [*Harig and Simons*, 2012]. Decreasing surface salinities imply an increase in vertical stratification in the region, which, via reduced upward nitrate supply, could account for record low estimates of nitrate drawdown in recent years (i.e., 2009–2011; Figure 3d). It was previously shown that episodic injections of nitrate during wind-driven mixing events supported a large portion (approximately 50%) of new production during summer in 1998 [*Tremblay et al.*, 2002b].

It follows from the previous discussion that the change in new and net productivity in BB jointly results from a drop in N_{ex} and a rise in N_{obs}. In this context the response should be visible from space. For the period
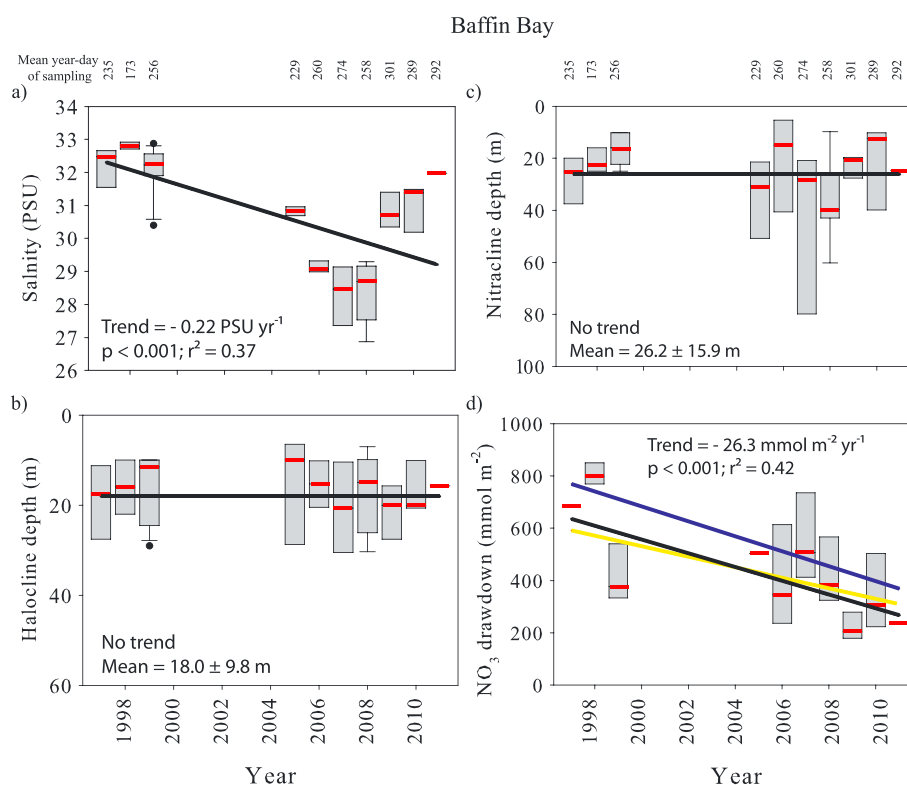
Baffin Bay

Figure 3. Box plots of the (a) weighted mean salinity in the first 50 m of the water column, (b) vertical position of the halocline, (c) nitracline depth, and (d) seasonal nitrate (NO_3^-) drawdown for Baffin Bay. Linear regression lines (trends) are given in black for the whole section, in blue for eastern Baffin Bay (-19.9 mmol m^{-2} yr^{-1}, $p = 0.002$, $r^2 = 0.28$) and in yellow for western Baffin Bay (yellow; -28.6 mmol m^{-2} yr^{-1}, $p = 0.018$, $r^2 = 0.39$). The mean year-day of sampling is noted on the upper axis. See Figure 2 for an explanation of the box plots.

spanning our maximum and minimum NCP estimates (1998–2009), *Bélanger et al.* [2013] reported a decrease of 55 g C m^{-2} yr^{-1} in total PP (obtained by multiplying their trend of -5 g C m^{-2} yr^{-1} by 11 years). This value compares favorably with the concomitant decrease in NCP reported here (50 g C m^{-2} yr^{-1}, assuming a molar drawdown C:N ratio of 7.1) but should not be expected to match it since it also includes the regenerated primary production. Spatially, the decrease noted by *Bélanger et al.* [2013] was also strongest in the west.

6. Nutrient Drawdown Ratios

The two calculation methods produced slightly different results for Si:N and N:P drawdown ratios in the two regions (see Tables S3 and S4 for details). For both ratios, differences were higher in Baffin Bay where the presence of distinct Pacific- and Atlantic-derived water masses causes larger uncertainties in N_{ex} for silicate and phosphate. Differences were highest for the N:P ratio, which is presumably more sensitive to variability in organic matter recycling, sampling date, and the composition of organisms affecting P drawdown. Seasonal time course studies in the coastal Beaufort Sea showed that a small drawdown of excess phosphate can occur after the exhaustion of nitrate, which may result from the constitution of internal P reserves [*Diaz et al.*, 2008, and references therein], nitrogen fixation [*Blais et al.*, 2012] and/or photochemical production of ammonium during summer [*Xie et al.*, 2012].

While interannual and spatial differences in drawdown ratios were observed, the values remained internally consistent in each region and showed no temporal trends. Combining estimates from the two methods, when possible, produced overall Si:N ratios of 1.6 ± 0.3 and 1.1 ± 0.4 in BS and BB, respectively. Matching N:P ratios were 11.6 ± 1.9 and 14.6 ± 4.5, respectively. These values were very similar to those observed during time-course studies of the spring bloom for each region [*Tremblay et al.*, 2002a, 2002b, 2008; *Simpson*

et al., 2008; *Forest et al.*, 2011], during which the overwhelming contribution of diatoms to primary production, phytoplankton abundance, and/or carbon biomass was ascertained [*Lovejoy et al.*, 2002; *Vidussi et al.*, 2004; *Brugel*, 2009]. In this context, the relative stability of Si:N drawdown ratios over time indicates that diatoms dominated NCP irrespective of temporal trends in the intensity of this production. This notion is reinforced by the lack of temporal trends in N:P ratios, which also shows that phosphate-based estimates of NCP would yield trends similar to those obtained with nitrate.

We speculate that the low Si:N ratios in Baffin Bay relative to the Beaufort Sea result from the presence of less silicified diatom assemblages, differences in growth conditions imparted by distinct physical and chemical settings, or a lesser contribution of diatoms to NCP in BB, which would be consistent with the relatively high N:P drawdown ratios observed there. While the Si:N ratios observed in the BS are well above the average value of 1.0 reported for cultured diatoms by *Brzezinski* [1985], our values remain within the envelope of interspecies variability observed in that study and are consistent with the importance of highly silicified diatoms (*Leptocylindrus* sp. and pennate forms) in the region [*Horner and Schrader*, 1982; *Sukhanova et al.*, 2009]. Less silicified *Thalassiosira* sp. typically dominate diatom biomass during the spring bloom in BB [*Lovejoy et al.*, 2002]. High Si:N ratios in the coastal BS could also be favored by the large fraction of diatom production occurring in the SCM, where reduced irradiance may favor silicon polymerization over nitrate-based protein synthesis. The latter requires energy and reducing power from photosystems while the former draws energy from cellular respiration [*Claquin et al.*, 2002]. Reduced iron availability has been invoked as a cause for high Si:N ratios in a variety of offshore environments (e.g., *Takeda et al.* [1998]) but is less probable in close proximity to the Beaufort Shelf [*Moore et al.*, 2004; *Klunder et al.*, 2012].

7. Ecological Consequences of Changing Net Community Production

Changes in the physical environment had regionally contrasted impacts on NCP in the Canadian Arctic. Despite their opposite temporal trends in productivity and different $Si:NO_3^-$ drawdown ratios, first-order changes in NCP in Baffin Bay and the coastal Beaufort Sea were likely mediated by diatoms. A corollary to this interpretation is that the production of nondiatom phytoplankton groups (e.g., flagellates like *Micromonas* sp.) is mostly supported by nitrogen recycling. So while changes in productivity have occurred, we found no clues that the functional composition of phytoplankton blooms has been radically altered so far.

In the offshore Beaufort Sea, freshwater-induced increases in stratification led to a shift toward small picophytoplankton and bacterioplankton in late summer, possibly leading to reduced vertical export and a less efficient food web [*Li et al.*, 2009]. In the coastal domain, however, diatoms appear to maintain their relative contribution to NCP when the spring bloom is also considered. We conclude that median diatom-driven NCP rose from $12.6 \, g \, C \, m^{-2}$ in 2003–2004 to $19.8 \, g \, C \, m^{-2}$ in 2010–2011 (using a C:N conversion factor of 7.1), increasing by 1.6-fold the amount of carbon available to consumers and/or export to the deep ocean and the benthos. By contrast, data from northern Baffin Bay imply a drop in diatom-mediated NCP from $63.6 \, g \, C \, m^{-2}$ in 1997–1998 to $21.6 \, g \, C \, m^{-2}$ in 2009–2011, reaching low productivity levels that are nearly on par with those of the coastal Beaufort Sea. This shift suggests that the North Water Polynya, formerly considered as a secular oasis of biological productivity [*Tremblay et al.*, 2006] is becoming oligotrophic in response to increasing stratification and reduced mixing and/or upwelling. This change is likely to adversely affect microzooplankton and the large populations of apex consumers (birds, bears, and whales) that locally depended on the herbivorous food web [*Strom and Fredrickson*, 2008]. Overall, our results demonstrate that the changing physical Arctic environment can impact marine productivity positively on interior shelves and negatively over outflow shelves.

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