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Key Points:

- The nutricline shoaling by an intrusion of Atlantic-origin cold saline water was observed in the northwestern Chukchi Sea in 2017
- Pacific-origin nutrients were lifted up to the surface layer by the intrusion of Atlantic-origin cold saline water
- The enhanced cyclonic ocean circulation triggered a pronounced transport of Atlantic-origin cold saline water to the western Arctic Ocean

Supporting Information:

- Supporting Information S1

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Atlantic-Origin Cold Saline Water Intrusion and Shoaling of the Nutricline in the Pacific Arctic

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Abstract Atlantic-origin cold saline water has previously not been considered an important contributor to the nutrient supply in the Pacific Arctic due to the effective insulation by the overlying Pacific-origin waters that separate the surface mixed layer from the deeper Atlantic Water. Based on hydrographic observations in the northwestern Chukchi Sea from 2015 to 2017, we demonstrate that the intrusion of Atlantic-origin cold saline water into the halocline boundary between Pacific and Atlantic-origin waters in 2017 lifted Pacific-origin nutrients up to the surface layer. We find that the cyclonic atmospheric circulation in 2017 was considerably strengthened, leading to lateral intrusions of two bodies of cold halocline water from the Eurasian marginal seas into the northwestern Chukchi Sea. Our results reveal that the intrusions of cold halocline waters caused unprecedented shoaling of the nutricline and anomalously high surface phytoplankton blooms in typically highly oligotrophic surface waters in the region during summer.

Plain Language Summary Nutrient depletion, especially nitrogen, in Arctic surface waters during the summer is common due to biological uptake and intense stratification caused by sea ice melting and riverine water inputs, which restricts the upward mixing of nutrients into the euphotic zone. Although Atlantic-origin cold saline water has previously not been considered an important contributor to the nutrient supply in the Pacific Arctic, the results presented here show that the intrusion of Atlantic-origin cold saline water into the halocline boundary layer between Pacific and Atlantic-origin waters in the summer of 2017 was an essential mechanism responsible for transporting Pacific-origin nutrients to the surface layer, leading to anomalously high surface phytoplankton blooms in typically highly oligotrophic surface waters in the northwestern Chukchi Sea.

1. Introduction

The warming (solar insolation) and freshening (sea ice melting and riverine water inputs) of the Arctic Ocean during summer increase stratification and suppress the upward mixing of nutrients into the euphotic zone (Codispoti et al., 2013). However, sea ice is now thinner and less compact (Kwok, 2018; Perovich et al., 2020); thus, the Arctic Ocean is more responsive to wind stress (Kwok et al., 2013), which enhances the nutrient supply (Bluhm et al., 2015). Shelf-break upwelling is becoming more prominent in the Arctic as the sea ice edge retreats poleward with ongoing climate change, exposing the shelf break to more direct wind forcing (Arrigo et al., 2014; Carmack & Chapman, 2003; Tremblay et al., 2011). Recently, Lewis et al. (2020) reported that annual net primary production (NPP) increased by 57% over the Arctic Ocean between 1998 and 2018. They also found that increased chlorophyll-a (Chl-a) was responsible for the sustained increase in annual NPP between 2009 and 2018, particularly along the interior shelf break. These results suggest that additional nutrients were supplied from increased vertical mixing near the shelf break into the nutrient-depleted upper euphotic zone (Arrigo & van Dijken, 2015; Lewis et al., 2020) and that the changes in ocean circulation in response to recent sea ice loss and increased wind mixing could significantly influence biological production (Ardyna & Arrigo, 2020).

The Arctic Ocean is experiencing radical modifications in its hydrographic properties and in its overall circulation (Ardyna & Arrigo, 2020). For example, Polyakov et al. (2017) reported that the recent increase in

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Atlantic water (AW) influence into the Arctic, the so-called "Atlantification" process, resulted in weakening of the halocline, shoaling of the AW layer, and increased winter ventilation. The Arctic changes associated with the advection of anomalous AW have already impacted biogeochemical components (e.g., Polyakov et al., 2020) and primary production (e.g., Oziel et al., 2017) in the Atlantic Arctic, suggesting that the changes in the circulation pathways of specific water masses can control the availability of nutrients in the Arctic Ocean (Polyakov et al., 2020).

The water column of the western Arctic (i.e., the Pacific sector) generally consists of a cold and relatively fresh surface mixed layer (SML, <50 m depth), Pacific-origin water (PW) layer that composes the upper halocline (depth < 150 m), and a warm and saline AW layer typically residing below 150 m (i.e., lower halocline layer, salinity [S] > 34 psu, potential temperature [θ] maximum) (Alkire et al., 2019; Codispoti et al., 2005; Korhonen et al., 2013). The PW can be further classified into two types based on seasonal modifications of the Chukchi Sea shelf: Pacific summer water (S = 31–32 psu, θ maximum, 50–100 m depth) and Pacific winter water ($S \approx 33$ psu, θ minimum, 100–150 m depth) (Nishino et al., 2013). In contrast, in the eastern Arctic (i.e., Atlantic sector), the PW layer is absent (Woodgate, 2013), and the AW is separated from the surface by a cold layer in which the S increases-a "cold halocline" (50–200 m depth, 34 psu < S < 34.5 psu, $\theta < -0.5$°C, Aagaard et al., 1981; Rudels et al., 1996; Steele et al., 1995) which is formed by either brine rejection-driven convection topped off with fresher cold waters during winter (convective halocline), or injection of cold salty shelf waters (advective halocline) (Steele & Boyd, 1998). The cold halocline layer is important in providing a density barrier trapping AW heat at depth way from the ice throughout the Arctic (Woodgate, 2013).

To date, the cold halocline water advected from the Atlantic sector into the Pacific sector has generally not been considered an important contributor to the nutrient supply due to effective insulation of the overlying PW (less saline and richer in nutrients than the AW) that separate the shallow SML from the warm and saline AW (Codispoti et al., 2013). Nevertheless, our newly observed data in the northwestern Chukchi Sea (Figure 1) reveal that an intrusion of Atlantic-origin saline cold water can play a significant role in transporting Pacific-origin nutrients to the surface layer, which resulted in anomalous surface blooms near the northwestern Chukchi Sea shelf break in the summer of 2017.

2. Results

2.1. Supply of Nutrient-Rich Deep Water to the Surface

Generally, the surface Chl-a concentrations in the northern Chukchi Sea during the summer are remarkably low (Figure S1) because nutrient depletion, especially nitrate (NO_3), in surface water is common during the summer due to biological uptake and intense stratification caused by freshwater input that restricts the vertical replenishment of surface nutrients (Carmack et al., 2006; Codispoti et al., 2005, 2013). However, hydrographic changes were observed in the northwestern Chukchi Sea from 2015 to 2017. In the summer of 2015, as in 2011–2014 (Figure S1), the surface Chl-a showed extremely low concentrations, ranging from 0.035 to 0.26 mg m^{-3}, due to water column stratification limiting nutrient availability (Figures 2a, 2d, 2g, and 2j). In contrast, the surface Chl-a concentrations, especially in the East Siberian Sea region (i.e., western stations), increased slightly (0.081–0.77 mg m^{-3}) in the summer of 2016 (Figure 2e) compared to 2015, and they increased more strongly on the northwestern Chukchi Sea shelf break in the summer of 2017, resulting in the highest observed values (0.28–2.4 mg m^{-3}) (Figure 2f). These anomalously high surface Chl-a concentrations in the summer of 2017 were accompanied by increases in sea surface S and surface nutrients (shown as phosphate [PO_4] concentration) (Figures 2i and 2l), suggesting that nutrient-rich deep water was supplied to the surface.

The vertical distributions of S and θ observed in 2015 along the Chukchi Sea shelf transect (Figure S2a) showed a typical vertical stratification (Figures S2d and S2g), resulting in extremely low-nutrient concentrations (below the detection limit for NO_3 and <0.75 μmol kg^{-1} for PO_4) in the upper layer (<20 m depth) (Figures S2j and S2m). The Chl-a concentration in the upper layer was lowest (<0.1 mg m^{-3}) (Figure S2p) due to NO_3 depletion (Figure S2j); however, it increased sharply with depth, showing a subsurface Chl-a maximum (SCM) at depths of 20–50 m. The S, θ, nutrients, and Chl-a observed in 2016 showed similar distribution patterns to those in 2015 (Figures S2e, S2h, S2k, S2n, and S2q). However, the vertical distributions observed

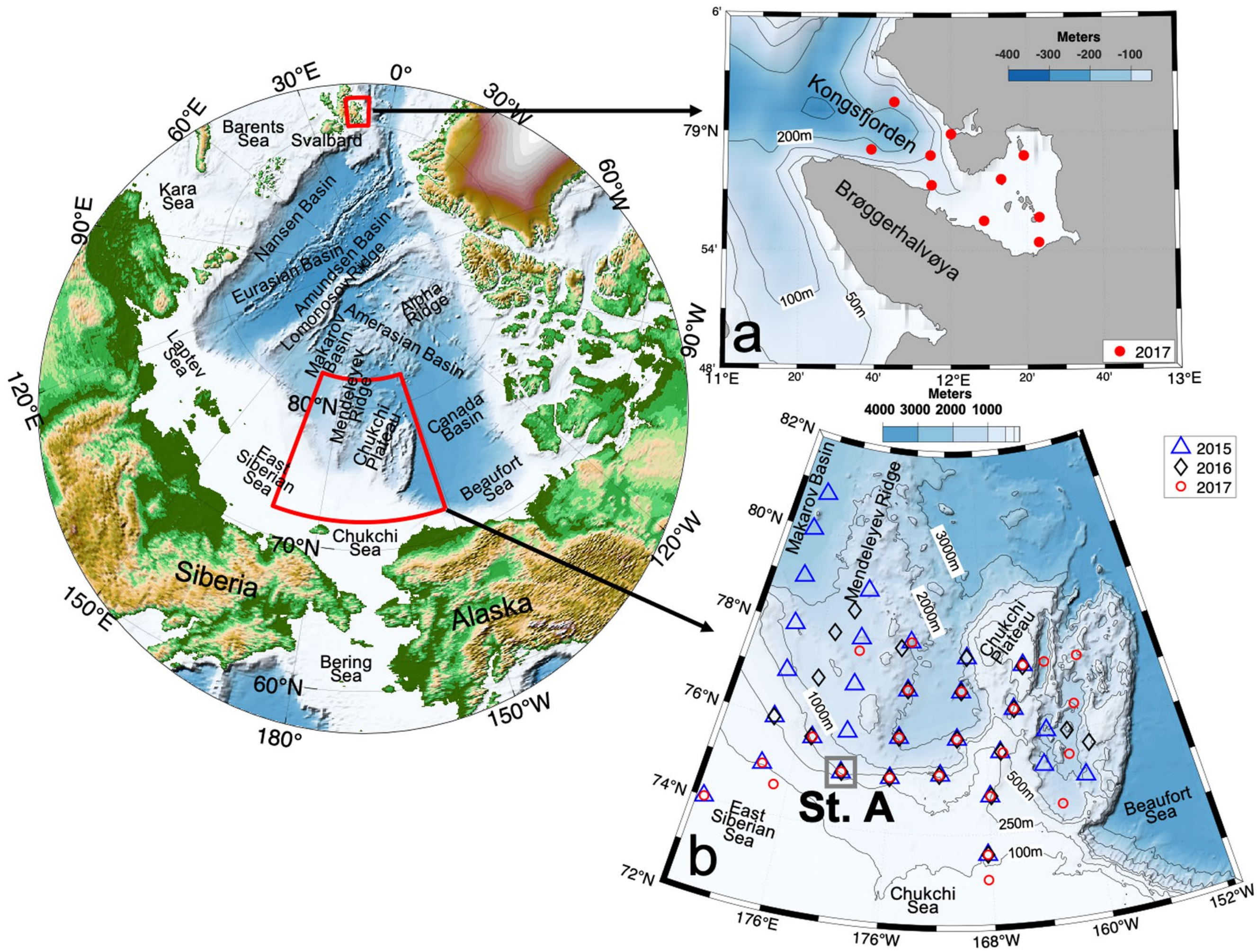

Figure 1. Hydrographic survey locations. Map showing bathymetric features and locations of the hydrographic survey in (a) Kongsfjorden, Svalbard, and (b) northern Chukchi Sea, Pacific Arctic. Blue triangles, black diamonds, and red circles represent seawater sampling stations in the summers of 2015, 2016, and 2017, respectively. The gray box shows the location of station A (St. A) where the most intense surface phytoplankton bloom occurred in 2017. Data from this station are shown in Figure 3.

in 2017 were distinct from those in 2015 and 2016. Interestingly, the lower halocline water ($S \approx 34$ psu) derived from shelf areas of the Atlantic sector of the Arctic Ocean (Polyakov et al., 2012; Randelhoff & Sundfjord, 2018) became shallower in the northwestern shelf break of the Chukchi Sea (Figure S2f), where the characteristics of Atlantic-origin waters were prominent (Figures S2i, S2l, and S2o). Shoaling of the Atlantic-origin water upper boundary was substantial, rising from ~150–170 m in 2015–2016 to ~80–120 m in 2017. As a result, the overlying nutrient-rich PW was lifted up to the surface layer, leading to anomalously high Chl-a concentrations (1.2–2.0 mg m^{-3}) in the upper 50 m in the northwestern shelf slope of the Chukchi Sea and the disappearance of SCM (Figure S2r). These results provide evidence that the upper halocline water was lifted by an intrusion of Atlantic-origin water, which resulted in the shoaling of the nutricline, producing favorable conditions for phytoplankton growth. Indeed, the PO_4 data clearly showed that the anomalously high Chl-a concentrations in the upper 50 m were caused by the entrainment of nutrients into the euphotic zone (Figure S2o).

We provide more detailed evidence that the anomalous 2017 surface summer bloom occurred in response to the nutrient supply from deep layers by the unprecedented intrusion of Atlantic-origin water into the western shelf beak of the Chukchi Sea using the data observed at station A (St. A, 75°N, 180°W, denoted in Figure 1), where the most intense surface phytoplankton bloom occurred in 2017. The vertical profiles

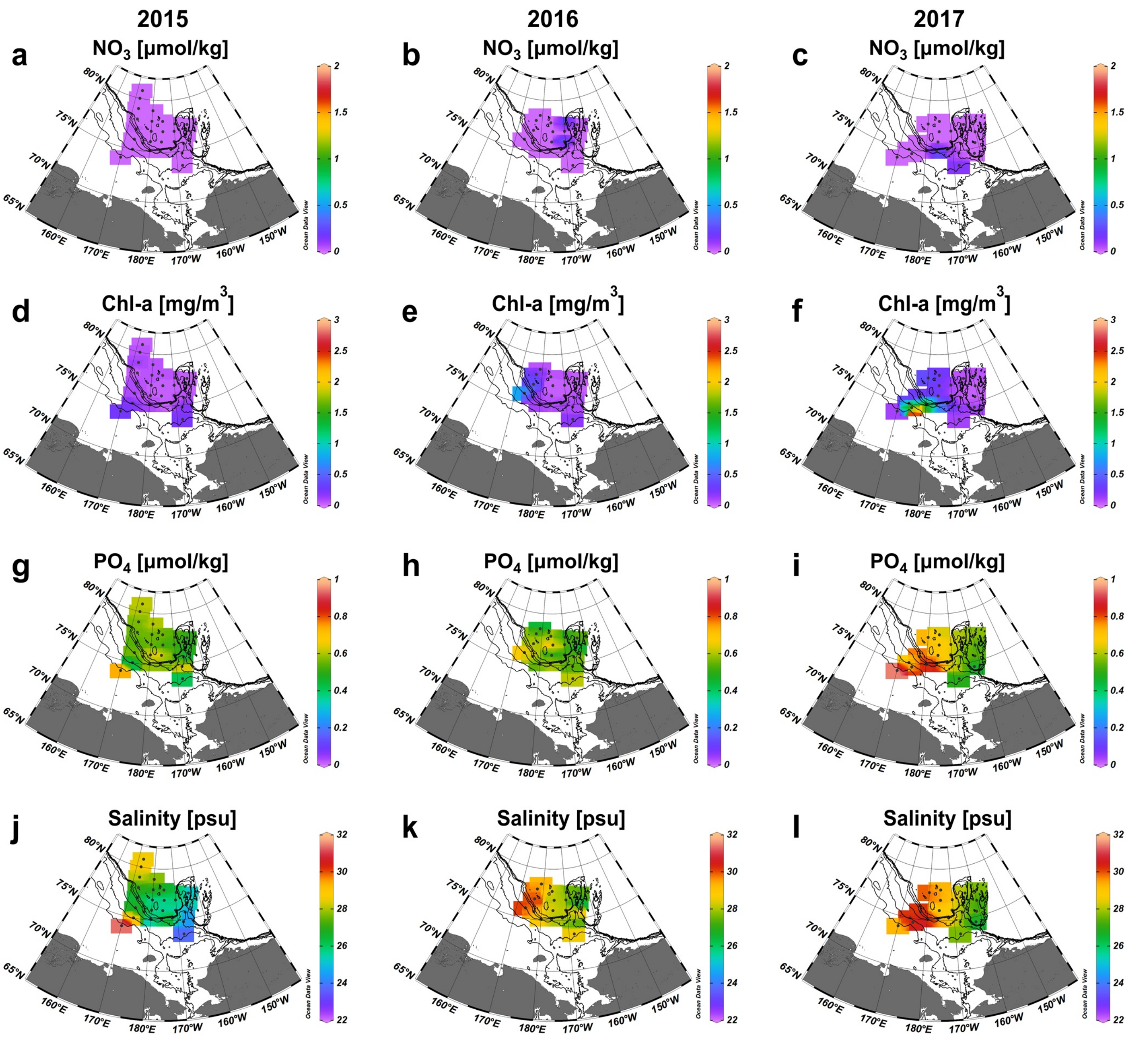

Figure 2. Observational evidence of the supply of nutrient-rich deep water to the surface water. Changes in (a–c) nitrate (NO_3) (d–f) chlorophyll-a (Chl-a) (mg m^{-3}), and (g–i) phosphate (PO_4) (μmol kg^{-1}) concentrations and changes in (j–l) salinity (psu) in sea surface water in the northern Chukchi Sea in the summers of 2015–2017.

of θ and S in 2015 and 2016 clearly show typical structures of Pacific- and Atlantic-origin waters in the northern Chukchi Sea (Figures 3a and 3b). In 2015 and 2016, the halocline boundaries between Pacific- and Atlantic-origin waters, which are defined as the deepest depth of maximum planetary potential vorticity, $PV = -(f/\rho)(d\rho/dz)$, which is akin to the buoyancy frequency (Nikolopoulos et al., 2009; Pickart et al., 2005), were located at depths of 140–150 m, whereas in 2017, it shoaled up to a depth of 95 m (Figures 3a–3c). In addition, another halocline boundary appeared at a depth of 70 m in 2017. The shoaling and appearance of these boundaries were induced by the intrusions of two different types of cold halocline waters: relatively high-salinity cold water (HSCW, $S \approx 34{\sim}34.5$ psu, red dashed horizontal line in Figure 3) and relatively low-salinity cold water (LSCW, $S \approx 32$ psu, red dotted horizontal line in Figure 3). The HSCW originates partly from the cold halocline layer lying below the cold, fresh SML and above the warm, salty Atlantic layer in the Eurasian Basin (Steele et al., 1995). The HSCW intruded into the layer between the PW and AW

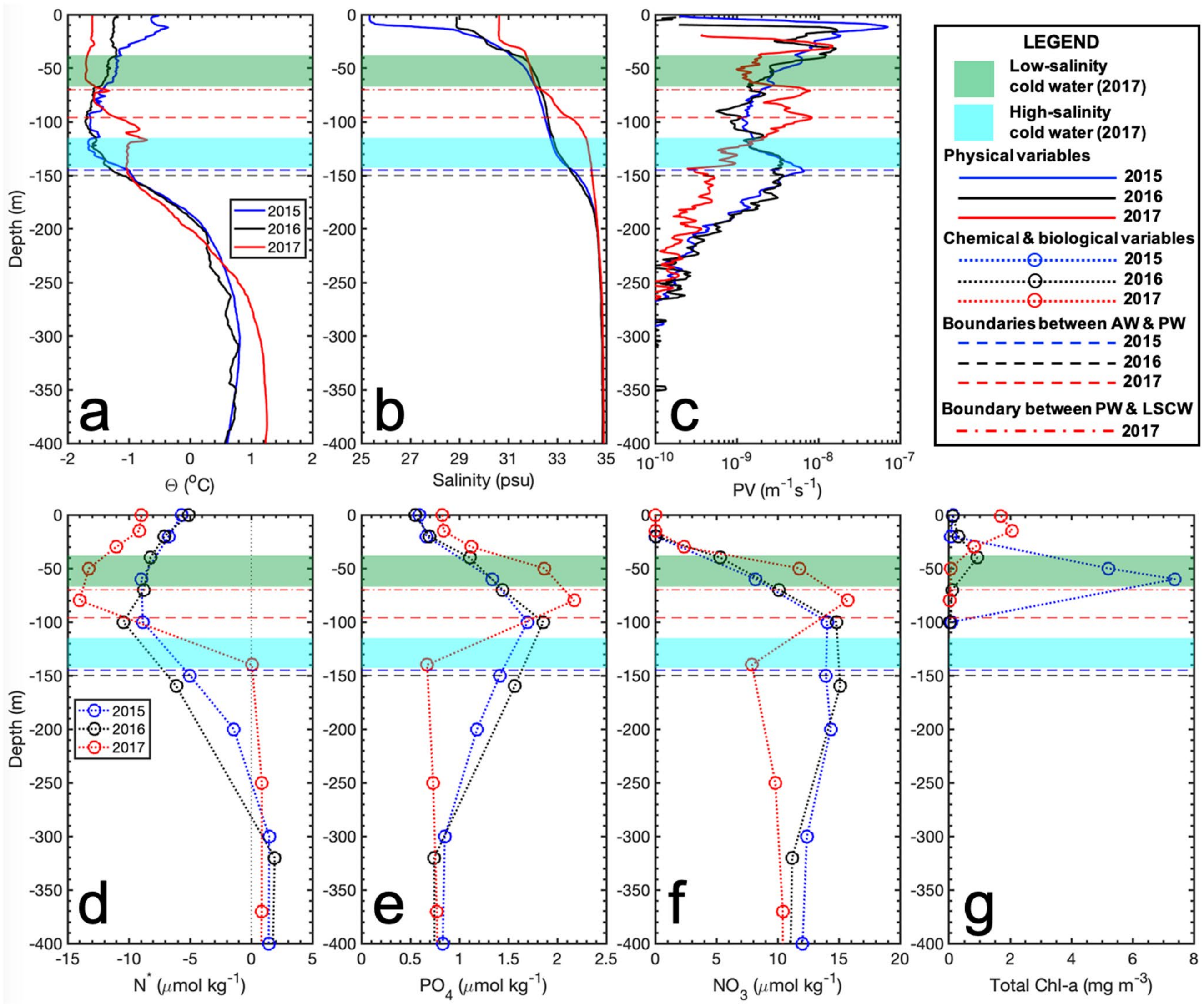

Figure 3. Vertical profiles of physical, chemical, and biological variables observed at station A (St. A) in the summers of 2015–2017. (a) Potential temperature (θ) (°C), (b) salinity (psu), (c) potential vorticity (PV) (m^{-1} s^{-1}), (d) N* (μmol kg^{-1}), (e) phosphate (PO_4) (μmol kg^{-1}), (f) nitrate (NO_3) (μmol kg^{-1}), and (g) total chlorophyll-a (Chl-a) (mg m^{-3}). The green and light-blue shaded areas indicate the low-salinity cold water (LSCW) and high-salinity cold water (HSCW) layers. Blue, black, and red solid lines (or open-circle dotted lines) represent the vertical profile of each variable observed in 2015, 2016 and 2017, respectively. Dotted lines in (d–g) are used to fill gaps in between the data. Blue, black, and red dashed horizontal lines in (a–g) indicate the boundary depths between Atlantic-origin and Pacific-origin waters (PW) observed in 2015, 2016, and 2017, respectively. The red dash-dotted horizontal lines in (a–g) represent the boundary depth between Pacific-origin water and LSCW. Intrusions of LSCW and HSCW were solely observed in 2017.

and pushed the halocline boundary up to 95 m depth. The HSCW occupied depths of 120–150 m, with a θ of nearly −1°C and S of 34.2∼34.5 psu. On the other hand, the LSCW observed in 2017 had characteristics ($S \approx 32$ psu, $\theta \leq -1.5$°C) similar to those of the fresh temperature minimum (frTmin) water ($S \approx 32$ psu, near-freezing temperature) observed over the Chukchi Abyssal Plain by Nishino et al. (2008), which is formed by winter cooling and convection of the upper part of western Chukchi summer water in the East Siberian Sea shelf area (Nishino et al., 2013). Thus, the LSCW is likely to be the modified western Chukchi summer water by cooling and convection on the East Siberian Sea shelf during the winter of 2016/2017. The LSCW was injected into the layer between the SML and PW and occupied depths of 40–65 m, with a θ of −1.65°C and S of 31.7–32.0 psu. The boundary between the LSCW and PW was characterized by another peak in PV at 70 m depth. The intrusions of two bodies of cold halocline water resulted in the changes in water column structure, including shoaling of the halocline boundary and uplift of the PW.

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The vertical profiles of N^* clearly showed the substantial shoaling of the Atlantic-origin water upper boundary (i.e., positive N^* values) due to the intrusion of HSCW, rising from ∼300–320 m in 2015–2016 to ∼140 m in 2017 (Figure 3d). As a result of this intrusion of HSCW into St. A along the Chukchi Sea shelf transect, nutrients were supplied to the surface from the uplifted upper halocline water (Figures 3e and 3f), which caused anomalously high Chl-a concentrations in oligotrophic surface waters in the summer of 2017 (Figure 3g). Furthermore, the NO_3-PO_4 relationship in 2017 yielded conclusive evidence for the intrusion of HSCW derived from the Atlantic sector into the northwestern Chukchi Sea shelf break, showing a clear bifurcation from the quasi-relationship when PO_4 concentrations were between 0.5 and 1.0 μmol kg^{-1} (i.e., moving towards the cluster of Atlantic-origin waters (the left cluster)) (Codispoti et al., 2009; Figures S3).

3. Discussion

The anomalous high surface Chl-a concentrations at St. A in 2017 was not explained by differences in sampling time (August 20), which was 9–14 days later than those in 2015 (August 6) and 2016 (August 11) because NO_3 depletion and further stratification suppressing nutrients input to the surface is expected in late August. In addition, during the summers (August) of 2015–2017, there were no significant interannual differences in the major controlling factors for primary production, such as sea ice concentration (SIC) and photosynthetically available radiation (PAR) in the northwestern Chukchi Sea (Figure S4). However, unlike in 2015 and 2016, high satellite-derived Chl-a concentration was observed in the northwestern Chukchi Sea in July 2017 (Figure S4), suggesting that additional nutrients could be supplied by shelf-break upwelling into the nutrient-depleted surface layer (Lewis et al., 2020), as discussed below, and that the sustained surface bloom was captured during our cruise.

The intrusions of two bodies of cold halocline water (i.e., HSCW and LSCW) observed in 2017 appear to have been induced by a drastic change in the atmospheric circulation system in the western Arctic Ocean (Figures 4 and S5). In recent years, the HSCW was mostly observed near the Makarov Basin and the Mendeleyev Ridge (Figures S6a and S6b). However, it was also found in the northwestern Chukchi Sea shelf break (i.e., St. A) in 2017 (Figure S6c). As shown in the mean sea surface wind and sea surface air pressure averaged from November to June (Figures 4a–4d), the cyclonic atmospheric circulation over the Eurasian Basin in 2017 was considerably strengthened and extended farther towards the Beaufort Gyre region than those in 2015, 2016, and the long-term mean climatology. Consequently, the cyclonic ocean circulation was enhanced in the northwestern Chukchi Sea, as indicated by sea ice motion vectors and their curls. In contrast, the anticyclonic circulation over the Beaufort Sea was considerably weakened in 2017 (Figure 4h). These results indicate that the enhanced cyclonic winds associated with the deepened low pressure over the Eurasian Basin in 2017 strengthened cyclonic sea ice motion, thereby driving the cold halocline waters from the eastern Arctic to the western Arctic Ocean. Similarly, a retreat of the cold halocline layer from the Amundsen Basin to the Makarov Basin was observed in the early 1990s due to a shift in the atmospheric wind forcing to a cyclonic circulation regime and relevant sea ice motion during the late 1980s (Steele & Boyd, 1998). Furthermore, in 2017, the enhanced positive curls (i.e., cyclonic winds and ice motion) near the Makarov Basin and the Mendeleyev Ridge likely induced Ekman suction, making the cold halocline layer shallow. Likewise, the LSCW spread from the East Siberian Sea to the Makarov Basin (Nishino et al., 2013) in 2016 (Figure S7b); however, it extended as far as the northwestern Chukchi Sea shelf break along the shelf slope in 2017 (Figure S7c). In addition, at St. A, the LSCW was observed only in 2017 (Figure 3a and 3b) when the cyclonic ocean circulation was expanded towards the Beaufort Gyre region (Figure 4h). Similar to our results, frTmin water was only found west of the Chukchi Plateau in the early 2000s, whereas it appeared west of the Mendeleyev Ridge in the late 2000s (Nishino et al., 2013), suggesting that the water mass boundary was shifted by the cyclonic regime of the Arctic Ocean circulation (McLaughlin et al., 2002; Proshutinsky & Johnson, 1997) and that the LSCW that formed in the East Siberian Sea shelf area was driven to St. A by the changes in the atmospheric circulation over the western Arctic Ocean. In addition to the anomalous shoaling of the nutricline caused by the simultaneous intrusions of the HSCW and the LSCW, the retreat of the ice edge beyond the shelf break provides upwelling favorable conditions along the shelf break (Carmack & Chapman, 2003), by which nutrient-rich deep water can be delivered to the surface layer (Bluhm et al., 2020; Spall et al., 2014; Tremblay et al., 2011). Indeed, in the summer of 2017, the area

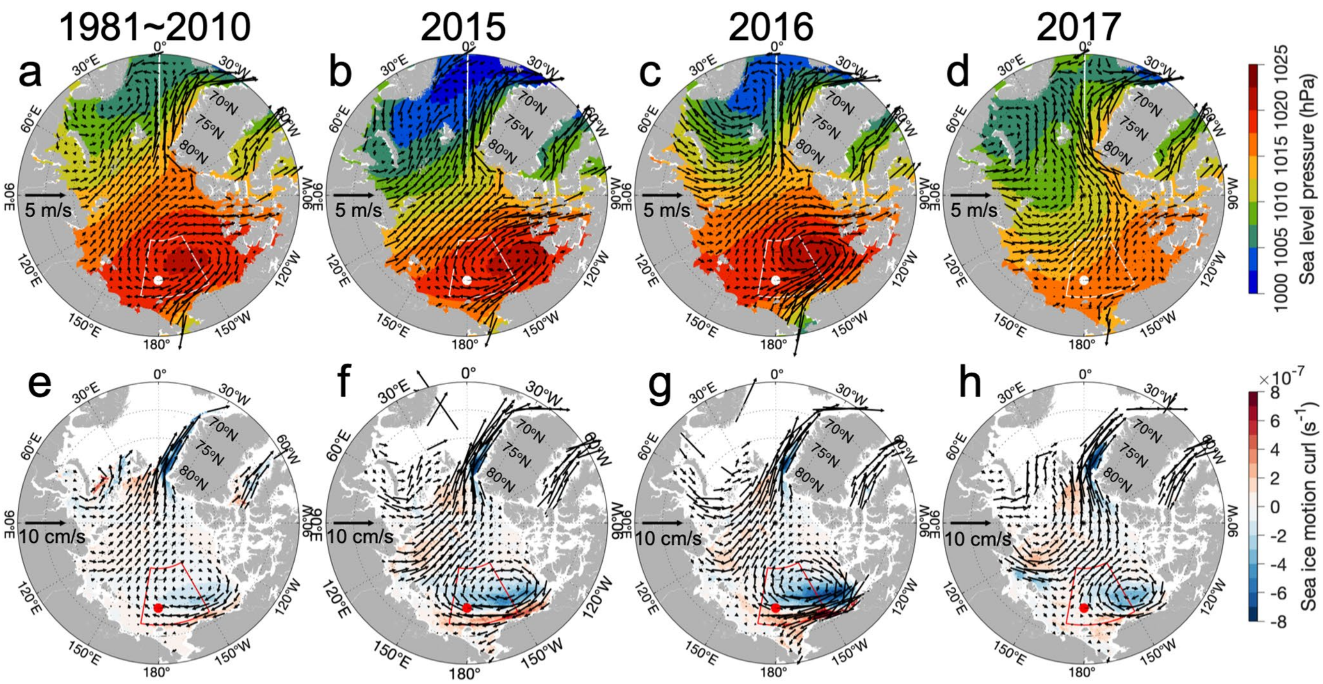

Figure 4. Spatial distributions of atmospheric and sea ice parameters. November-June mean fields of 10-m wind vectors (ms^{-1}, vectors) and sea level pressure (hPa, color-shaded) for (a) 1981–2010 climatology (b–d) the years 2015, 2016, and 2017 (e–h) Same as in (a–d) but for sea ice motion vectors (cm s^{-1}) and their curl (×10^{-7} s^{-1}, color-shaded). The white in (a–d) and red shapes in (e–h) delimit the study area. The location of station A (St. A) (white solid circles in a–d and red solid circles in e–h) is also shown.

of positive wind stress curl was widened beyond the slopes in the northwestern Chukchi Sea, suggesting that shelf-break upwelling possibly occurred around St. A (Figure S8). We thus conclude that the enhanced cyclonic circulation in 2017 allowed the HSCW and the LSCW to flow into the East Siberian/Chukchi shelf margins. The HSCW and the LSCW intruded directly into the layers between the PW and the existing AW, and between the surface and the PW, respectively. The nutrient-rich PW and LSCW uplifted by the HSCW led to unprecedented shoaling of the nutricline in the northwestern Chukchi Sea. Furthermore, coincident with shoaling of the nutricline, shelf-break upwelling induced by positive wind stress curl around the retreated ice edge area appeared to promote the supply of nutrients to the surface layer, thus resulting in the anomalous high surface summer bloom in the region.

The recent changes in water mass structure in the northwestern Chukchi Sea shelf region and the consequences of these changes for the shoaling of the nutricline and primary production are shown conceptually in Figure 5. In 2015 and 2016, the HSCW and LSCW did not extend as far as the northwestern Chukchi Sea shelf region due to the strong anticyclonic circulation, influencing the deepened nutricline and the SCM layer via typical stratification (Figure 5a). However, the influence of AW has recently increased due to declining sea ice cover and weakening of stratification in the layers over the AW (i.e., Atlantification), extending into the eastern Eurasian Basin (Polyakov et al., 2017). Shoaling of the AW and decreased vertical stratification observed in the eastern Eurasian Basin produced favorable conditions for the expansion of Atlantic-origin waters. In addition to the increased AW influence, the enhanced cyclonic winds in the Arctic Ocean in 2017 triggered a pronounced transport of the HSCW and the LSCW to the northwestern Chukchi Sea shelf break along the shelf slope. The simultaneous intrusions of the HSCW and the LSCW caused anomalous shoaling of the nutricline, with consequences for marine biological production by possible shelf-break upwelling (Figure 5b).

Under ongoing climate change, it is expected that water mass structures will be considerably modified in the Arctic Ocean (Polyakov et al., 2017, 2020), and their modification will have an impact on primary productivity (Randelhoff et al., 2018). With the potential for the persistence of Atlantic-origin cold saline water intrusion into the northwestern Chukchi Sea shelf break region, nutrient availability may be

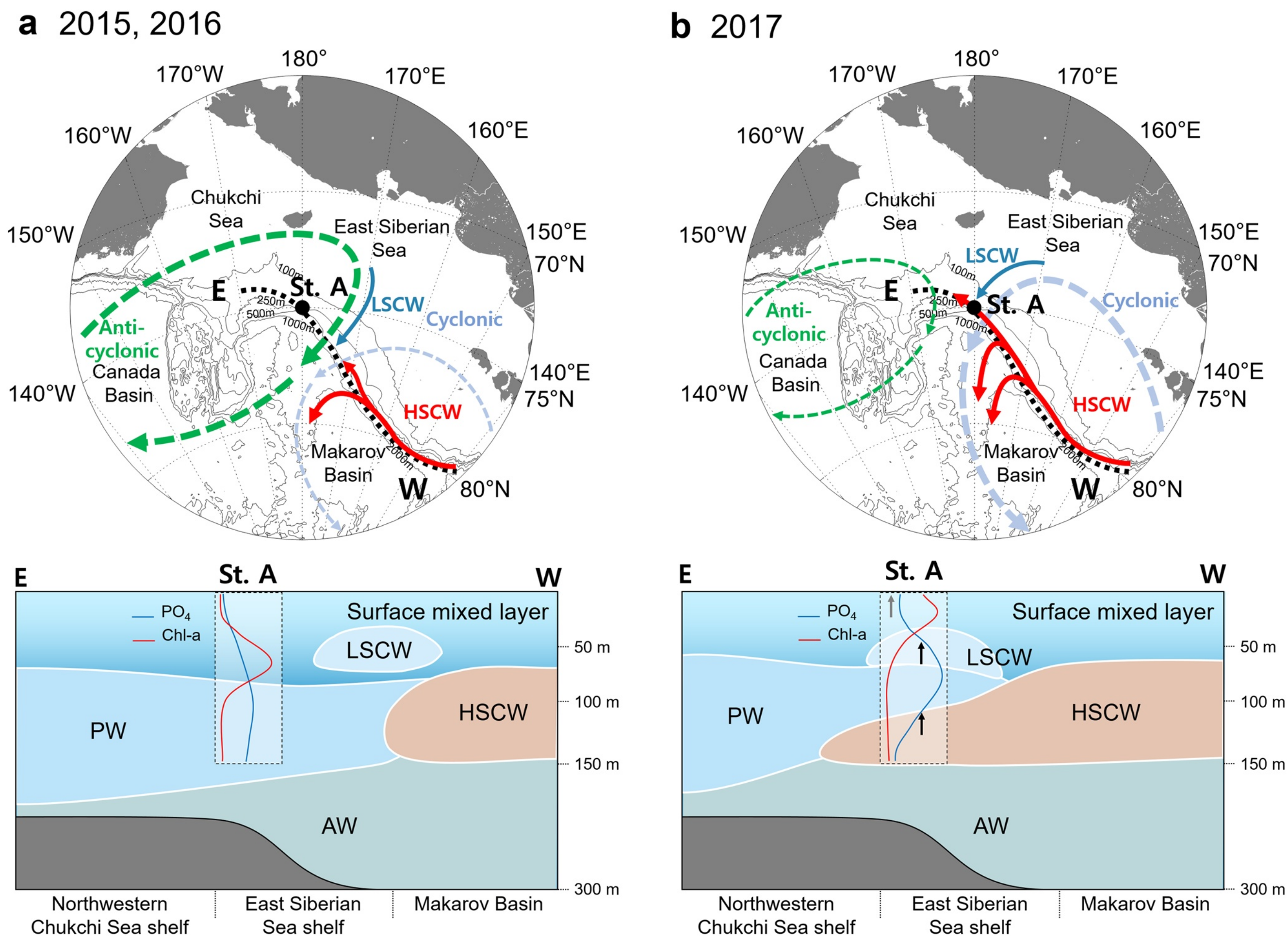

Figure 5. Schematic illustrations of the water mass circulation and structure in the northwestern Chukchi Sea. At the top are plain views and at the bottom are section views for the summers of (a) 2015, 2016, and (b) 2017. The green dashed and light-blue dashed arrows indicate the anticyclonic and cyclonic ocean circulations, respectively. The red and blue arrows show the high-salinity cold water (HSCW) and low-salinity cold water (LSCW) paths. The water column enclosed by the black dashed line represents the location of station A (St. (a). The data obtained at St. A were used to illustrate the conceptual vertical profiles of phosphate (PO_4) and chlorophyll-a (Chl-a) concentrations. The black upright arrows in the bottom panel of (b) indicate shoaling of the nutricline by the intrusions of HSCW and LSCW. The gray upright arrow also show shelf-break upwelling induced by upwelling-favorable winds. In the study area, the lower and upper halocline layers lie between the Pacific-origin water (PW) and the Atlantic water (AW) and between the surface mixed layer (SML) and the PW, respectively, although two halocline layers are not indicated.

significantly altered in summer. With the shoaling of the nutricline, nutrient-rich PWs are more likely to reach highly oligotrophic surface waters, thus resulting in changes in marine primary productivity and marine ecosystems in the northern Chukchi Sea. If the circulation pattern changes back and forth (i.e., anticyclonic and cyclonic), the Atlantic-origin cold saline waters may retreat or advance repeatedly across the northwestern Chukchi Sea shelf break region. Specifically, we speculate that even if the anticyclonic circulation pattern swings back to normal conditions, as long as Atlantic-origin cold saline waters remain in the northern Chukchi Sea, the nutricline will be shoaled further by the PWs that overlie the Atlantic-origin cold saline waters. Our results highlight the shift in a water mass boundary due to a change in circulation pattern and its impact on nutricline shoaling as a feedback to the rapid environmental changes that have occurred in the Arctic Ocean over the past decade.

Conflict of Interest

The authors declare that they have no competing interests.

Data Availability Statement

All data are available on the KOPRI data servers accessible through https://kpdc.kopri.re.kr/search/80785502-2cb4-4146-a799-b7c76d65f47c.

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References

Aagaard, K., Coachman, L. K., & Carmack, E. (1981). On the halocline of the Arctic Ocean. *Deep Sea Research Part A. Oceanographic Research Papers*, *28*(6), 529–545. https://doi.org/10.1016/0198-0149(81)90115-1

Alkire, M. B., Rember, R., & Polyakov, I. (2019). Discrepancy in the identification of the Atlantic/Pacific front in the central Arctic Ocean: NO versus nutrient relationships. *Geophysical Research Letters*, *46*, 3843–3852. https://doi.org/10.1029/2018GL081837

Ardyna, M., & Arrigo, K. R. (2020). Phytoplankton dynamics in a changing Arctic Ocean. *Nature Climate Change*, *10*(10), 892–903. http://doi.org/10.1038/s41558-020-0905-y

Arrigo, K. R., Perovich, D. K., Pickert, R. S., Brown, Z. W., van Dijken, G. L., Lowry, K. E., et al. (2014). Phytoplankton blooms beneath the sea ice in the Chukchi sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *105*(C), 1–16. https://doi.org/10.1016/j.dsr2.2014.03.018

Arrigo, K. R., & van Dijken, G. L. (2015). Continued increases in Arctic Ocean primary production. *Progress in Oceanography*, *136*(C), 60–70. https://doi.org/10.1016/j.pocean.2015.05.002

Bluhm, B. A., Janout, M. A., Danielson, S. L., Ellingsen, I., Gavrilo, M., Grebmeier, J. M., et al. (2020). The Pan-Arctic continental slope: Sharp gradients of physical processes affect pelagic and benthic ecosystems. *Frontiers in Marine Science*, *7*, 544386. http://doi.org/10.3389/fmars.2020.544386

Bluhm, B. A., Kosobokova, K. N., & Carmack, E. C. (2015). A tale of two basins: An integrated physical and biological perspective of the deep Arctic Ocean. *Progress in Oceanography*, *139*, 89–121. https://doi.org/10.1016/j.pocean.2015.07.011

Carmack, E., Barber, D., Christensen, J., Macdonald, R., Rudels, B., & Sakshaug, E. (2006). Climate variability and physical forcing of the food webs and the carbon budget on panarctic shelves. *Progress in Oceanography*, *71*(2–4), 145–181. https://doi.org/10.1016/j.pocean.2006.10.005

Carmack, E., & Chapman, D. C. (2003). Wind-driven shelf/basin exchange on an Arctic shelf: The joint roles of ice cover extent and shelf-break bathymetry. *Geophysical Research Letters*, *30*(14), 1778. https://doi.org/10.1029/2003GL017526

Codispoti, L. A., Flagg, C., Kelly, V., & Swift, J. H. (2005). Hydrographic conditions during the 2002 SBI process experiments. *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(24–26), 3199–3226. https://doi.org/10.1016/j.dsr2.2005.10.007

Codispoti, L. A., Flagg, C. N., & Swift, J. H. (2009). Hydrographic conditions during the 2004 SBI process experiments. *Deep Sea Research Part II: Topical Studies in Oceanography*, *56*(17), 1144–1163. https://doi.org/10.1016/j.dsr2.2008.10.013

Codispoti, L. A., Kelly, V., Thessen, A., Matrai, P., Suttles, S., Hill, V., et al. (2013). Synthesis of primary production in the Arctic Ocean: III. Nitrate and phosphate based estimates of net community production. *Progress in Oceanography*, *110*, 126–150. https://doi.org/10.1016/j.pocean.2012.11.006

Korhonen, M., Rudels, B., Marnela, M., Wisotzki, A., & Zhao, J. (2013). Time and space variability of freshwater content, heat content and seasonal ice melt in the Arctic Ocean from 1991 to 2011. *Ocean Science*, *9*(6), 1015–1055. https://doi.org/10.5194/os-9-1015-2013

Kwok, R. (2018). Arctic sea ice thickness, volume, and multiyear ice coverage: Losses and coupled variability (1958–2018). *Environmental Research Letters*, *13*(10), 105005. http://doi.org/10.1088/1748-9326/aae3ec

Kwok, R., Spreen, G., & Pang, S. (2013). Arctic sea ice circulation and drift speed: Decadal trends and ocean currents. *Journal of Geophysical Research: Oceans*, *118*, 2408–2425. https://doi.org/10.1002/jgrc.20191

Lewis, K. M., van Dijken, G. L., & Arrigo, K. R. (2020). Changes in phytoplankton concentration now drive increased Arctic Ocean primary production. *Science*, *369*, 198–202. http://doi.org/10.1126/science.aay8380

McLaughlin, F., Carmack, E., Macdonald, R., Weaver, A. J., & Smith, J. (2002). The Canada Basin, 1989–1995: Upstream events and far-field effects of the Barents Sea. *Journal of Geophysical Research*, *107*(C7), 3082. https://doi.org/10.1029/2001JC000904

Nikolopoulos, A., Pickart, R. S., Fratantoni, P. S., Shimada, K., Torres, D. J., & Jones, E. P. (2009). The western Arctic boundary current at 152°W: Structure, variability, and transport. *Deep-Sea Research Part II Topical Studies in Oceanography*, *56*(17), 1164–1181. https://doi.org/10.1016/j.dsr2.2008.10.014

Nishino, S., Itoh, M., Williams, W. J., & Semiletov, I. (2013). Shoaling of the nutricline with an increase in near-freezing temperature water in the Makarov Basin. *Journal of Geophysical Research: Oceans*, *118*(2), 635–649. https://doi.org/10.1029/2012JC008234

Nishino, S., Shimada, K., Itoh, M., Yamamoto-Kawai, M., & Chiba, S. (2008). East–west differences in water mass, nutrient, and chlorophyll a distributions in the sea ice reduction region of the western Arctic Ocean. *Journal of Geophysical Research*, *113*(5), C00A01. https://doi.org/10.1029/2007JC004666

Oziel, L., Neukermans, G., Ardyna, M., Lancelot, C., Tison, J. L., Wassmann, P., et al. (2017). Role for Atlantic inflows and sea ice loss on shifting phytoplankton blooms in the Barents Sea. *Journal of Geophysical Research: Oceans*, *122*(6), 5121–5139. http://doi.org/10.1002/2016JC012582

Perovich, D., Meier, W., Tschudi, M., Hendricks, S., Petty, A. A., Divine, D., et al. (2020). *Sea ice [in NOAA Arctic report Card 2020]*. Available at: http://www.arctic.noaa.gov/Report-Card

Pickart, R. S., Weingartner, T. J., Pratt, L. J., Zimmermann, S., & Torres, D. J. (2005). Flow of winter-transformed Pacific water into the Western Arctic. *Deep-Sea Research Part II Topical Studies in Oceanography*, *52*(24–26), 3175–3198. https://doi.org/10.1016/j.dsr2.2005.10.009

Polyakov, I. V., Alkire, M. B., Bluhm, B. A., Brown, K. A., Carmack, E. C., Chierici, M., et al. (2020). Borealization of the Arctic Ocean in response to anomalous advection from sub-Arctic seas. *Frontiers in Marine Science*, *7*, 1–32. http://doi.org/10.3389/fmars.2020.00491

Polyakov, I. V., Pnyushkov, A. V., Alkire, M. B., Ashik, I. M., Baumann, T. M., Carmack, E. C., et al. (2017). Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. *Science*, *356*, 285–291. https://doi.org/10.1126/science.aai8204

Polyakov, I. V., Pnyushkov, A. V., & Timokhov, L. A. (2012). Warming of the intermediate Atlantic water of the Arctic Ocean in the 2000s. *Journal of Climate*, *25*(23), 8362–8370. https://doi.org/10.1175/JCLI-D-12-00266.1

Proshutinsky, A. Y., & Johnson, M. A. (1997). Two circulation regimes of the wind-driven Arctic Ocean. *Journal of Geophysical Research*, *102*(C6), 12493–12514. https://doi.org/10.1029/97JC00738

Randelhoff, A., Reigstad, M., Chierici, M., Sundfjord, A., Ivanov, V., Cape, M., et al. (2018). Seasonality of the physical and biogeochemical hydrography in the inflow to the Arctic Ocean through Fram Strait. *Frontiers in Marine Science*, *5*, 1–16. https://doi.org/10.3389/fmars.2018.00224

Randelhoff, A., & Sundfjord, A. (2018). Short commentary on marine productivity at Arctic shelf breaks: Upwelling, advection and vertical mixing. *Ocean Science*, *14*(2), 293–300. https://doi.org/10.5194/os-14-293-2018

Rudels, B., Anderson, L. G., & Jones, E. P. (1996). Formation and evolution of the surface mixed layer and halocline of the Arctic Ocean. *Journal of Geophysical Research*, *101*(C4), 8807–8821. http://doi.org/10.1029/96JC00143

Spall, M. A., Pickart, R. S., Brugler, E. T., Moore, G. W. K., Thomas, L., & Arrigo, K. R. (2014). Role of shelfbreak upwelling in the formation of a massive under-ice bloom in the Chukchi Sea. *Deep-Sea Research Part II Topical Studies in Oceanography*, *105*, 17–29. https://doi.org/10.1016/j.dsr2.2014.03.017{Spreen:2008ch}

Steele, M., & Boyd, T. (1998). Retreat of the cold halocline layer in the Arctic Ocean. *Journal of Geophysical Research: Oceans*, *103*(C5), 10419–10435. https://doi.org/10.1029/98JC00580

Steele, M., Morison, J. H., & Curtin, T. B. (1995). Halocline water formation in the Barents Sea. *Journal of Geophysical Research*, *100*(C1), 881–894. https://doi.org/10.1029/94JC02310

Tremblay, J. É., Bélanger, S., Barber, D. G., Asplin, M., Martin, J., Darnis, G., et al. (2011). Climate forcing multiplies biological productivity in the coastal Arctic Ocean. *Geophysical Research Letters*, *38*(18), L18604. https://doi.org/10.1029/2011GL048825

Woodgate, R. (2013). Arctic Ocean circulation: Going around at the top of the world. *Nature Education Knowledge*, *4*, 8.

References From the Supporting Information

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Devol, A. H., Codispoti, L. A., & Christensen, J. P. (1997). Summer and winter denitrification rates in western Arctic shelf sediments. *Continental Shelf Research*, *17*(9), 1029–1050. https://doi.org/10.1016/S0278-4343(97)00003-4

Fairall, C. W., Bradley, E. F., Hare, J. E., Grachev, A. A., & Edson, J. B. (2003). Bulk parameterization of air-sea fluxes: Updates and verification for the COARE algorithm. *Journal of Climate*, *16*(4), 571–591. http://doi.org/10.1175/1520-0442(2003)016<0571:BPOASF>2.0.CO;2

Gordon, L. I., Jennings Jr, J. C., Ross, A. A., & Krest, J. M. (1993). *A suggested protocol for continuous automated analysis of seawater nutrients (phosphate, nitrate, nitrite and silicic acid) in the WOCE Hydrographic Program and the Joint Global Ocean Fluxes Study, WOCE Operations Manual, Volume 3, Section 3.1, Part 3.1.3 WHP Operations and Methods*. WHP Office Report WHPO 91-1, WOCE Report No. 68/91, Nov. 1994, Revision 1. Woods Hole, MA.

Gruber, N., & Sarmiento, J. L. (1997). Global patterns of marine nitrogen fixation and denitrification. *Global Biogeochemical Cycles*, *11*(2), 235–266. https://doi.org/10.1029/97GB00077

Jones, E. P., Anderson, L. G., & Swift, J. H. (1998). Distribution of Atlantic and Pacific waters in the upper Arctic Ocean: Implications for circulation. *Geophysical Research Letters*, *25*(6), 765–768. http://doi.org/10.1029/98GL00464

Lee, Y., Yang, E. J., Park, J., Jung, J., Kim, T. W., & Lee, S. (2016). Physical-biological coupling in the Amundsen Sea, Antarctica: Influence of physical factors on phytoplankton community structure and biomass. *Deep-Sea Research Part I*, *117*(C), 51–60. https://doi.org/10.1016/j.dsr.2016.10.001

McDougall, T. J., & Baker, P. M. (2011). Getting started with TEOS-10 and the Gibbs Seawater (GSW) oceanographic toolbox. *SCOR/IAPSO WG*, *127*, 1–28.

Mizuno, K., & Watanabe, T. (1998). Preliminary results of in-situ XCTD/CTD comparison test. *Journal of Oceanography*, *54*(4), 373–380. https://doi.org/10.1007/BF02742621

Spreen, G., Kaleschke, L., & Heygster, G. (2008). Sea ice remote sensing using AMSR-E 89-GHz channels. *Journal of Geophysical Research*, *113*, C02S03. http://doi.org/10.1029/2005JC003384

Tschudi, M., Meier, W. N., Stewart, J. S., Fowler, C., & Maslanik, J. (2019). *Polar pathfinder daily 25 km EASE-grid sea ice motion vectors, version 4, boulder, Colrado USA National Snow and Ice Data Center., distributed in netCDF format by the Integrated Climate Data Center (ICDC)*. University of Hamburg. http://icdc.zmaw

Yamamoto-Kawai, M., Carmack, E., & McLaughlin, F. (2006). Nitrogen balance and Arctic throughflow. *Nature*, *443*(7107), 43. https://doi.org/10.1038/443043a

Yamamoto-Kawai, M., McLaughlin, F. A., Carmack, E. C., Nishino, S., & Shimada, K. (2008). Freshwater budget of the Canada Basin, Arctic Ocean, from salinity, δ18O, and nutrients. *Journal of Geophysical Research*, *113*, C01007. http://doi.org/10.1029/2006JC003858