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LETTER

Freshening leads to a three-decade trend of declining nutrients in the western Arctic Ocean

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Abstract

Rapid warming and sea-ice loss in the Arctic Ocean are among the most profound climatic changes to have occurred in recent decades on Earth. Arctic Ocean biological production appears to have been reduced as a result, but the consequences for nutrient concentrations are unknown. We have assembled a collection of historical field data showing that average concentrations of the macronutrients nitrate and phosphate have decreased by 79% and 29%, respectively, in surface waters of the western Arctic Ocean basin over the past three decades. The field observations and results from numerical ocean simulations suggest that this long-term trend toward more oligotrophic (nutrient-poor) conditions is driven primarily by the compound effects of sea-ice loss: a reduced resupply of nutrients from subsurface waters (due to fresh water addition and stronger upper-ocean stratification) coincident with increased biological consumption of nutrients (due to the greater availability of light needed for photosynthesis).

1. Introduction

Arctic Ocean sea-ice cover has been shrinking in recent decades in response to global warming (Kwok 2018, Stroeve and Notz 2018). The dramatic loss of summer ice extent (a 14%/decade reduction between 1979 and 2012) (Parkinson and Comiso 2013) has triggered major changes in ocean freshwater cycle and storage (Haine et al 2015, Brown et al 2020), primary production (PP) (Lewis et al 2020), carbon cycling (Cai et al 2010), ocean acidification (Yamamoto-Kawai et al 2009, Qi et al 2017), and ecosystem (Li et al 2009, Box et al 2019). Whether critical changes have also occurred in Arctic Ocean nutrient dynamics is unclear but important to know. The major nutrients nitrogen (N) and phosphorus (P), which play a significant role in marine food webs and carbon dioxide (CO₂) budget, are the primary limiting nutrients in global ocean (Moore et al 2013a). Globally, surface concentrations of nitrate (NO₃⁻) and phosphate (PO₄³⁻) are tending to decrease in association with surface ocean warming and increased stratification (Sarmiento et al 2004). The recent rapid changes in the Arctic are expected to have similarly important consequences for regional nutrient availability and cycling, as an increase in upper-ocean stratification (due to the ongoing increase of heat and freshwater contents) would be expected to hinder the upward supply of nutrients from deeper waters (McLaughlin and Carmack 2010, Tremblay et al 2015).

Due to the polar amplification of climate warming and the relative paucity of human impacts in the Arctic region, the Arctic Ocean is a particularly well-suited system in which to observe the impacts of climate change on nutrient stocks and dynamics. Much effort has been devoted to the study of Arctic nutrient
Figure 1. Location of sampling stations on the western Arctic Ocean during 1987–1996 (red dots), 1997–2006 (green dots), and 2007–2016 (blue dots). The gray lines indicate 50, 100, 1000 and 2000 m isobaths.

distributions and biological productivity (Nishino et al 2008, Demidov et al 2017, Zhuang et al 2020a), nutrient tracers and budgets (Cooper et al 1999, Torres-Valdés et al 2013, Zhuang et al 2019), annual nutrient dynamics in the coastal ocean (Tremblay et al 2008), but long-term changes in nutrient stocks of the western Arctic Ocean basin have not been previously studied.

In this work, we describe changes in nutrient concentrations across three decades of accelerating sea-ice loss in the Pacific sector of the Arctic Ocean (175° E–135° W, 75°–85° N): 1987–1996, 1997–2006, and 2007–2016. We used a total of 1300 nutrient data records from several databases: 78 data points from the first decade, 826 from the second decade, and 396 from the third. We also simulated nutrient changes by year with a version of the Regional Arctic System Model (RASM, 9 km grid). Below we present the long-term nitrate and phosphate trends in terms of study-region averages by decade from the field observations and by year from the model output.

2. Materials and methods

2.1. Data compilation and analysis

Nutrient and hydrographic data were obtained for the following Arctic summer cruises (Late July to October) (figure 1): 1989, 1991, 1993, 1994, 1996, 1997, 2002, and 2005, from the World Ocean Database (WOD; www.nodc.noaa.gov/cgi-bin/OC5/WOD); the Louis S. St. Laurent cruises of 2004, 2005, 2009, 2011, and 2013, from the Carbon Dioxide Information Analysis Center (http://cdiac.ornl.gov/oceans/datmet.html); the Polarstern cruises of 2007, 2011, and 2015, from the Marine Network for Integrated Data Access (http://manida.awi.de/); and the Xuelong cruises of 1999, 2003, 2008, 2010, 2012, 2014, and 2016, from the Chinese National Arctic and Antarctic Data Center (www.chinare.org.cn:8000/en/index/). Ice concentration data for the month of September were obtained from the National Snow & Ice Data Center (http://nsidc.org/data). For spatial visualization and analysis of the nutrient and hydrographic data, we used Ocean Data View (ODV) version 4.4.1 (Schlitzer 2018).

Nutrient samples were measured on board for nitrate plus nitrite (NO$_3^-$ + NO$_2^-$), phosphate (PO$_4^{3-}$), and silicate (Si(OH)$_4$) using standard colorimetric methods (Grasshoff et al 1999) adapted for a continuous flow analyzer (Skalar San++, Breda, Netherlands) during the Xuelong cruises. Analytical precision was $\pm$2% for both NO$_3^-$ + NO$_2^-$ and PO$_4^{3-}$, and was $\pm$2.5% for Si(OH)$_4$. The detection limits were 0.1 µM for NO$_3^-$ + NO$_2^-$, 0.03 µM for PO$_4^{3-}$, and 0.1 µM for Si(OH)$_4$.

In deep waters (>500 m depth), where nutrient concentrations should be relatively stable, the nitrate and phosphate data exhibited a good consistency across the various cruises (figure S1), demonstrating the reliability of our comparison of surface water nutrient changes over time. Decadal averages for the nutrient data were calculated at 30 m depth in two ways: (a) by averaging over all data points within the study region, and (b) by averaging over all data points within each 2° × 10° grid cell (figure S2) and then calculating the average of those averages. For nitrate and phosphate, the differences between the results of these two methods were small (figure S3 and table S1 (available online at stacks.iop.org/ERL/16/054047/mmedia)). In this paper, we report results in terms of the first method. We used 30 m as a specific depth to better observe expansion of oligotrophic water.

PP rates were obtained in 1994 and 2010 by an NaH$^{14}$CO$_3$ uptake method (Gosselin et al 1997, Hill and Cota 2005) and in summer 2008 by a $^{13}$C enrichment technique (Lee et al 2012). Data have
been published in 1994 (Gosselin et al 1997) and 2008 (Lee et al 2012). The samples were collected in ice-covered waters. To cast the results in terms of open-water PP rates (i.e., without shading by sea ice), we used the equation of Gosselin et al (1997).

2.2. Numerical ocean simulations

The biogeochemical cycling module of the RASM consists of the Los Alamos National Laboratory ice model and the Parallel Ocean Program, which includes a nutrients component (Jin et al 2016, 2018). This module is a medium-complexity, nutrients–phytoplankton–zooplankton–detritus model derived from Moore et al (2004, 2013b). The model includes 26 state variables: the dissolved nutrients nitrate, ammonium, phosphate, silicate, and iron; three types of phytoplankton (diatoms, small phytoplankton or flagellates, and diazotrophs), with explicit carbon, iron, and chlorophyll-a pools for each group, an explicit silicon pool for diatoms, and an implicit carbonate pool for small phytoplankton; a herbivorous zooplankton pool; the dissolved organic pools of carbon, nitrogen, iron, and phosphorus; oxygen; dissolved inorganic carbon; and alkalinity. The model domain includes the northern hemisphere north of 30° N (with a rotated sphere such that an equator crosses the North Pole), a horizontal resolution of approximately 9 km, and 45 vertical layers (5 m layers within the top 20 m, with layer thicknesses gradually increasing to 300 m at the deepest ocean bottom). Initial conditions for the chemical variables nitrate, phosphate, and silicate were obtained from the gridded World Ocean Atlas (WOA2013); initial conditions for the other constituents were obtained from a global model simulation by Moore et al (2004).

3. Oligotrophic trend in the Arctic Ocean

The 30 years of observations show a northwestward expansion of nitrate-depleted water (NO$_3^-$ < 1 μM) within the Pacific sector of the Arctic Ocean (figure 2). Nitrate has proven to be the major limiting nutrient in many Arctic waters, including the Beaufort Sea (Tremblay et al 2008), the Kara Sea (Demidov et al 2014, Makkaveev et al 2015) and the western Arctic Ocean (Zhuang et al 2020b). The decrease of nitrate stock in the basin areas (i.e., where water depths are greater than 200 m) is seen in the decadal change in average nitrate concentration at 30 m depth (figure 3(a)) and in the average concentration within the upper 30 m of the water column (figure S4(a)). The average nitrate concentration at 30 m depth decreased from 2.9 ± 2.6 μM during 1987–1996 to 1.7 ± 1.2 μM during 1997–2006 and then 0.6 ± 0.9 μM during 2007–2016. The average phosphate concentration decreased from 1.03 ± 0.29 μM during 1987–1996 to 0.90 ± 0.14 μM during 1997–2006 and then 0.73 ± 0.11 μM during 2007–2016. These numbers indicate a 79% reduction in surface nitrate over the three decades and a 29% reduction in surface phosphate. In other words, the western Arctic has become increasingly oligotrophic over the past 30 years, with a measurable decline in bioavailable nitrate and phosphate in the upper ocean. The reduction of nitrate is more than twice that of phosphate.

These trends occur in tandem with ongoing sea-ice loss and freshening in the study area. In 1987–1996, the average September sea-ice extent was 7.0 (±0.6) × 10$^6$ km$^2$ (table S2). In the following two decades, the average fell to 6.3 (±0.4) × 10$^6$ km$^2$ and then 4.8 (±0.5) × 10$^6$ km$^2$. At the same time, the average 30 m salinity in the basin areas declined from 31.31 ± 0.98 during 1987–1996 to 30.44 ± 0.71 during 1997–2006 and then 29.15 ± 0.93 during 2007–2016. These numbers indicate a 31% reduction in September sea ice extent and a 7% reduction in salinity. Consistent with these changes, the average potential density (σ$_0$) at 30 m sharply decreased, from 25.38 ± 0.77 during 1987–1996 to 24.47 ± 0.57 during 1997–2006 and then 23.33 ± 0.75 during 2007–2016. The relatively fresh surface ocean layer (defined by a salinity of 31 at its base) also expanded vertically, with a thickness of 34 ± 18 m during 1987–1996, 41 ± 18 m during 1997–2006, and 52 ± 14 m during 2007–2016.

For insight into processes that might be driving these changes, we simulated ocean conditions with RASM (9 km grid), a physical-biological coupled numerical mode (Jin et al 2016). The simulation results (1987–2009) show declining concentrations of nitrate and phosphate at 30 m depth (figure 3(b)), with nitrate decreasing at a rate of 1.7 μM per decade and phosphate decreasing at a rate of 0.11 μM per decade. These rates are in good agreement with the observed (1987–2016) rates of about 1.1 μM and 0.15 μM per decade and are much greater than rates estimated for the global ocean. For surface nitrate, the western Arctic rate of decline is approximately 20–30 times the estimated global rate (0.06 μM per decade) (Boyd et al 2015); for phosphate, the western Arctic rate of decline is approximately 2–3 times the global rate (0.05 μM per decade) (Boyd et al 2015). Note that the modeled and observed decadal averages of nitrate and phosphate shown an average different of 21% (figure 3(b)).

4. Mechanisms of the oligotrophication

Several processes could have contributed or led to the observed reduction of surface nutrients. One possibility is dilution by the recently larger inputs of low-nitrate river water (Lara et al 1998, Guo et al 2004) and sea-ice meltwater burden (Zhuang et al 2017). However, average surface salinity in our study area decreased by only ∼7% over the three decades of study (figure 3(a)). Direct dilution is therefore not likely responsible for the observed much larger trend.
of declining surface nutrients. Pacific inflow through the Bering Strait is another major source of freshwater to the Arctic Ocean, but this inflow water is stored below the sea surface once it enters the western Arctic basins (Timmermans et al 2017).

Another possible explanation is a decrease in the upward supply of nutrients from subsurface waters (figure 4). As the surface ocean has freshened, the density of the surface layer has decreased (figure 5) and its thickness has increased (table S2). The density of the deeper waters fed by Pacific inflow remains unchanged. The greater difference between surface and subsurface densities (and thus stronger stratification) inhibits the upward mixing of saline,
nutrient-rich Pacific waters into the upper layer (figure 4). The reduction of mixing depth (Peralta-Ferriz and Woodgate 2015) and deepening of the density-contrast barrier (Tremblay et al 2015, Polyakov et al 2018) makes it even more difficult for deepwater nitrate to replenish the sunlit, nutrient-depleted surface waters. This is especially so in the Canada Basin, where wind-driven convergence has led to intensification of the Beaufort Gyre and additional freshwater accumulation within the surface waters of the gyre (Giles et al 2012). Recent observations indicate also a deepening of the nutricline (2003–2009) due to accelerated sea-ice melt and surface freshening (McLaughlin and Carmack 2010). The Arctic Ocean surface layer has experienced more rapid increase in stratification than most other ocean basins (Gruber 2011), thus limiting upward nutrient supply for biological production.

Consistent with this scenario, the 23 year RASM simulations indicate a decrease of upward nutrient supply across the 30 m surface of the western Arctic Ocean. Contributing factors include a strengthening of upper-ocean stratification (evident as a two-decade increase in the modeled density difference between 0 m and 30 m; figure S5(a)) and an increase in wind-driven Ekman (downward) pumping after sea-ice retreat (evident as increasingly negative vertical velocities at 30 m; figure S5(b)). Without this upward resupply, the nitrate stock in the surface water is readily consumed by local biological processes (i.e. primary production).

Satellite-based estimates indicate a recent (1998–2009) 20% increase in total annual PP over the Arctic Ocean (Arrigo and Van Dijken 2011), which has been ascribed to an increase of light availability in the newly open waters exposed by sea ice retreat though much of the increase occurred in the ocean margins (Chen et al 2002, Arrigo and Van Dijken 2011). Over the three decades of this study, the rates of PP measured in the summertime western Arctic have increased in the slope/southern basin areas, where summertime sea-ice cover is diminishing and enormous reduction in nutrient concentrations occur (figure 6(a) and table S3). With sea ice retreat and the increase of PP come more nutrient consumption and an expansion of oligotrophic conditions,

Figure 3. (a) Decadal changes in average September sea-ice extent and average summertime salinity, potential density ($\sigma_\theta$), and nitrate and phosphate concentrations at 30 m depth. The dashed outline on the globe delineates the study area. (b) Modeled and observed summertime concentrations of surface nitrate and phosphate. The model (Regional Arctic System Model, RASM) outputs are the study-area averages at 30 m depth. The dashed lines are linear regression trend lines. The vertical red and blue shading show the observed decadal average NO$_3^-$ and PO$_4^{3-}$ concentrations at 30 m depth, and the accompanying thin red and blue lines show the corresponding model decadal averages.
Figure 4. Schematic illustration of the effects of long-term sea-ice loss on upper waters of the western Arctic Ocean: pre-melt (left), mid-melt (middle), and post-melt (right). The white blocks indicate ice cover, and the yellow arrows indicate incident and reflected sunlight. The turquoise shading of the water column represents nutrient concentrations, with darker shading indicating higher concentrations. ‘PW’ represents the inflow of nutrient-rich Pacific water (green arrow) through the Bering Strait. As sea ice melts each summer, freshwater accumulates in the upper ocean (blue arrow), resulting in a thicker, fresher, lower-density surface layer: the density-contrast barrier at the base of the surface layer (dashed gray line) deepens. The mixing (i.e. resupply) of nitrate across the base of the surface layer (red arrows) is now inhibited by the greater density difference between the surface and subsurface layers. As sea ice recedes, more sunlight penetrates the water column and PP increases (green dots), as does nutrient consumption and downward export due to the sinking of phytoplankton (solid orange line). The green dots represent the dominant phytoplankton (large and small). As melting progresses and nutrients continue to decline, smaller algae come to dominate (due to the competitive advantage afforded by their lower nitrate demand) and particles tend to involve in nutrient recycling (dashed orange line). Over recent decades, as the summertime extent of post-melt conditions has dramatically increased, the upper western Arctic Ocean has become increasingly impoverished with respect to nutrients.

Figure 5. Vertical distribution of potential density ($\sigma_\theta$) (kg/m$^3$) during the periods 1987–1996, 1997–2006, and 2007–2016 in the Pacific sector of the Arctic Ocean. $\sigma_\theta$ in surface layer decreased through time. which has limited the further increase of phytoplankton production (Coupel et al 2015, Ji et al 2019) and thus the biological drawdown of CO$_2$ (Cai et al 2010) in the Arctic Ocean basin. Shelfbreak upwelling would increase biological production in the coastal waters (Tremblay et al 2011, Zhuang et al 2020a), however failed to induce nutrients resupply off the shelf (Tremblay et al 2011). A recent report suggested that freshening of the western Arctic inhibits ocean to absorb CO$_2$ (Woosley and Millero 2020).

Estimation of the nitrate:phosphate changes associated with various ocean processes (figure 6(b)) also indicate that biological consumption without sufficient resupply is a plausible explanation for the observed trend of nutrient decline. In figure 6(b), the black diamond shows the average nitrate and phosphate concentrations measured during the first decade of sampling in the slope/southern basin (>200 m depths but south of 77.0° N); the locations of the black triangle and the plus symbol show the declines evident in subsequent decades—declines in nitrate and phosphate concentrations and also the nitrate:phosphate ratio. In considering what might have driven these shifts, we again examine freshwater dilution, biological uptake and diminished resupply. Dilution by nitrate-poor freshwater would have reduced the original seawater nitrate content by less than 10% (based on the observed decline of salinity), whereas the measured decline was nearly 80%. Estimating the effect of biological influences is more complex, as the variable stoichiometry of phytoplankton uptake must be taken into account: phytoplankton absorb nutrients with various N:P ratios in a variety of nutrient settings (Geider and La Roche 2002, Mills et al 2015). When nitrate is plentiful, phytoplankton absorb nutrients with an N:P ratio of 16:1 (shown by the red line on figure 6(b)); when nitrate is in short supply, the ratio is closer to 5:1 (shown by the yellow
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Figure 6. (a) Euphotic zone primary production rates measured in 1994, 2008, and 2010 in the western Arctic Ocean. Shelf stations are those located where the seafloor was <200 m deep; slope/southern basin and northern basin stations are those located where the seafloor was >200 m deep, with the dividing line between southern and northern being 77° N. Correction for the effects of sea ice on underwater irradiance has been applied to all data. (b) Observations and mechanisms of nitrate:phosphate change in slope/southern basin (>200 m depths but south of 77.0°N). The black diamond shows nutrient conditions (include error bars) during the first decade of observations, and the arrows show the effects of various ocean processes on that initial average NO$_3^-$:PO$_4^{3-}$. The vertical influx of nutrients (blue arrow) would tend to increase the concentrations of both nutrients at an N:P ratio of 11 adopted from Mills et al (2015). In the scenario shown in figure 4, this resupply would be hindered by the stronger vertical stratification associated with ice melt and surface freshening. Nitrogen fixation and denitrification (green arrows) would tend to increase and decrease the nitrate concentration, respectively, with no direct effect on phosphate. The pink zone shows the effects of biological consumption, with the bounds defined by biological consumption under nitrate-replete (red arrow) and nitrate-deficient (yellow arrow) conditions. The characteristics of the sea-ice meltwater and river water end-members are from Zhuang et al (2017) and Lara et al (1998), respectively. FW = freshwater.

line) (Geider and La Roche 2002, Weber and Deutsch 2010). Biological uptake, then, would have served to shift the original point of average nitrate and phosphate (black diamond) down into the pink zone of figure 6(b), as observed. The nutrient measurements indicate an N:P uptake ratio of ~10 during the second decade of observations ($\Delta$NO$_3^-$ = 3.2 µM and $\Delta$PO$_4^{3-}$ = 0.33 µM), followed by a ratio closer to 6 during the most recent decade ($\Delta$NO$_3^-$ = 0.8 µM and $\Delta$PO$_4^{3-}$ = 0.12 µM). As expected, the N:P uptake ratio has shifted downward as nitrate has become more scarce.

Other biogeochemical processes can also influence nitrate concentrations (figure 6(b)). Arctic Ocean denitrification is important but would not significantly affect upper basin waters. This process occurs mainly in sediments of the continental shelves (Chang and Devol 2009). However, the affected bottom waters are unable to spread up into the low-salinity surface layer of the Arctic basins (Timmermans et al 2017). In low-latitude oceans, nitrogen fixation is important, as nitrogen depletion under conditions of adequate phosphate often promotes the growth of diazotrophs (Karl et al 1995), organisms that can utilize atmospheric N$_2$ to supply ‘new’ nitrogen to the system. In the western Arctic Ocean, however, N$_2$ fixation is likely suppressed by low water temperatures (Blais et al 2012). Indeed, observations of phytoplankton pigments during recent summer cruises indicate low activities of N$_2$-fixing organisms in western Arctic basin areas (Zhuang et al 2018).
5. Conclusions

Collectively, these diverse observations and simulations paint a consistent picture—that the three-decade trend of declining nutrients in the Pacific sector of the Arctic Ocean is likely due to reduced resupply from subsurface waters coincident with increased biological consumption. Through time, surface freshening has strengthened vertical stratification and weakened the upward transport of nutrients from subsurface waters. At the same time, greater summertime sea-ice loss and the resulting greater availability of light has allowed for an expansion of open waters and an increase of phytoplankton production and nutrient consumption. Moreover, unlike in low-latitude oceans, biological N\textsubscript{2} fixation is not available as a compensating response. As a result, the western Arctic Ocean basins are the most nitrate-depleted of all the world’s oceans, and recent levels of nitrate in the euphotic zone are insufficient for continuous phytoplankton growth throughout the summer. Because the annual cycle of winter ice formation and ever-increasing summer melting will continue for many decades (Wang and Overland 2009), we predict that the trend of Arctic Ocean oligotrophication might continue in the coming decades as well.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

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