Sea-ice retreat controls timing of summer plankton blooms in the Eastern Arctic Ocean

Markus A. Janout[1] (iD)**, Jens Hölemann[1]** (iD)**, Anya M. Waite[1,2]** (iD)**, Thomas Krumpen[1],**
Wilken-Jon von Appen[1] (iD)**, and Fedor Martynov[3]**

[1]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, [2]FB2 Biology/Chemistry, University of Bremen, Bremen, Germany, [3]Arctic and Antarctic Research Institute, St. Petersburg, Russia

Abstract Two full-year mooring records of sea-ice, physical, and bio-optical parameters illuminate tight temporal coupling between the retreating seasonal ice edge and the summer phytoplankton bloom on the Laptev Sea shelf. Our records showed no sign of pelagic under-ice blooms despite available nutrients and thinning sea ice in early summer, presumably because stratification had not yet developed. Chlorophyll blooms were detected immediately after the ice retreated in late May 2014 and late July 2015. Despite radically different timing, the blooms were similar in both magnitude and length, interpreted as community-level nutrient limitation. Acoustic backscatter records suggest the delayed 2015 bloom resulted in lower zooplankton abundance, perhaps due to a timing mismatch between ice algal and pelagic blooms and unfavorable thermal conditions. Our observations provide classical examples of ice-edge blooms and further emphasize the complexity of high-latitude shelves and the need to understand vertical mixing processes important for stratification and nutrient fluxes.

1. Introduction

Sea ice dominates many aspects of the Arctic ecosystem, as it regulates air-sea heat fluxes, mechanical mixing, and light availability for primary production. Under a changing climate, the sea-ice cover has recently retreated to record low summer extents such as those observed in 2007 and 2012 [*Comiso et al.*, 2008; *Perovich et al.*, 2012]. Trends in open water duration, delayed freezeup, and air temperatures are positive in nearly all Arctic sectors [*Stroeve et al.*, 2014], which has substantial consequences for regional ecosystems and global climate.

Primary production is generally limited by nutrients and light, which are in turn controlled by the presence of sea ice and the stratification needed to maintain algae suspended in the euphotic zone. Secondary producers depend on this primary production, but their biomass and reproduction success are controlled by additional factors such as the timing of the bloom [*Søreide et al.*, 2010; *Leu et al.*, 2011], ocean temperatures [*Feng et al.*, 2016], and predation. Much of the deep central Arctic Ocean maintains its ice cover year-round, and vertical mixing and nutrient replenishment is overall weak, so that the central Arctic is characterized by low pelagic production and an ecosystem that is dominated by ice-dwelling species [*Gosselin et al.*, 1997; *Boetius et al.*, 2013; *Kohlbach et al.*, 2016]. However, nearly half of the Arctic Ocean area is occupied by seasonally ice-covered shelf seas with ice edges that increasingly retreat well poleward of the shelf breaks, which fundamentally changes the light regime along the Arctic periphery [*Perovich et al.*, 2008; *Slagstad et al.*, 2015].

Numerical model-based and remote sensing-based Arctic Ocean ecosystem studies predict earlier blooms [*Kahru et al.*, 2011] and an overall increase in biological productivity under diminishing sea-ice cover [*Arrigo et al.*, 2008; *Popova et al.*, 2012; *Slagstad et al.*, 2015]. Regional patterns in biological production depend on a combination of physical parameters that are not yet fully understood due to the challenging nature and difficult field conditions of the Arctic Ocean. Further, physical processes in the Arctic such as eddies, meanders, and boundary currents occur on smaller scales (1–10 km) than at lower latitudes, which requires high, and computationally expensive resolution to realistically simulate coupled physical and biogeochemical processes. Satellite-based chlorophyll studies rely on observations for calibration, which is further complicated by regional differences in water mass composition, for instance, on the large river-dominated Siberian shelves where suspended and dissolved bio-optical properties may bias the satellite interpretations [*Matsuoka et al.*, 2007; *Arrigo and van Dijken*, 2011; *Heim et al.*, 2014]. Finally, the timing of spring blooms is extremely difficult to predict as they may occur initially as under-ice blooms [*Strass and Nöthig*, 1996; *Arrigo et al.*, 2014] during a time of year when much of the Arctic Ocean is not yet accessible by ship.
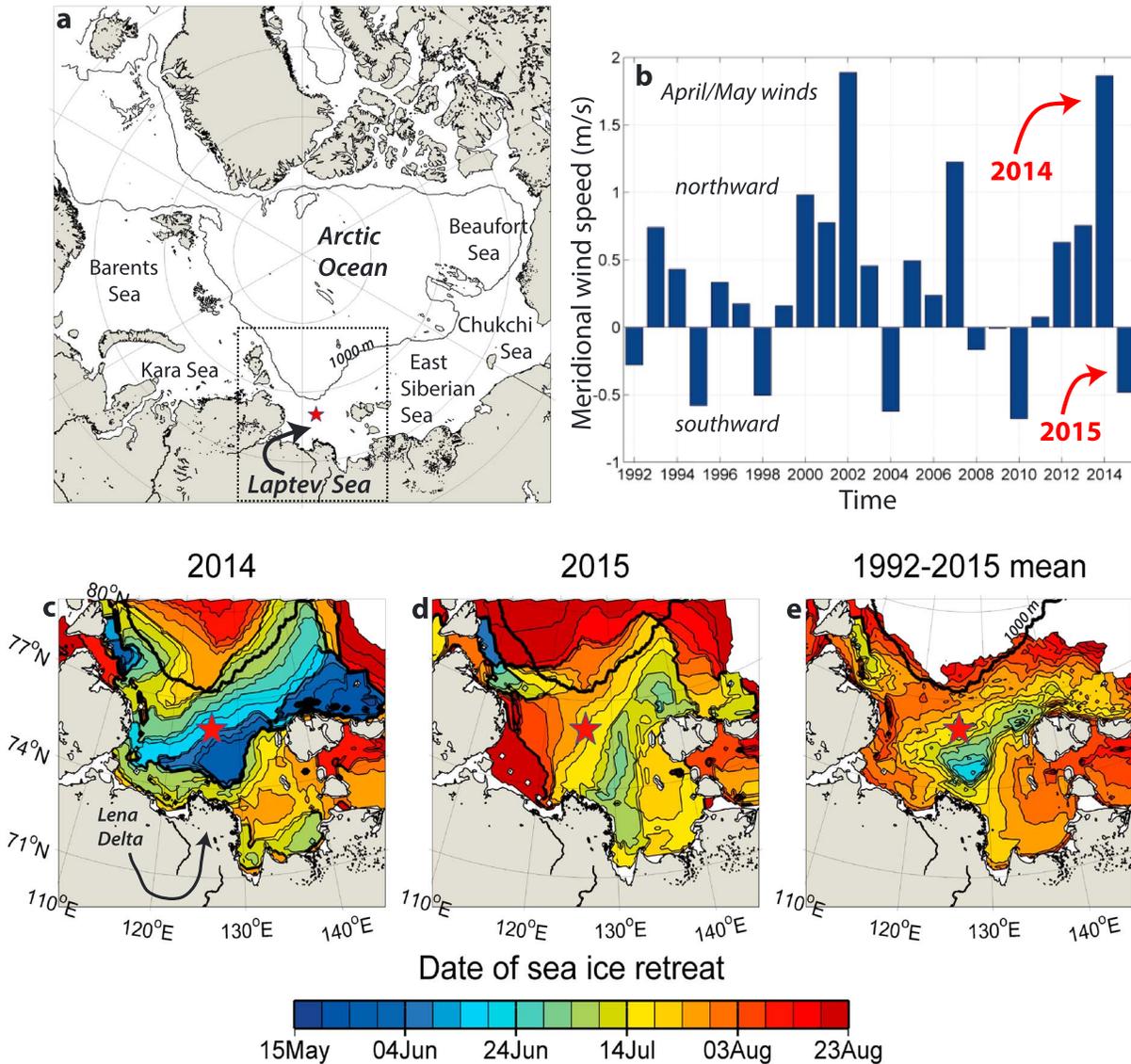
Figure 1. (a) Map of the Arctic Ocean including the mooring location (red star), names of the marginal shelf seas, and the 1000 m isobath. (b) Average April–May ERA-Interim [*Dee et al.*, 2011] meridional winds (1992–2015) near the mooring location. The box in Figure 1a highlights (c–e) the study region, where the colors (5 day increments) show the date of sea ice retreat in 2014 (Figure 1c) and 2015 (Figure 1d) compared with a 1992–2015 average (Figure 1e; note that grid points where ice was retained year-round in more than half of the years were left blank).

The shallow Siberian shelves cover a significant part of the Arctic Ocean and are crucial pathways for river water [*Morison et al.*, 2012], as well as for sea-ice production and export [*Alexandrov et al.*, 2000]. Despite their importance, these shelves remain among the poorest understood Arctic regions. Our recent multidisciplinary Russian-German research activities focused their efforts on the Laptev Sea shelf where we operated an under-ice mooring equipped with bio-physical sensors from 2013 to 2015. The data from this mooring have provided new insights regarding sea-ice retreat and the timing of the spring bloom.

2. Data and Methods

2.1. Data

The mooring (76°N, 126°E; Figure 1) was deployed during two consecutive full-year cycles (2013–2015) on the 45 m deep central Laptev Sea shelf, with September deployments and recoveries during
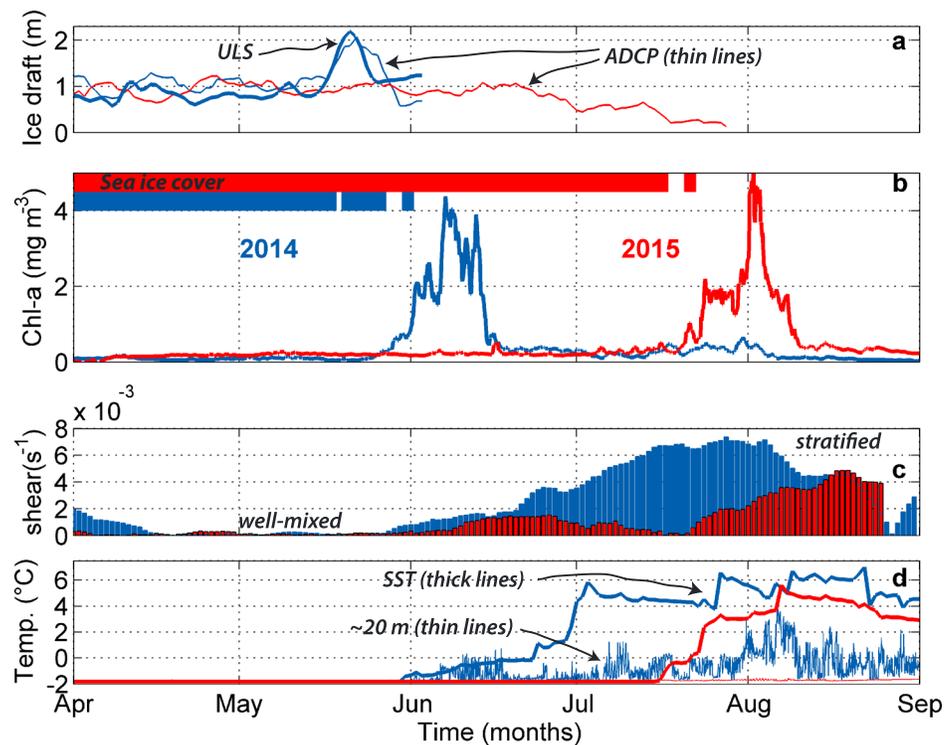
Figure 2. Ocean and sea-ice parameters from the central Laptev Sea shelf in April–August 2014 (blue) and 2015 (red): (a) ADCP-derived (thin lines) and ULS-measured ice draft (m, thick blue line; 2014 only); (b) ADCP-derived sea-ice cover at the mooring location (horizontal lines) and 1 day smoothed chlorophyll *a* measured at ~22 m (thick lines). (c) Vertical shear of the M_2 tide (major axis) computed between 5 and 20 m depth, here used as a qualitative measure of stratification (near-zero values imply well-mixed conditions). (d) Daily mean satellite-derived sea surface (thick lines) and half-hourly mooring-sampled 20 m temperatures (°C, thin lines).

Laptev Sea expeditions aboard R/V *Viktor Buinitsky*. The mooring was equipped with four CTD (conductivity-temperature-depth) recorders (*Sea-Bird Electronics 37*) mounted evenly spaced between ~22 m and the seafloor. A *Wetlabs Ecotriplet* sensor was mounted right above the upper *SBE37* and collected three-hourly information on fluorescence. Raw data were converted to chlorophyll *a* (Chl *a*) by using the factory formula and adjusted to the baseline with in situ measured Chl *a* values. Currents were recorded hourly in 1 m bins with upward looking 300 kHz *Teledyne RD Instruments Workhorse Sentinel* Acoustic Doppler Current Profilers (ADCP) mounted near the seafloor. The ADCP's bottom tracking function was used to derive information on sea-ice drift and daily mean ice thickness, estimated from the distance between the transducer to the underside of the ice. These were compared with the daily mean ice thickness above the mooring in 2013–2014 (Figure 2), recorded with an upward looking sonar (ULS, *IPS5* by *ASL Environmental Sciences Inc.*, sampling rate 1 Hz). The ADCP's echo intensity of the sound reflectance on particles was used to gain qualitative information on the presence and vertical distribution of zooplankton. The raw data were converted into mean volume backscatter (MVBS) following *Cisewski and Strass* [2016]. Satellite sea-ice concentration data were made available by the Institut français de recherche pour l'exploitation de la mer [*Ezraty et al.*, 2007] and are based on 85 GHz Special Sensor Microwave Imager brightness temperatures, using the Arctic Radiation and Turbulence Interaction STudy Sea Ice algorithm developed at the University of Bremen [*Spreen et al.*, 2008], which result in 12.5×12.5 km^2 pixel sizes. The date of sea-ice retreat (Figure 1) was estimated for each year at each grid point and defined as the first day in a series of at least 10 days with a sea-ice concentration of zero. Daily mean sea surface temperatures (SSTs) were extracted from the Arctic L4 SST product *METNO-ARC-SST-HR-L4-NRT-OBS*, provided by Global High Resolution SST, the Norwegian Meteorological Institute, and the Copernicus Marine Environment Monitoring Service regional data assembly center with a 0.03° spatial resolution. Validation of this product against observations showed a mean difference of −0.58 K with a standard deviation of 0.63 K (technical details are provided in *Høyer and She* [2007]).

2.2. Limitations and Opportunities of Moored Observations

In regions such as the Laptev Sea, sea-ice ridges require that oceanographic moorings remain at a safe distance below the surface, which traditionally leads to missing CTD and bio-optical observations from the upper ~20 m and further prevents quantification of water column stratification. This paper discusses the timing of summer plankton blooms relative to sea-ice retreat based on a moored (~22 m) chlorophyll time series, which requires a qualitative understanding of the seasonal cycle of stratification in order to put the midwater (20–25 m) processes in perspective with the upper (0–15 m) layer. Water column structure can be inferred from the ADCP record since vertical velocity shear is generally maximal in the pycnocline [*Howard et al.*, 2004; *Randelhoff et al.*, 2014]. In the Laptev Sea, semidiurnal tides dominate the variability of currents and shear [*Janout and Lenn*, 2014], and hence, the vertical structure of the semidiurnal M_2 tide (extracted from the ADCP record using the MATLAB T-Tide package [*Pawlowicz et al.*, 2002]) is used as a proxy for stratification. Periods of weak tidal shear coincide with weak stratification, and a small vertical difference between the M_2-major axis at 5 m and 20 m (Figure 2) implies that stratification was absent prior to the ice retreat in both 2014 and 2015. So while a single fluorometer mounted at ~22 m could not have captured blooms that may have occurred in shallow near-surface meltwater lenses [*Gradinger*, 1996], it would have likely registered indications of substantial production near the surface in a weakly stratified water column as for instance underlined by fluorescence-profiles sampled during a Bering Sea ice-edge bloom [*Cooper et al.*, 2012]. The necessary limitations of our measurements prohibit an overly detailed discussion on biological and physical near-surface processes, and further largely ignore the three dimensionality of the Laptev shelf system, but should overall provide first-order knowledge of the oceanographic conditions as well as of the timing of sea-ice retreat and the summer pelagic plankton bloom.

3. Results and Discussion

3.1. The Spring Blooms in 2014 and 2015 and Associated Environmental Conditions

A clear relationship between the retreating sea-ice cover and the highest annual accumulation of water column Chl *a* (at ~22 m) was established from a 2 year time series on the central Laptev Sea shelf (Figure 2). The sea-ice season at this location extended from late October until late May in 2014 and until mid-July in 2015 (Figure 1). Both years were characterized by very low pelagic Chl *a* levels throughout the ice-covered season. However, as soon as the ice retreated, Chl *a* increased rapidly, peaking at 4–5 mg m^{-3} (daily means) approximately 1 week after the ice retreat. Curiously, both peaks were nearly similar in magnitude and duration, which might be explained by mixed layer nutrient limitation. Our observations nicely mirror results from previous subarctic ecosystem studies [*Waite et al.*, 1992], which measured a 2–3 weeklong spring bloom (similar to ours) at the base of the mixed layer. Their bloom started approximately 1 week earlier near the surface, which is consistent with our observed delay between sea-ice retreat and the 22 m chlorophyll peak. The 6–8 week delay between the 2014 and 2015 blooms (Figure 2) is expected to have substantial impacts on the ecosystem as will be discussed later.

On average, sea-ice retreat in the Laptev Sea starts in June north of the Lena Delta (Figure 1) in the prominent polynya regions along the fast ice edge [*Bareiss and Görgen*, 2005]. The ice first retreated there in 2014, although earlier than average (Figure 1). Anomalously strong southerly winds in April and May 2014 (Figure 1) initially opened the polynya and replaced the 1–2 m thick ice cover present in January–March with thinner (<1 m) ice above the mooring (Figure 2). The winds led to offshore-directed sea-ice drift (13 cm s^{-1}) and upper ocean (0–20 m) currents (6 cm s^{-1}), shortly before the ice disappeared in late May 2014. Similar winds and early ice retreat were observed in 2012, which then led to extremely warm waters [*Janout et al.*, 2016] in a completely ice-free Laptev Sea and a marginal ice zone that retreated far beyond the shelf break. In contrast, winds over the central shelf were weak in spring and early summer 2015 (Figure 1), and the sea-ice cover remained closed south of the mooring site, underlined by weak ice drift and ocean currents (both <3 cm s^{-1}). Sea ice first disintegrated due north of the Lena River outflow, followed by a slow westward progression of the ice edge, which reached the mooring in late July 2015 (Figure 1).

Our moored observations provide two examples of classical ice-edge blooms. Considering a well-mixed water column before the ice retreat (see section 2.2), we expect that our observations would have captured indications if there had been any substantial under-ice blooms such as observed near the Chukchi Sea shelf break [*Arrigo et al.*, 2014]. The nutrient-rich Chukchi Sea was stratified under a closed ice cover following

upwelling events [*Spall et al.*, 2014], and a bloom was initiated there in early July once light levels became sufficient through thinning ice and melt ponds. The Laptev Sea shelf is also nutrient-replenished in winter, as supported by maximum nitrate (6.6 μM) and phosphate (1.1 μM) levels measured in March/April 2009– 200 km south of the mooring site. This leaves light and stratification as key potentially limiting parameters for bloom primary production and biomass. Because tides and other physical processes on the central shelf help to erode the seasonal stratification through shear instabilities and enhanced ice-ocean stress, the water column is presumably well mixed by winter or spring [*Janout et al.*, 2016]. This would cause algae cells to settle out of the euphotic zone and prevent growth, even if sufficient light was available under the ice. Further, based on previous Arctic under-ice light measurements, extensive snowmelt and melt pond formation and therefore enhanced transmissivity of light through the ice are not expected until midsummer [*Perovich and Polashenski*, 2012; *Arndt and Nicolaus*, 2014]. Applying these insights to the Laptev Sea, prebloom light conditions were quite different between years—likely sufficient to potentially promote growth under the thinning ice in July 2015 but unlikely under >1 m thick ice as early in the year as May 2014. However, under-ice stratification was absent or weak in both years, and (as argued earlier) any substantial under-ice production should have at least led to excursions from the baseline in our Chl *a* record. We therefore hypothesize that the onset of stratification after ice retreat is a key mechanism triggering the onset of the summer bloom via increases in light availability to phytoplankton as the mixed layer shallows.

3.2. Ice Melt Versus Solar Warming: What Sets the Stratification After Ice Retreat?

The onset of stratification is driven by a number of mechanisms associated with the freshening and warming of waters at the ice edge. In 2015, the south-to-north ice retreat in the eastern Laptev Sea resulted in the maintenance of ice on the central shelf until mid-July, in contrast to the earlier retreat in 2014, with profound consequences on water column structure in these contrasting years. As detailed in section 2.2, we inferred that the water column was well mixed under the ice in both years. When the ice was removed by southerly winds in May 2014, our ice thickness time series indicates a rapid transition from 0.5 to 1 m thick ice to open water in late May. While some melt always occurs along the marginal ice zone, significant local ice melt and associated melt-induced stratification were unlikely due to the rapid sea-ice export. Soon after the ice retreated, SST increased and warming was observed in our 22 m temperature record, which implies that the depth where the Chl *a* peak was measured was in the pycnocline. In 2015, local melt was more likely at this advanced time of year, when strong winds and ice drift were absent, and melt-induced stratification was likely considerably stronger than during 2014. Hence, in contrast to the 2014 middepth warming signal, the 22 m temperatures in 2015 remained cold (−1.8 to −1.5°C) throughout the summer, implying that this depth was located at the base of the seasonal pycnocline and not in immediate contact with warm near-surface waters. Strong offshore winds such as observed in spring 2014 precondition the region for early ice retreat with large thin ice areas [*Krumpen et al.*, 2013], which disintegrate faster and are exported more efficiently by winds. This ultimately leads to early open waters with weaker temperature-controlled stratification. In 2015 offshore winds were absent, and local melt likely produced a stronger salinity-stratified water column, with a retreating ice edge at the central shelf mooring that was 6–8 weeks later than the previous year.

3.3. Timing of the Bloom and Consequences for Secondary Producers

The summer bloom is likely to have been initiated by increased stratification triggering growth via relief of light limitation at the ice edge. This was visible in data from both 2014 and 2015, despite radically different atmospheric and sea-ice conditions, which led to a nearly 2 month shift in the timing of the summer bloom between the two years (Figure 2). The importance of timing of sea-ice retreat on primary and secondary producers was previously highlighted by ecosystem studies northeast of Svalbard by using a suite of moored and shipboard biophysical observations also during two contrasting years [*Leu et al.*, 2011]. There, the dominant copepod species *Calanus glacialis* reproduces during the solar zenith angle-controlled ice algal bloom, and then depends on a favorable timing of the pelagic bloom for their offspring to build up lipids. Unfavorable timing occurred in the second year of their study, when a 1 month delay in ice retreat resulted in a fivefold lower observed *Calanus* biomass, which then implies consequences for higher trophic levels.

Despite limited ancillary observations, we can gather qualitative ideas regarding the presence and vertical migration of zooplankton relative to the bloom from an acoustic backscatter record. Zooplankton are widely
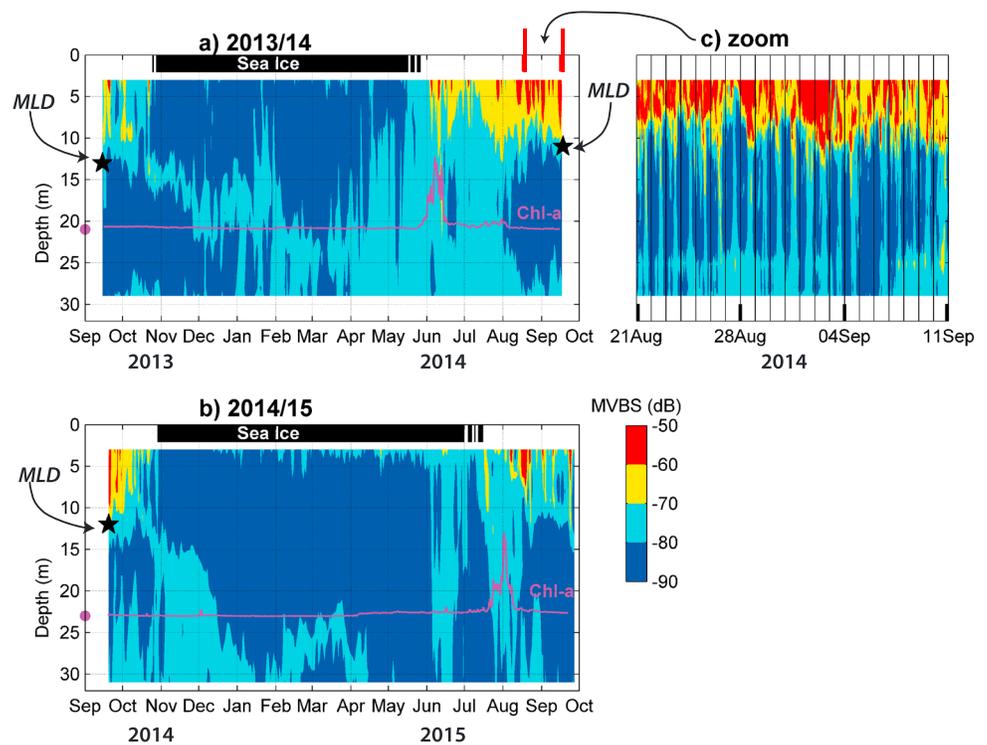
Figure 3. Daily mean volume backscatter (MVBS, in dB) in (a) 2013–2014 and (b) 2014–2015 from the two yearlong ADCP echo intensity records. The black bars indicate the presence of sea ice, and the Chl *a*-time series (magenta line) is overlaid at the depth of measurement (magenta dot) to indicate the bloom's timing relative to MVBS. The black stars at the beginning and end of the record indicate the position of the pycnocline from CTD profiles that were measured in September 2013 and 2014 (2015 profile is not available). Hourly values of MVBS during a subset (21 August to 13 September 2014) indicate diel vertical zooplankton migration.

assumed to be the main scatterers at the operating frequency of our ADCP [*Cisewski and Strass*, 2016, and references therein], especially during the growing season in summer and fall when zooplankton are most abundant and active. During winter and spring, turbulent microstructure at the pycnocline and near-surface may have enhanced the backscatter unrelated to zooplankton [*Ross and Lueck*, 2003]. Indeed, this is confirmed by maximum shear levels generally found at the pycnocline coincident with elevated back-scatter, which only holds during the biologically quiet season. Clear indication of the dominance of zoo-plankton in our data set was manifested in diel vertical migration (Figure 3), when zooplankton vertically migrate in an attempt to avoid predation [*Lampert*, 1989]. In 2014, backscatter was strongly enhanced after the ice retreated and the Chl *a* levels increased in early June. The levels remained high for nearly 2 months and then decreased in August. Curiously, backscatter also increased in June 2015 for a few weeks under the ice perhaps due to grazing on ice algae [*Runge and Ingram*, 1991; *Søreide et al.*, 2010] before it was reduced again until the ice finally retreated. After that a backscatter maximum was found near the surface and subsequently deepened, which we infer was the zooplankton's descent to graze on sedimenting algae, as highlighted by the temporal match between increasing backscatter and Chl *a* at 22 m (Figure 3). The backscatter remained elevated throughout the water column for the duration of the 2–3 weeklong Chl *a* peak measured at depth and retreated to the upper 15 m as soon as Chl *a* declined (Figure 3). After the 2014 peak, Chl *a* remained slightly elevated until it dropped to base levels in August. This indicates that a small but steady food source may be available at or below the pycnocline throughout the summer and underlines the necessity to quantify nutrient fluxes and diapycnal mixing processes. While the backscatter records only allow a qualitative zooplankton assessment [*Fielding et al.*, 2004], our data suggest that the earlier sea-ice retreat in 2014 led to more favorable zooplankton condi-tions compared with the late ice retreat in 2015. Whether the secondary producers benefitted from a favorable timing between ice algal and pelagic blooms [*Søreide et al.*, 2010; *Leu et al.*, 2011] remains spec-ulation and can only be addressed by more extensive biological sampling.

3.4. Thermal Conditions and Ecological Consequences

In addition to the difference in timing of food availability, these two years were characterized by contrasting thermal conditions. SST during the bloom in early June 2014 were below 0°C, while the surrounding waters during the late-July 2015 bloom were 2–4°C during this advanced time of year. However, mean upper ocean temperatures (averaged between SST and our 22 m CTD) from 1 June through 31 August were warmer in 2014 (1.3°C) than in 2015 (−0.6°C), due to the longer open water period and more effective solar warming in 2014. Secondary producers depend on the summer bloom for their development and to store lipids, which helps their survival through the overwintering stages. Hence, zooplankton reproduction and developmental success is controlled by both food availability and thermal conditions. A 2° temperature increase on summer average (such as we found in the Laptev Sea in 2014 relative to 2015) may reduce the development time from egg to adult by as much as 40 days [*Feng et al.*, 2016], which significantly improves the chances of reaching the diapause stage and surviving through winter.

Our analysis emphasizes the importance of the bloom's timing and the associated ocean temperatures on higher trophic levels, as was previously highlighted in Bering Sea ecosystem studies [*Wiese et al.*, 2012]. There, enhanced Pollock survival was linked with the availability of large copepods favoring an early bloom in cold water, while smaller copepods and warm water blooms were less favorable for Pollock survival [*Coyle et al.*, 2011]. Unfortunately, the impact of the observed contrasting thermal conditions on higher trophic levels in the Laptev Sea remains undetermined. Zooplankton were only sampled in September 2014 following the early bloom and warm summer waters and were then dominated by small copepods (*Oithona similis*; E. Abramova, unpublished data). Earlier surveys found a large biomass of small brackish and euryhaline copepods on the shallow shelf, while larger copepods such as *C. glacialis* were most abundant in the deeper northern Laptev Sea [*Kosobokova et al.*, 1998; *Lischka et al.*, 2001]. Previously, interannual differences in abundance and species composition throughout the shelf were primarily linked with the variable distribution of the Lena River plume [*Abramova and Tuschling*, 2005], but the long open water seasons and strong temperature variability observed in recent years [*Janout et al.*, 2016] might additionally lead to shifts in species distribution in a warming Arctic Ocean [*Feng et al.*, 2016].

4. Summary and Conclusion

A 2 year oceanographic mooring deployment (2013–2015) on the central Laptev Sea shelf equipped with bio-physical and sea-ice sensors documented the pelagic algal bloom under very contrasting environmental conditions. In 2014, enhanced southerly winds removed the pack ice north of the landfast ice zone at ~10 km d^{-1} until the ice edge passed the central shelf mooring location in late May. In contrast, winds were weak and variable in 2015, which led to localized melt and a nearly 2 month delay in ice retreat compared with the previous year. Nevertheless, in both years the blooms started almost immediately after the ice retreat and were similar in magnitude and duration, which contradicts simple predictions that the observed trends to earlier ice retreat will automatically result in higher productivity. Instead, they emphasize the potential role of nutrient limitation in bloom termination and the need to better understand vertical mixing and associated nutrient fluxes to the upper ocean. Based on the backscatter records (Figure 3) and overall warmer ocean conditions in 2014, it seems plausible that favorable timing of the bloom and thermal conditions during summer promote zooplankton through efficient grazing of primary production, which may benefit pelagic members of the food chain to the disadvantage of benthic communities as described for the Pacific Arctic sector [*Grebmeier et al.*, 2006].

We argue that stratification and (in one out of two years) light are the limiting parameters controlling the onset of the summer bloom, both of which are mediated by the sea-ice cover. Light measurements do not exist for this period, but in particular, the deteriorating and likely melt-ponded ice cover before the late-July 2015 bloom gives reason to assume that light levels should have been sufficient to promote under-ice growth [*Perovich and Polashenski*, 2012]. Stratification was inferred from the vertical structure of currents and tides (section 2.2), and our data suggested, for both years, that stratification prior the ice retreat (Figure 2) was too weak to keep algae suspended in the euphotic zone. Whether under-ice blooms presently occur under different preconditions on the central Laptev Sea shelf, or perhaps closer to freshwater sources where stratification is more likely to persist under the ice, remains undetermined and requires more observations.

Our measurements illustrate that first-order information regarding the timing of the summer bloom can be gained by adding single bio-optical instruments to oceanographic moorings. These types of measurements are particularly valuable for remote, seasonally ice-covered regions such as the Laptev Sea that are under present ice conditions inaccessible for shipboard biological in situ sampling in early summer. However, the level of interpretation is limited by the lack of specifically targeted biological observations and missing bio-physical near-surface measurements. These are urgently needed to quantify the seasonal variability of stratification and to understand the vertical progression of phytoplankton blooms, in spite of risks of ice keels that occasionally exceed 15 m at this location. The challenge remains to generate comprehensive sets of physical, biogeochemical, and higher trophic level observations, which are needed to gain a solid understanding of the present state in order to provide meaningful predictions for Arctic ecosystems under a changing climate.

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