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Revealing the seasonal cycles of Arctic phytoplankton: insights from year-round chlorophyll monitoring

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Abstract

LETTER

Rapid Arctic Ocean warming has caused severe sea ice decline, impacting light distribution, phytoplankton blooms, and primary production. We investigated Arctic phytoplankton bloom timing using continuous chlorophyll-a fluorescence data obtained from three Korea Arctic Mooring Systems (KAMSs) deployed north of the East Siberian Sea (KAMS1), north of the Chukchi Sea (KAMS2), and the middle of the Northwind Ridge (KAMS4). Our findings revealed that the bloom initiation times were June 4 (\pm 28 d) in KAMS1, June 24 in KAMS2, and May 21 $(\pm 6 \text{ d})$ in KAMS4, when the sea ice concentration (SIC) was >90% and the ice thickness was 1-2 m, indicating that the under-ice phytoplankton blooms (UIBs) developed 1-2 months before the sea ice retreated (mid-July, when SIC was <80%). Peak bloom and termination times were consistently observed in early August and mid-October, respectively. The average phytoplankton bloom lasted for approximately four months, longer than the open water periods at the mooring sites. However, the timing of the phytoplankton blooms from the biogeochemical model-based reconstructions was, on average, 6–10 weeks later than that deduced from the observed data. Furthermore, the maximum chlorophyll-a concentration observed during the bloom peak was approximately ten-times higher than that indicated by the biogeochemical model-based reconstructions (1.81 vs. 0.17 mg $^{-3}$). The differences in chlorophyll-a concentrations and bloom timings indicate that biogeochemical models remain insufficient for simulating the phytoplankton dynamics of the Arctic Ocean, such as UIBs and the subsurface chlorophyll maximum layer. Based on the continuously observed chlorophyll-a concentrations, we gained a precise understanding of the seasonal cycles of Arctic phytoplankton, including UIBs. These valuable data will contribute to improving the accuracy of biogeochemical models of the Arctic Ocean.

1. Introduction

Rapid warming in the Arctic Ocean has resulted in severe sea ice decline, accompanied by a decrease in the volume of perennial sea ice. In particular, sea ice condition alterations and early retreat influence water column light distribution, affecting total seasonal primary production and the marine phytoplankton bloom period. For example, under dominant first-year ice in the Arctic Ocean, wider melt pond coverage has greater light transmission than bare ice, causing a change in the underwater light field (Kwok *et al* 2011, Stroeve and Notz 2018, Shu *et al* 2022). Early sea ice retreats or delayed sea ice advances have led to changes in the early phytoplankton and fall blooms in the Arctic Ocean (Kahru *et al* 2011, Ardyna *et al* 2014, Manizza *et al* 2023). Two factors contribute to primary production increase in the Arctic Ocean. Phytoplankton growing season extension due to early sea ice retreat resulted in a 30% increase in the annual primary production between 1998 and 2012 (Arrigo and van Dijken 2015). Additionally, new nutrient influx into the Arctic Ocean sustained an increase in phytoplankton biomass between 2012 and 2018 (Lewis *et al* 2019). These findings confirm that rapid sea ice changes have a substantial impact on phytoplankton growth and primary production. However, this has mainly been documented in coastal or shelf areas in open water (Horvat *et al* 2017, Lowry *et al* 2018). To gain a comprehensive understanding of the response of phytoplankton to rapid environmental changes in the Arctic Ocean, it is crucial to investigate phytoplankton dynamics in open water and under sea ice.

Phytoplankton development is constrained by extremely low light and cold water conditions beneath the sea ice in the Arctic Ocean (Nansen 1902, Gran 1904). However, under-ice phytoplankton blooms (UIBs) have been observed since the 1950s in various regions of the Arctic Ocean, including the central Arctic Ocean (Apollonio 1959, English 1961), coastal Alaska (Yager et al 2001), the Beaufort Sea (Mundy et al 2009), and other local regions (Martin et al 2002, Leu et al 2011). These UIBs has been suggested to contribute to an approximately 12% increase in primary production in the Arctic Ocean (Perrette et al 2011, Arrigo *et al* 2012). Recently, the large UIBs have been observed on the Chukchi shelf, leading to the recognition of UIBs as a common phenomenon (Arrigo et al 2012, Lowry et al 2014, Ardyna et al 2020). However, the actual seasonal cycles and bloom timings of UIBs have not been well determined or understood because of the lack of continuous measurements. Thus, continuous data on phytoplankton biomass under sea ice are essential to determine the actual UIBs in seasonally ice-melting areas and higher-latitude regions.

We installed chlorophyll-a (Chl-a) fluorometers in the Korean Arctic Mooring System in the western Arctic Ocean in 2018 and have been continuously operating them to date. Moored fluorometers provide long-term continuous data at specific depths and certain locations to investigate the seasonal cycles of phytoplankton. Additionally, these observational data can be valuable for validating biogeochemical models and serve as evidence for predicting the seasonal cycle of Arctic phytoplankton in the future. Validating biogeochemical model products is crucial because they are essential for investigating the impacts of ongoing climate change on the marine environment of the Arctic Ocean (Schourup-Kristensen et al 2018). Therefore, the objectives of this study were to (1) determine the actual phytoplankton bloom timing from under sea ice to open water using continuous chlorophyll-a data obtained from mooring systems deployed at three different sites and (2) suggest how the observed timing differs from the timings simulated using Global and Arctic Ocean biogeochemical analysis data.

2. Methods

2.1. Year-long chlorophyll-a measurement

We determined chlorophyll-a levels year-round using moored fluorometers (Seapoint) with a data logger (RBRvirtuoso³, RBR) installed near the surface layer of the Korean Arctic Mooring System (KAMS) in the western Arctic Ocean. The three KAMSs are operative at different sites: north of the East Siberian Sea (KAMS1), north of the Chukchi Sea (KAMS2), and in the middle of the Northwind Ridge (KAMS4) (figure 1(a)). Information on the sensor depths and measurement periods for the individual KAMSs is presented in figure 1(b) and table 1. The moored Chla fluorescence values were corrected using the Chla concentrations obtained from the bottle samples to calculate the phytoplankton phenology. Niskin bottle-sampled seawater was filtered (500 ml) using a glass fiber filter (GF/F, Whatman) and extracted in the dark for 24 h with 90% acetone. The extracted samples were analyzed using a fluorometer (Trilogy, Turner Designs) calibrated with a purified Sigma Chla standard solution (Parsons et al 1984). The Chl-a fluorescence profile at each mooring site was obtained during summer field surveys using a fluorometer (ECO FL, WET Labs), which was calibrated using the Chl-a concentration sampled in a Niskin bottle (Ko et al 2022). The subsurface chlorophyll maximum (SCM) depth was determined based on the depth at which the highest value was observed for the Chl-a fluorescence profile in summer filed surveys.

2.2. Phytoplankton bloom timing calculation

The depth at which the fluorometer was installed varied each year, resulting in diverse patterns in Chla concentration and its annual cycle. To determine the bloom timing from Chl-a concentration, the Gaussian method was deemed suitable because it is insensitive to changes in Chl-a concentration and allows stable calculations (Zhao *et al* 2022). The corrected Chl-a concentrations obtained from the mooring sites were applied to the adjusted Gaussian curve fitting method to calculate the seasonal timing of the phytoplankton (Yamada and Ishizaka 2006, Thomalla *et al* 2011, Park *et al* 2019).

This method can be used to continuously infer chlorophyll dynamics, the equation (Park *et al* 2019) used is as follows:

$$C(\mathbf{x}) = C_0 + h \times e^{\frac{-(x-t_m)^2}{2\sigma^2}} + \frac{d}{1 + e^{\frac{-(x-t_m)}{2\sigma}}}$$
(1)

where C_0 is the initial Chl-a concentration, *h* is the bloom amplitude, *x* is time, tm is the time of the bloom peak, sigma is the bloom width, and *d* is the residual Chl-a concentration. $t_m \pm 2\sigma$ accounts for 95% of the Chl-a distribution. In this study, the



Figure 1. Map of chlorophyll-a fluorometers moored in the north of Chukchi Sea and schematic diagrams of the mooring system. (a) Map of mooring stations and the timing of sea ice retreat (color-shaded) which was estimated based on the average daily sea ice concentration ($\leq 80\%$) between 2018 and 2020. The black squares indicate the locations of three Korean Arctic Mooring Systems (KAMS1, 2, and 4). The black solid lines represent the bathymetric contours for 100 and 1000 m. (b) Schematic diagrams of KAMS1 (left), KAMS2 (middle), and KAMS4 (right). The green solid line represents the subsurface chlorophyll maximum (SCM) depth during the summer season in individual years. The blue ovals indicate the chlorophyll-a fluorometer installed on each mooring system.

phytoplankton bloom period was calculated as the differences between the initiation and termination time, and the initiation and termination times of the phytoplankton blooms were defined using the following equation (Yamada and Ishizaka 2006):

$$t_{i,t} = t_m \pm 2\sigma. \tag{2}$$

2.3. Sea ice data

Sea ice concentration (SIC), sea ice thickness (SIT), snow depth, and melt pond fraction data were used to interpret sea ice conditions around the three mooring sites. Daily SIC data with 25 km resolution were obtained from the National Snow and Ice Data Center. SIT and snow depth data were downloaded from the European Space Agency Soil Moisture and Ocean Salinity Online Dissemination Service (https:// smos-diss.eo.esa.int/oads/access/). These data have the same resolution as the SIC data, but are only available during the winter season (October to May). Daily melt pond fraction data provided by Bremen University (www.uni-bremen.de/) were measured using the Ocean and Land Color Instrument with a 12.5 km resolution. Sea ice data were extracted and averaged for each mooring site.

2.4. Ocean biogeochemistry analysis data

To reasonably compare the Chl-a concentration obtained from our localized mooring systems with the simulated model results, we needed to consider the operational modeling systems with a highresolution horizontal grid (less than 25 km) and a biogeochemical model specifically designed for the Arctic Ocean. Finally, we used two analysis datasets provided by Copernicus (www.copernicus.eu/ en) to compare the observed Chl-a annual cycles with the simulated results-one was the Global Ocean Biogeochemistry Analysis and Forecast (GOBAF, daily) based on the Pelagic Interactions Scheme for Carbon and Ecosystem Studies biogeochemical model with a 1/4° horizontal resolution and 50 vertical levels (https://doi.org/10.48670/moi-00015) and the other was the Arctic Ocean Biogeochemistry Analysis and Forecast (AOBAF, daily) that spans the whole Arctic Ocean with a 6.25 km horizontal resolution and 40 vertical levels (https://doi.org/ 10.48670/moi-00003). AOBAF was produced using the TOPAZ5 physical model and the biological ECOSystem Model (ECOSMO). We used threeyear (2018-2020) data for GOBAF and two-year (2019-2020) data for AOBAF. The chlorophyll

Table 1. Phytoplankton phenology estimated from chlorophyll-a concentrations in observed data (OBS) at the Korean Arctic Mooring System (KAMS) stations and Global and Arctic Ocean Biogeochemistry Analysis and Forecast data (GOBAF, AOBAF) (SCM: subsurface chlorophyll maximum depth; t_i : initiation time of bloom; t_m : maximum time of bloom; t_t : termination time of bloom; Peak concentration: seasonal maximum chlorophyll-a concentration (mg m⁻³)).

Station (year)	Туре	Depth (m)	SCM (m)	t _i (days)	t _m (days)	t _t (days)	Bloom period (days)	Peak concentration (mg m ⁻³)
KAMS1 (2018– 2020)	OBS		28-34	June 4 (±28)	August 2 (± 18)	October 1 (± 23)	$119 (\pm 36)$	3.04 ± 0.71
	GOBAF	37–44	NA	June 23 (±26)	September 23 (±7)	November 27 (±1)	158 (±27)	$\textbf{0.29}\pm\textbf{0.08}$
	AOBAF		NA	September 8 (±38)	November 7 (±15)	January 6 (±7)	120 (±45)	0.06 ± 0.05
	OBS		28-34	July 29 (±20)	September 1 (±13)	October 6 (±11)	69 (±20)	0.83 ± 0.41
	GOBAF	67–74	NA	June 4 (±68)	September 25 (±37)	December19 (± 49)	198 (±34)	0.10 ± 0.01
	AOBAF		NA	August 11 (±12)	October 27 (±5)	January 22 (±6)	164 (±6)	0.03 ± 0.04
KAMS2 (2020)	OBS Gobaf Aobaf	68	47 NA NA	June 24 August 2 August 20	August 19 October 22 November 6	October 14 January 5 January 23	112 156 156	1.44 0.12 0.01
KAMS4 (2019– 2020)	OBS		51, 68	May 21 (±6)	August 1 (± 15)	October 12 (± 23)	$122 (\pm 14)$	1.63 ± 0.29
	GOBAF	52, 58	NA	June 17 (±60)	October 1 (± 18)	December 8 (± 18)	175 (±42)	0.13 ± 0.04
	AOBAF		NA	July 20	September 8	October 28	100	0.04 ± 0.06

parameters (mg m⁻³) from both datasets were averaged over the depths corresponding to the installation depths of the individual chlorophyll-a fluorometers in the mooring systems for a reasonable comparison with the observed Chl-a concentration. The Chla concentration from the two analysis datasets was used to determine the phytoplankton bloom timing using the adjusted Gaussian curve fitting method, as used for the observational data.

3. Results

3.1. Seasonal cycles of phytoplankton obtained from continuous observed data

To investigate the seasonal cycles of Arctic phytoplankton, we examined phytoplankton bloom timing estimated from the Chl-a concentrations observed at the three mooring sites. The bloom timings showed some yearly and vertical variations; however, the Chl-a concentration generally increased prior to sea ice retreat. In the upper part of Chl-a fluorometer of KAMS1, approximately 40 m near the summer SCM layer, Chl-a concentration was approximately 0.1 mg m⁻³ during winter and began to increase between April and June (figure 2(a)). The onset of phytoplankton blooms was estimated to be June 4 (±28 d) on average between 2018 and 2020 (table 1). For KAMS4 (52-58 m) around the SCM layer, winter Chl-a concentrations ranged between 0.1 and 0.3 mg m⁻³, and phytoplankton blooms

typically began on May 21 (±6 d) in 2019-2020 (figure 2(d)). The total water depth at the mooring sites was >500 m, suggesting that the phytoplankton likely originated from the water column or vegetative cells generated by melting sea ice (figure 1(b)). After sea ice retreated at KAMS1 and KAMS4 stations, the peak times of phytoplankton bloom were similar, occurring on August 2 (±18 d) and 1 (±15 d) on average, respectively. However, the maximum Chl-a concentration at KAMS1 was 46% higher than that at KAMS4 (3.04 \pm 0.71 vs. 1.63 \pm 0.29 mg m⁻³). Subsequently, the Chl-a concentration decreased rapidly at both mooring sites between early and mid-October as the sea ice advanced and light availability decreased. The bloom periods at the two mooring sites were similar (119 \pm 36 vs. 122 \pm 14 d); however, KAMS1 exhibited the longest bloom period of 160 d in 2020.

Chl-a fluorometers were installed at 67-74 m at KAMS1 and KAMS2, corresponding to the depths below the summer SCM layer (figure 1(b) and table 1). In the lower part of KAMS1 (67-74 m), the Chl-a concentration began to increase at least one month later than in the upper part (37-44 m). Thus, the onset of the bloom was estimated to be on approximately July 29 (figure 2(b)). At 68 m in KAMS2, phytoplankton blooms began on June 24, approximately one month earlier than on July 29 in KAMS1 (figure 2(c)). The peak blooms in the lower layer at KAMS1 and KAMS2 took place on



lines represent the daily time series of sea ice concentrations (%) around each mooring station. The colored lines represent the fitting lines for chlorophyll-a concentration estimated using the adjusted Gaussian curve fitting method.

September 1 $(\pm 13 \text{ d})$ and August 19, respectively, which were later than the peak blooms near the SCM layer. Additionally, the maximum Chl-a concentration at KAMS2 was higher than that at KAMS1 (1.44 vs. 0.83 \pm 0.41 mg m⁻³). In 2020, the SCM depth at KAMS2 was approximately 47 m, deeper than the 30 m depth at KAMS1. As a result, the maximum Chla concentration at KAMS2, which is close to the SCM layer, exceeded that at KAMS1 (figure S1). Similar to the observations in the periphery of the SCM layer, the termination times of bloom were recorded on October 6 $(\pm 11 \text{ d})$ and October 14 below the SCM layers of KAMS1 and KAMS2, respectively. The bloom period of phytoplankton in the lower part of KAMS1 was 69 (\pm 20 d), which was shorter than 112 d observed at KAMS2.

3.2. Difference between chlorophyll-a simulated

using biogeochemical analysis data and in-situ data The vertical distribution of the Chl-a concentrations extracted from the two biogeochemical analysis datasets showed similar trends at the three mooring sites (figure 3). GOBAF demonstrated that, in the surface layer, the Chl-a concentration during winter was nearly 0.1 mg m⁻³ and started to increase in June (figures 3(a)-(c)). Subsequently, in August and September, the surface layer exhibited the peak concentration of Chl-a, ranging from 0.7 to 0.9 mg m^{-3} , while the Chl-a concentration at 40 m was as low as 0.5 mg m⁻³. The Chl-a concentration decreased after October and reached winter Chla concentration in November. In contrast, AOBAF indicated that the Chl-a concentration during winter was notably low ($<0.01 \text{ mg m}^{-3}$) and began to rise from mid-July in the surface layer (figures 3(b), (d) and (f)). Notably, the Chl-a concentration at KAMS1 and KAMS2 showed two peaks $(1-2.5 \text{ mg m}^{-3} \text{ and}$ $0.8-1 \text{ mg m}^{-3}$) in the surface layer during summer, and that at KAMS4 showed one peak (0.4-1 mg m⁻³). The Chl-a concentrations showed a slow decrease from October to December in the upper layer. Overall, the two biogeochemical analysis datasets were insufficient to represent the vertical distribution of Chl-a characterizing the summer SCM. Additionally, the timing and concentrations of observed Chl-a showed significant differences from the reanalysis data, with these differences being more pronounced in AOBAF compared to that in GOBAF.

The timing of the phytoplankton blooms was estimated using Chl-a concentrations from biogeochemical analysis data at depths comparable to those installed in each mooring system (figure 4 and table 1). At KAMS1 and KAMS4 station locations, around the summer SCM layer, the initiation times





of blooms were in mid-June, and the peak times were estimated on September 23 (±7 d) and October 1 $(\pm 18 \text{ d})$, respectively, in GOBAF (figures 4(a) and (d) and table 1). The termination times of blooms were estimated to be November 27 $(\pm 1 \text{ d})$ and December 8 (\pm 18 d), respectively. In general, the bloom times estimated from GOBAF were four to nine weeks later than the observed times (figure 5(a) and table 1). Furthermore, the Chl-a concentrations during the peak were 0.29 \pm 0.08 and 0.13 \pm 0.04 mg m⁻³, respectively, which were more than 10-times lower than the observed values (figures 4(a) and (d) and table 1). Similarly, in the AOBAF, phytoplankton blooms at KAMS1 and KAMS4 occurred 2-14 weeks later than did the observed blooms (figure 5(b)and table 1). The peak time Chl-a concentrations were also extremely low, ranging from 0.06 \pm 0.05– 0.04 \pm 0.06 mg m⁻³ (table 1). For KAMS1 (67– 74 m) and KAMS2 (68 m), corresponding to depths below the SCM layer, the bloom times estimated from GOBAF and AOBAF were 2-15 weeks late (figure 5), and the maximum Chl-a concentration was $\leq 0.10 \text{ mg m}^{-3}$, which was significantly

lower than the observed value (figures 4(b) and (c) and table 1). Both biogeochemical analysis datasets simulated the bloom times of phytoplankton much later than the observed times, and the Chl-a concentration was simulated to be relatively low.

4. Discussion and conclusions

Our observations confirmed the presence of UIBs prior to the sea ice retreat in the Arctic Ocean. Although sea ice retreat typically occurred around mid-July at the mooring sites (figure 1(a)), the Chl-a concentration near the summer SCM layer began to increase between April and June (figure 2). Specifically, the onset time was estimated to be June 4 (± 28 d) in the north of the East Siberian Sea (KAMS1) and May 21 (± 6 d) in the middle of the Northwind Ridge (KAMS4) (table 1). Additional reports confirmed that UIBs are present before sea ice retreat. For instance, on the continental slope of the Chukchi Sea near the mooring sites, phytoplankton growth under sea ice was observed from late June to late July in 2011 and 2014 (Arrigo *et al* 2014,



Figure 4. Comparison of averaged chlorophyll-a concentration (mg m⁻³) from the Global and Arctic Ocean Biogeochemistry Analysis and Forecast datasets (GOBAF and AOBAF) with observed data (OBS). (a) chlorophyll-a concentration (37–44 m) at Korean Arctic Mooring System (KAMS)1 between 2018 and 2020, (b) chlorophyll-a concentration (67–74 m) at KAMS1 between 2018 and 2020, (c) chlorophyll-a concentration (68 m) at KAMS2 in 2020, (d) chlorophyll-a concentration (52–58 m) at KAMS4 between 2019 and 2020. All units are mg m⁻³. The colored lines indicate the fitting lines obtained by applying the adjusted Gaussian curve fitting method for observed (green circle), GOBAF (blue square), and AOBAF (red triangle) data, respectively. The gray dotted line represents the daily time series of averaged sea ice concentration (%) during individual mooring periods. The blue shading box represents the average bloom period calculated from observed data at individual KAMS stations.

Hill et al 2018). Boles et al (2020) also reported that the winter Chl-a concentration in the mixed layer of Amundsen Basin was 0.15 mg m⁻³, which started to increase in early May and reached 0.5 mg m^{-3} by late June in 2017, indicating that phytoplankton began to thrive under sea ice. UIBs have been identified in various regions; however, the specific timing of UIBs formation varies. In our study, the onset of UIBs was different at each mooring site. This was likely associated with differences in light availability between each site, which is considered the primary limiting factor for phytoplankton growth in the Arctic Ocean during spring when sea ice is present (Hill et al 2018, Ardyna and Arrigo 2020). The sea ice concentration at mooring sites during the onset of UIBs was mostly similar, with values exceeding 85%. On the other hand, the melt pond fraction around the SCM layer at KAMS1 and KAMS4 ranged between 8 and 9%, and between 15 and 17%, respectively. In layers below the SCM, such as the lower part at KAMS1 and KAMS2, the melt pond fraction exceeded 20% (table S1). The difference in light availability may be attributed to variations in sea ice conditions at each mooring site, leading to variability in the onset of UIBs. Using the year-round Chl-a concentration

observed in mooring systems under sea ice, our study unequivocally confirmed the occurrence of UIBs in the northern Chukchi Sea 1-2 months before the sea ice retreats, rather than bloom initiation starting in ice-free areas and migrating to higher-latitude regions (Perrette et al 2011, Johnsen et al 2018). Furthermore, this UIB phenomenon could be a signal not only from pelagic algae but also possibly from sympagic ice algae, and the presence of sympagic ice algae may vary at different mooring sites (Gal et al 2022). Rapid climate change-induced alterations in sea ice distribution are expected to considerably affect future UIB changes in the Arctic Ocean. Therefore, continuous UIB observations would enhance our understanding of seasonal phytoplankton dynamics and primary productivity in this region.

Identifying the exact seasonal cycles of primary producers in the Arctic Ocean is essential to understand future changes in primary production, food webs, and carbon cycles. In the Arctic Ocean, the retreat of sea ice generally intensifies surface stratification. This, in turn, limits the additional nutrient supply and leads to surface nitrogen depletion, which is required for phytoplankton growth (Ardyna and Arrigo 2020). Consequently, this process leads to a



Figure 5. Time gaps of initiation (yellow bars), peak (green bars), and termination (blue bars) of phytoplankton bloom determined using (a) Global and (b) Arctic Ocean Biogeochemistry Analysis and Forecast datasets from observed data (OBS) at individual Korean Arctic Mooring System (KAMS) stations. A positive value indicates the time estimated from analysis data delays from the observed ones (in weeks). Two fluorometers were installed at KAMS1; U and L represent the upper and lower fluorometer, respectively.

formation of a SCM during summer (Ko et al 2020, Bruyant et al 2022). After sea ice retreat at KAMS1 and KAMS4, the Chl-a concentration near the SCM layer reached its maximum after 2-4 weeks, indicating a period of SCM layer formation (figure 2 and table 1). During SCM layer development, nutrient availability in the SCM layer at KAMS1 was higher than that at KAMS4 (Gal et al 2022, Ko et al 2022). This difference may contribute to variations in maximum Chl-a concentration between the two mooring sites $(3.04 \pm 0.71 \text{ vs. } 1.63 \pm 0.29 \text{ mg m}^{-3})$. Meanwhile, the onset times of the lower parts of KAMS1 and KAMS2 began on July 29 (±20 d) and June 24, respectively, approximately one month later than that observed near the SCM layer. Bloom terminations occurred in mid-October, resulting in a bloom period of approximately 10-16 weeks below the SCM layer. These bloom periods were slightly shorter than 17 weeks of the average bloom period near SCM (table 1). As the SCM layer is typically formed at a depth of approximately 1%-5% of the surface light intensity (Martin et al 2012), the environment below the SCM layer can encounter limited or low-light conditions. These light conditions may have contributed to the delay and shorter bloom period of Chl-a signals in the lower parts. Our continuous multi-year observations also indicated that the actual growing period of phytoplankton in the northern Chukchi Sea lasted for approximately four months, which was longer than the open water period (table S1). One of the major advantages of our approach is that it provides insights in to the precise seasonal changes in

phytoplankton beyond the open-water period when satellite observations are possible.

Our results revealed that the seasonal Chl-a peaks from the two biogeochemical analysis datasets occurred approximately 6-10 weeks after the observed peak timing (figures 4 and 5). In other words, these analysis datasets did not represent the occurrence of UIBs, resulting in a significant delay not only in the peak timing but also in the termination time of blooms. This discrepancy between the observations and these analysis datasets is probably due to the failure of the biogeochemical model to properly simulate light conditions within the water column prior to sea-ice retreat and the inadequate parameterization of Arctic phytoplantkon in the under-ice environment (Schourup-Kristensen et al 2018). Sea ice cover exhibits various forms, such as bare ice, snow-covered ice, and ponded ice, resulting in varying degrees of light transmittance (Perovich 1990, Frey et al 2011). In the Arctic Ocean, light transmittance begins to increase owing to snowmelt in spring and continues to rise until melt ponds are formed (Katlein et al 2019). Additionally, Arrigo et al (2014) reported that the light transmittance of ponded ice was more than four times higher than that of bare ice (46.7%-58.6% vs. 12.7%-17.5%, respectively) on the continental shelf of the Chukchi Sea in July 2011. Because the sea ice status in spring significantly influences light distribution in the water column, we compared the simulated sea ice conditions of the model with satellite sea ice data to assess their accuracy. Although satellite data for March and April exhibited relatively higher SIT (1.7 \pm 0.1 vs. 1.5 ± 0.2 m, respectively) or lower snow cover (16 ± 1 vs. 17 \pm 3 cm, respectively) compared to the simulated sea ice conditions, simulated sea ice concentrations were consistent with satellite data (figure S2). These sea-ice conditions alone cannot account for the differences in the timing of phytoplankton blooms in the biogeochemical data. Matthes et al (2020) reported that enhanced light transmission through sea ice melt ponds could trigger the initiation of UIBs. In addition, it has been reported that a 10% melt-pond fraction in the first-year ice provides sufficient transmitted light to support phytoplankton growth (Palmer et al 2013). However, the biogeochemical analysis data used in this study did not provide melt pond fractions and thus could not be compared. Our results show that the melt pond fraction during the initiation of the phytoplankton bloom within the SCM layer ranged from approximately 8% to 17% (table S1), indicating that the conditions for UIB formation had already been met. Accurately simulating light distribution under sea ice in biogeochemical models is crucial for understanding the seasonal dynamics of phytoplankton in the Arctic Ocean. Yumruktepe et al (2022) reported an increase in the difference in Chl-a concentrations between the field

and ECOSMO, the biological model used in AOBAF, as the depth increased. This result is similar to the significant differences in Chl-a concentrations between the observations and the two biogeochemical analysis datasets near the SCM in our study. The cause of this mismatch might be attributed to the lack of consideration for variability in the carbon to Chl-a ratio under low light conditions (Anugerahanti et al 2021). The vertical distribution of summer phytoplankton should be enhanced through improved parameterization for high-latitude phytoplankton functional groups (Schartau et al 2017). Thus, improvement of the deficiency of the model addressed in this context can potentially ensure substantial progress in comprehending and forecasting the ecological dynamics of Arctic phytoplankton.

The key findings of our research are presented by the confirmation of the occurrence mechanism of Arctic Ocean UIBs, accurate seasonal cycles, and discrepancies in observation and analysis data. Our continuous monitoring of Chl-a concentration revealed that UIBs are a common phenomenon in the Arctic Ocean and can manifest in various regions. Seasonally ice-free conditions in the Arctic Ocean could potentially accelerate the shrinking snow cover of sea ice and the formation of melt ponds (Kwok 2018, Stroeve and Notz 2018). This allows for increased light transmission and provides favorable conditions for phytoplankton growth at an earlier time (Horvat et al 2017). Moreover, 20% of productivity in the Arctic Ocean could occur in ice-covered areas (Schourup-Kristensen et al 2018). Therefore, the importance of UIBs and the actual phytoplankton growth period should be further emphasized for phytoplankton dynamics and primary production in the Arctic Ocean. These critical insights should be integrated into biogeochemical models. We anticipate that our valuable data will enhance the understanding and predictive capabilities of biogeochemical modelers regarding the dynamics of the food web and carbon cycle in the Arctic Ocean by improving their models.

Data availability statement

The data supporting the findings of this study are openly available upon request and approval at the following URL: https://kpdc.kopri.re.kr/search/ fc6875ea-de40-40ae-b74b-3cd9c6f8fdf8.

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