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Weddell Sea Phytoplankton Blooms Modulated by Sea Ice Variability and Polynya Formation

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Key Points:
- Autonomous float observations are used to characterize the evolution and vertical structure of phytoplankton blooms in the Weddell Sea
- Bloom duration and total carbon export were enhanced by widespread early ice retreat and Maud Rise polynya formation in 2017
- Early spring bloom initiation creates conditions for a distinguishable subsurface fall bloom associated with mixed-layer deepening

Supporting Information:
- Supporting Information S1

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Abstract Seasonal sea ice retreat is known to stimulate Southern Ocean phytoplankton blooms, but depth-resolved observations of their evolution are scarce. Autonomous float measurements collected from 2015–2019 in the eastern Weddell Sea show that spring bloom initiation is closely linked to sea ice retreat timing. The appearance and persistence of a rare open-ocean polynya over the Maud Rise seamount in 2017 led to an early bloom and high annual net community production. Widespread early ice retreat north of Maud Rise in 2017, however, had a similar effect, suggesting that the polynya most impacted the timing of bloom initiation. Still, higher productivity rates at Maud Rise relative to the surrounding region are observed in all years, likely supported by flow-topography interactions. The longer growing season in 2017–2018 also allowed for separation of distinct spring and fall bloom signals, the latter of which was primarily subsurface and associated with mixed-layer deepening.

Plain Language Summary Antarctic sea ice retreat each spring regulates the growth of tiny algae called phytoplankton, which form the base of marine food webs and absorb carbon dioxide from the atmosphere through photosynthesis. Massive holes in the Antarctic sea ice, called polynyas, are also thought to support phytoplankton growth. Measuring the biological activity in the sea ice zone is difficult, however, because these environments are hard to access. In this study, we analyze observations from robotic floats in the Weddell Sea, including two floats near the ice edge and two floats that sampled in an offshore polynya that formed over a seamount called Maud Rise. The data show that opening of the polynya in 2017 triggered an early and prolonged phytoplankton bloom associated with high carbon sequestration. However, a similarly early bloom was observed far to the north of Maud Rise, induced by a widespread early ice retreat in that year, suggesting that the polynya did not greatly impact the bloom intensity. Instead, circulation over Maud Rise leads to high biological productivity in all years, even those without polynyas. The lengthened growing season in 2017–2018 also permitted the isolation of a fall bloom, which occurred primarily below the sea surface.

1. Introduction

Primary productivity in the Southern Ocean, which is limited mainly by iron and light (de Baar et al., 1995; Mitchell et al., 1991), is heterogeneous in space and time. Past studies, which have relied on temporally limited shipboard measurements and remote sensing of near-surface chlorophyll, suggest that the Weddell Sea has particularly high biological production (Arrigo et al., 2008; Jennings et al., 1984; Vernet et al., 2019). This is thought to be related to the high surface iron concentrations in the region (Tagliabue et al., 2012). However, lack of in situ data has prevented characterization of the evolution and vertical structure of Weddell Sea phytoplankton blooms. Understanding the drivers of primary productivity in this region is particularly important given the central role of the Weddell Sea in the meridional overturning circulation and global biogeochemical cycling through Antarctic Bottom Water formation (Brown et al., 2015; Gill, 1973; Orsi et al., 2002).

Sea ice cover exerts significant control over Southern Ocean phytoplankton blooms, which are commonly observed along the seasonally retreating ice edge (Arrigo et al., 2008; Briggs et al., 2018; Smith & Nelson, 1986). These ice edge blooms have been attributed to alleviation of light limitation within stable, shallow melt layers (Park et al., 1999; Smith & Nelson, 1985, 1986; Taylor et al., 2013), iron delivery from melting

ice (Bathmann et al., 1997; Croot et al., 2004; Geibert et al., 2010; Lannuzel et al., 2008; Sedwick & DiTullio, 1997), and bloom seeding by release of ice algal stocks (Fryxell & Kendrick, 1988; Smith & Nelson, 1985, 1986; Wilson et al., 1986). Numerical models estimate that blooms within the marginal ice zone (MIZ), defined as the region with sea ice present in the last 14 days, contribute about 15% of Southern Ocean net primary productivity (Taylor et al., 2013). Furthermore, satellite-derived estimates indicate that the Weddell Sea sector is host to the most productive MIZ in the Southern Ocean, due in part to its larger area relative to other sectors (Arrigo et al., 2008).

Coastal polynyas have also been recognized as sites of elevated productivity and are often associated with high biomass of upper trophic level organisms and substantial carbon export to the ocean interior (Arrigo & van Dijken, 2003; Arrigo et al., 2015; Smith & Gordon, 1997). The productivity of these recurring openings is due to relief of light limitation (Arrigo & van Dijken, 2003) and iron delivery through sediment resuspension, ice shelf melt, upwelling or vertical mixing of subsurface waters, and other processes (Arrigo et al., 2015; Planquette et al., 2013; St-Laurent et al., 2019). Still, regional variability in coastal polynya productivity and carbon sequestration remains a subject of active research (Arrigo et al., 2008; Lee et al., 2017; Yager et al., 1995, 2016). A satellite-based analysis of 37 Antarctic coastal polynyas showed that total primary production varies by 2 orders of magnitude across polynyas (Arrigo & van Dijken, 2003).

Even less understood are the biogeochemical implications of offshore ("open-ocean" or "sensible heat") polynyas, which are maintained by vigorous convective mixing of subsurface heat (Gordon, 1978; Martinson et al., 1981). Open-ocean polynyas are particularly challenging to study since some only appear every few decades, as opposed to nearly annual coastal polynyas. Major offshore polynyas appeared in the Weddell Sea in 2016 (27 July to 17 August) and 2017 (3 September to 17 November) over the Maud Rise seamount, the largest such events in the region since the 1970s (Carsey, 1980). Studies have attributed their formation to severe storms and low upper-ocean stratification (Campbell et al., 2019; Cheon & Gordon, 2019; Francis et al., 2019; Jena et al., 2019). It is unknown whether offshore polynyas such as these may enhance primary productivity because in situ historical measurements are nonexistent. Here, we use observations from autonomous biogeochemical profiling floats to characterize the full, depth-resolved temporal evolution of blooms in the eastern Weddell Sea. These floats captured four complete bloom cycles, obtaining measurements from the ice edge and within both the 2016 and 2017 polynyas (Campbell et al., 2019). This allows us to examine the effects of interannual variability, ice retreat, and polynya formation on bloom phenology and structure in this region. We also use these data and model output to examine the relative magnitudes of primary productivity at Maud Rise and within the broader Weddell Sea seasonal ice zone (SIZ).

2. Data and Methods

This study uses in situ data from autonomous biogeochemical floats deployed by the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project (Talley et al., 2019). SOCCOM floats measure temperature, salinity, pressure, dissolved oxygen, nitrate, pH, fluorescence, and backscatter over the top 2,000 m of the water column every 10 days. The quality-controlled data from the 24 June 2019 SOCCOM snapshot are used in this analysis (http://doi.org/10.6075/J0GH9G8R). All profiles are linearly interpolated onto a regular depth axis with 5 m vertical resolution. In addition to autonomous float measurements, we analyze monthly near-surface chlorophyll from the Moderate-Resolution Imaging Spectroradiometer (MODIS) Aqua satellite (https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua). Level 3 binned data at 9 km resolution are used. The NOAA/NSIDC Climate Data Record of daily passive microwave sea ice concentration (Version 3 on a 25 km grid; http://nsidc.org/data/G02202) is used to identify the date of ice retreat, taken to be the first day that ice concentration at a location decreases below 20%. Bathymetry from the ETOPO1 1 arc minute global relief model (http://www.ngdc.noaa.gov/mgg/global/) is shown in Figure 1. We also analyze output from the data-assimilating Biogeochemical Southern Ocean State Estimate (B-SOSE) to investigate the importance of Maud Rise to total Weddell Sea productivity. The solution used in this analysis Iteration 133, evolved from Verdy and Mazloff (2017) has 1/6° horizontal resolution and runs from 1 January 2013 to 31 December 2018.

Here, we investigate the coupling between physical and biological processes in the Maud Rise region using data from four SOCCOM floats deployed in late 2014 and early 2015. Floats 5904468 and 5904471 (the "Maud Rise floats," "MR1" and "MR2," respectively) circulated closely around Maud Rise for 4 years, while floats 5904467 and 5904397 (the "Gyre floats," "WG1," and "WG2," respectively) remained in the eastern cell of

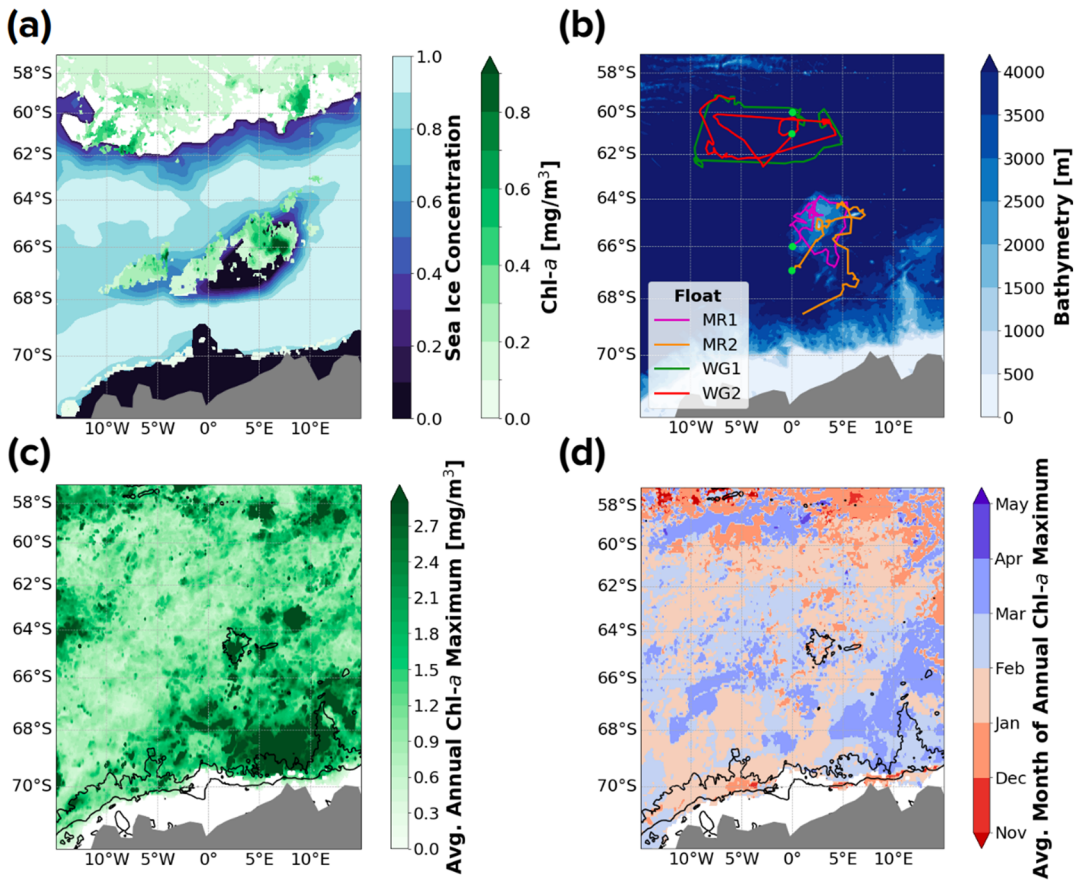

Figure 1. (a) November 2017 satellite sea ice concentration from NOAA/NSIDC Climate Data Record (blue shading) and MODIS Aqua near-surface chlorophyll concentration (green shading); white space denotes open water with no ocean color data for November 2017. (b) Autonomous float trajectories from the Maud Rise region overlaid on ETOPO1 bathymetry. Starts of float trajectories are marked with green circles. (c) The average annual maximum chlorophyll value over 2002–2018 for each grid point calculated from MODIS Aqua chlorophyll and (d) the average month in which the maximum chlorophyll value occurred, with black contours outlining the 500 and 2,500 m isobaths from ETOPO1 bathymetry.

the Weddell Gyre (Orsi et al., 1993; Reeve et al., 2019), north of the seamount (see trajectories in Figure 1b). Interannual variability in bloom phenology is analyzed using chlorophyll *a* (chl-*a*) profiles derived from fluorescence. Data processing and corrections applied to the raw fluorometer data are described by Johnson, Plant, Coletti, et al. (2017). To examine the physical drivers of bloom initiation, mixed-layer depth (MLD) is calculated using a density criterion with a threshold value of $\Delta\sigma_\theta = 0.03\ \text{kg m}^{-3}$ (de Boyer Montégut et al., 2004; Dong et al., 2008). The chlorophyll column inventory ($[\text{Chl}_{\text{tot}}]$) is taken to be the vertical integral of chl-*a* over the top 200 m of the water column (Grenier et al., 2015). Bloom stages are defined for each annual cycle starting from 1 July in a given year: The *onset* is the first increase in column inventory, the *climax* is the maximum rate of increase, and the *apex* is the maximum value (Behrenfeld, 2010; Llort et al., 2015).

Since the floats are being advected and may sample high-frequency events like synoptic storms, each float time series is smoothed by a 30-day running mean to highlight variability at seasonal time scales (Uchida et al., 2019). The median float displacement over the course of a full bloom cycle from October to May was 150 km, or 19 km over a 30-day period. Under-ice positions are estimated using linear interpolation. Here, we treat each time series as a quasi-Eulerian measurement of the bloom at a particular location. Float MR2 did drift south of Maud Rise toward the end of the 2018–2019 bloom cycle (see supporting information Figure S1). This could explain some of the differences between MR1 and MR2 during the 2018–2019 bloom cycle. However, both floats sampled at Maud Rise during the 2016 and 2017 polynya events (Campbell et al., 2019), so results pertaining to the role of the polynya in modulating primary productivity are robust.

Table 1
Float-Based Estimates of Annual Net Community Production (mol C/m^2/yr) from Nitrate Drawdown Using an Integration Depth of 200 m

ID (WMO ID)	2015–2016	2016–2017	**2017–2018**	2018–2019
MR1 (5904468)	1.72	2.60	**3.35**	2.52
MR2 (5904471)	2.19	1.95	**3.54**	1.68
WG1 (5904467)	0.76	2.20	**2.25**	1.69
WG2 (5904397)	1.23	1.25	**1.99**	1.29

Note. Results from the year of the largest polynya event, 2017–2018, are marked in bold.

In order to investigate the carbon export associated with polynya productivity, we estimate annual net community production (ANCP) from the nitrate drawdown measured by the floats in each bloom cycle. We use an integration depth of 200 m, following Johnson, Plant, Dunne, et al. (2017). Values are reported in Table 1 (nitrate measurements are shown in Figure S2). Net community production is the difference between total primary production and respiration in the upper ocean. The annual integral, or ANCP, corresponds approximately to the annual carbon export into the ocean interior (Falkowski et al., 2003). This calculation does not account for horizontal advection. For example, in situ measurements from the Amundsen Sea polynya suggest that even highly productive polynyas can have minimal carbon sequestration due to lateral transport by the local circulation (Lee et al., 2017). That said, estimates of the interannual variability in ANCP at Maud Rise can help indicate the role of the polynya in regulating carbon export and thus local atmospheric carbon dioxide (CO_2) levels.

3. Results

The seasonal cycles of chlorophyll column inventory (Figure 2) demonstrate significant interannual variability in bloom timing and magnitude for a given float. Spatial variability in bloom phenology can also be assessed by comparing the Maud Rise floats (Figures 2a and 2b) to the Gyre floats (Figures 2c and 2d).

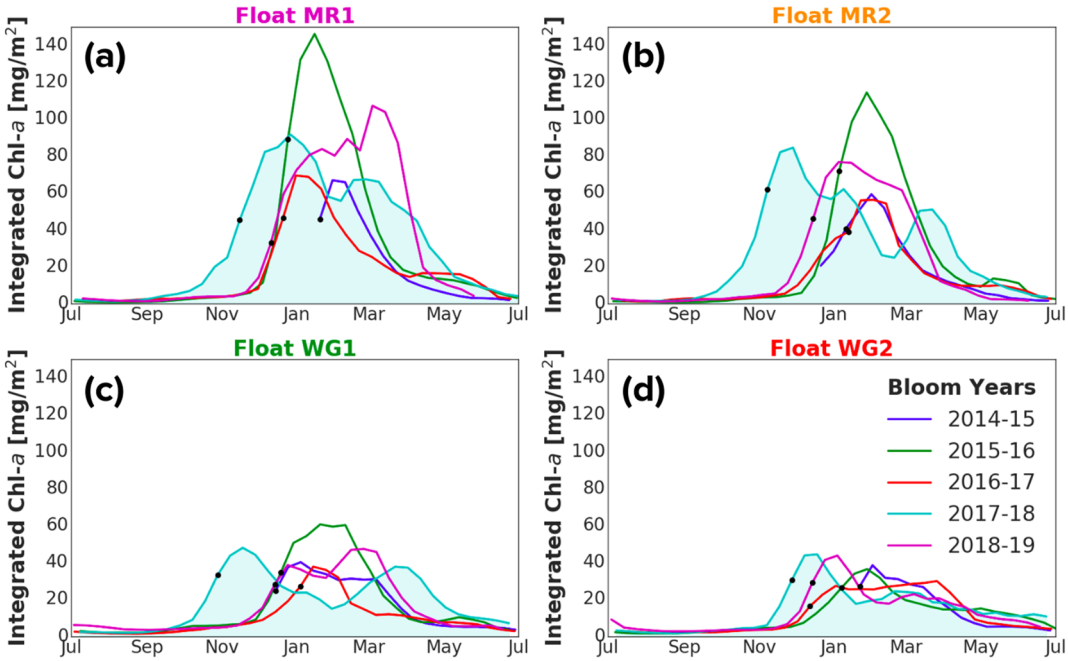

Figure 2. Float time series of chlorophyll column inventory for each annual bloom cycle starting on 1 July from 2014 to 2018. Black dots mark the bloom climax for each bloom cycle. Cycles are plotted for the Maud Rise floats (a) MR1 and (b) MR2, as well as the Gyre floats to the north of Maud Rise (c) WG1 and (d) WG2. Panel labels are colored to match the corresponding float trajectories in Figure 1b. The year of the largest polynya event, 2017–2018, is highlighted with cyan shading.

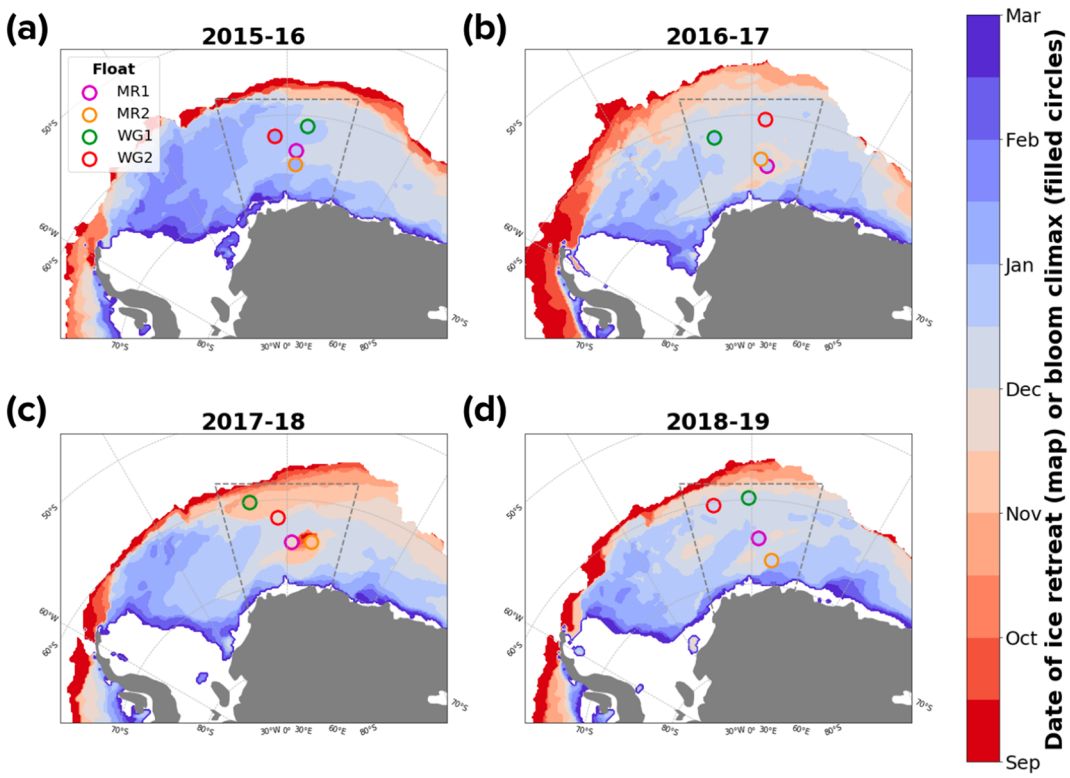

Figure 3. Map shading indicates the sea ice retreat date for (a) 2015–2016, (b) 2016–2017, (c) 2017–2018, and (d) 2018–2019. Circles mark the location, and fill color denotes the date of the bloom climax for each corresponding bloom cycle. Dashed lines indicate the approximate map boundaries from Figure 1.

The maximum [Chl_{tot}] in the years examined are 1.5 or more times greater for the Maud Rise floats. This is independent of polynya formation, which occurred in 2016 and 2017 only. In fact, the year with the highest recorded [Chl_{tot}] value at Maud Rise was 2015–2016, a non–polynya year. Satellite chlorophyll from 2002–2018 suggests that the average annual maximum chlorophyll concentrations are elevated at Maud Rise compared to the surrounding region (Figure 1c). The mean values over the approximate location of Maud Rise (within 63–67°S, 0–10°E) are higher than the mean over the entire domain north of the continental shelf (taken to be north of 68°S) at the 95% confidence level, as determined by a two-sided *t* test.

While the presence of the polynya did not seem to drastically affect the maximum [Chl_{tot}] value, Figure 2 demonstrates that the bloom initiation was more than 1 month earlier in the 2017–2018 bloom cycle (cyan). This corresponds to the larger of the recent polynya events, which attained a maximum area of about 50,000 km^2 (Campbell et al., 2019). The bloom in that year was also sustained longer, with two separate peaks in [Chl_{tot}] visible for all the floats. In fact, during the 2017–2018 bloom cycle, MR1 measured the largest annually integrated chlorophyll column inventory of any Southern Ocean float in the entire SOCCOM array. The 2017–2018 season also featured the highest ANCP at Maud Rise, indicating the potential for more carbon export into the ocean interior. In contrast, the smaller 2016 polynya event, which featured a maximum area of about 33,000 km^2 (Campbell et al., 2019), apparently had little effect on the bloom timing, length, or carbon sequestration in that year.

The early bloom initiation in 2017, also observed in MODIS satellite chlorophyll data (Figure 1a), is consistent with a relief of light limitation due to the persistence of the polynya into early spring. This explains why the 2016 polynya had little impact on that year's bloom, since it closed in mid-August, when light levels are still too low to support rapid phytoplankton growth (Mitchell et al., 1991; Smith et al., 2000). The Gyre floats also recorded an early bloom in 2017, despite being hundreds of kilometers from the polynya. This can be understood in the context of the earlier sea ice retreat, shown in Figure 3. There is a close correspondence between the timing of the bloom climax and sea ice retreat (i.e., the color of filled circles generally match their surrounding area). This suggests that the early ice retreat in 2017–2018 led to an early bloom in

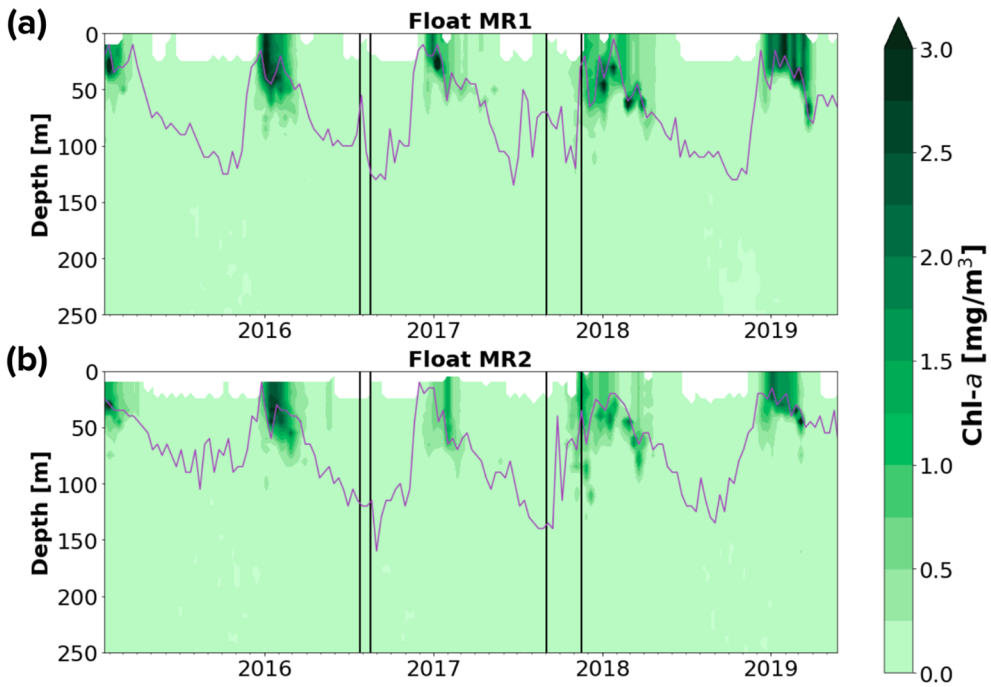

Figure 4. Observations of upper-ocean chlorophyll concentration from the Maud Rise floats (a) MR1 and (b) MR2. Mixed-layer depth is overlaid in purple. Vertical black lines mark the start and end dates of the 2016 and 2017 polynya events.

the northeastern Weddell Gyre, as well as at Maud Rise (the monthly evolution of satellite-derived sea ice concentration and chlorophyll in 2017–2018 is shown in Figure S3).

In addition to its early initiation, the 2017–2018 bloom was unusually long lasting. Following the initial rise and decline in [Chl_{tot}], all floats measured a secondary peak of chlorophyll column inventory in March 2018. Figure 4 shows that the timing of the initial spring bloom corresponds to seasonal mixed-layer shoaling. The concurrent sea ice retreat, mixed-layer shoaling, and chlorophyll increase suggest that the spring bloom is enabled by reduced turbulent mixing within shallow melt layers and hence increased light exposure. The fall bloom in 2017–2018, on the other hand, coincided with rapid mixed-layer deepening. During this secondary bloom, chlorophyll was concentrated within subsurface peaks located at or just below the MLD and generally below depths featuring high chlorophyll concentration during the earlier spring bloom. A similar bloom structure was observed by the Gyre floats (Figure S4).

4. Discussion and Conclusions

Autonomous float observations from Maud Rise reveal substantial interannual variability in bloom timing and magnitude, which can only be partially attributed to the presence of the polynya. In all years, bloom initiation immediately followed the date of the sea ice retreat and coincided with mixed-layer shoaling, consistent with existing understanding of ice edge blooms (Briggs et al., 2018; Park et al., 1999; Perrette et al., 2011; Smith & Nelson, 1985, 1986; Wilson et al., 1986). More recently, the importance of MLD to bloom development has been questioned (Behrenfeld, 2010; Behrenfeld & Boss, 2014; Franks, 2015; Taylor & Ferrari, 2011). For example, top-down controls (e.g., grazing pressure) may exert significant influence over Southern Ocean bloom cycles (Smith & Lancelot, 2004). Nevertheless, we presume that the observed spring bloom is initially light limited. Iron is expected to be plentiful in the surface ocean after deep winter mixing (Arrigo et al., 2017; Tagliabue et al., 2014), though there is some evidence that spring blooms near Maud Rise may be at least occasionally iron limited (Bathmann et al., 1997; Croot et al., 2004; Geibert et al., 2010).

Findings here suggest that the opening of the polynya in 2017 increased light availability and triggered a bloom more than 1 month earlier compared to other years. This was not unique to Maud Rise, however, and floats far to the north of the polynya also recorded an early bloom corresponding to large-scale earlier

sea ice retreat that year. The 2016 polynya, on the other hand, had little impact on primary productivity because it closed before light levels had increased enough to support rapid phytoplankton growth. While the 2017 polynya event did impact the bloom timing at Maud Rise, the maximum chlorophyll column inventory in that year was not unusually high. The largest recorded [Chl_{tot}] value occurred in 2015–2016, a non–polynya year with an anomalously shallow, stratified mixed layer during the bloom initiation, which deepened rapidly thereafter (Figure S6). This suggests that iron entrained during summer mixing is important to bloom development (Carranza & Gille, 2015). Although the [Chl_{tot}] values were not anomalously high in 2017–2018, the highest ANCP occurred that year. Still, it appears that the subsurface iron supplied by vigorous deep convection during the 2017 polynya (Campbell et al., 2019) is not substantially greater than the upper limit of normal interannual variability.

Comparing the [Chl_{tot}] values for all floats across all years indicates that chlorophyll concentrations at Maud Rise are higher than in the surrounding region, regardless of polynya formation (Figure 2). This is also reflected in the longer-term satellite record (Figure 1c), as well as in model output from B-SOSE (Figure S7), which suggests that ANCP over Maud Rise (within 63–67°S, 0–10°E, normalized by area) is 36% higher than the average within the Weddell SIZ. Enhanced primary productivity is consistent with previous observations of high krill concentrations, pelagic species richness, and benthic organic matter fluxes at Maud Rise (Brandt et al., 2011). This phenomenon has also been observed at other seamounts in the Southern Ocean, with productivity likely fueled by the supply of limiting micronutrients to the euphotic zone through topography-induced mixing (Meredith et al., 2003; Prend et al., 2019; Sokolov & Rintoul, 2007). At Maud Rise, flow-topography interactions generate eddies that enhance heat supply to the surface ocean and induce sea ice divergence, contributing to polynya formation (de Steur et al., 2007; Holland, 2001; Lindsay et al., 2004). We hypothesize that upward nutrient fluxes may arise from isopycnal doming within these eddies as well as elevated diapycnal mixing over Maud Rise.

Early spring bloom initiation at Maud Rise, driven by the 2017 polynya event, extended the growing season by more than 1 month and led to the separation of distinct spring and fall peaks in [Chl_{tot}]. While the spring bloom is closely tied to the timing of the sea ice retreat and may be initially light limited, the fall bloom is likely micronutrient limited, since the bioavailable iron in the euphotic zone is generally consumed during the spring bloom. The fall bloom is associated with mixed-layer deepening, which has been shown to sustain late summer and fall phytoplankton growth in a pattern consistent with nutrient entrainment (Carranza & Gille, 2015). Diapycnal mixing, in addition to mixed-layer entrainment, may also be an important iron supply mechanism sustaining late summer and fall blooms (Frants et al., 2013). The seasonal progression from light to iron limitation has been observed in biogeochemical modeling of an Antarctic coastal polynya environment (Oliver et al., 2019). However, this succession is not unique to polynya years (Figure 4).

We hypothesize that the spring and fall bloom signals in [Chl_{tot}] are not distinguishable in most years. A distinct fall bloom is only possible when the growing season is sufficiently long, such as in 2017–2018. This is consistent with the observation of double bloom structures in 2017–2018 in the northeastern Weddell Gyre (Figure 2). It should be noted that carbon-to-chlorophyll ratios may vary, especially over a long growing season (Smith & Kaufman, 2018), and photoacclimation in low light can drive deep chlorophyll maxima (Steele, 1962). However, vertical profiles of particulate organic carbon derived from float optical backscatter measurements following Haëntjens et al. (2017) also show the same pattern of high subsurface biomass in fall (Figure S8). In addition to iron entrainment, it is also possible that this deep biomass maximum is related to light-dependent grazing (Moeller et al., 2019) or a decrease in predator-prey encounter rates as the mixed layer deepens (Behrenfeld, 2010).

The longer growing season in 2017–2018 led to higher ANCP and therefore potentially more carbon export into the ocean interior, suggesting that offshore polynyas can impact atmospheric CO_2 levels through carbon sequestration. A prolonged growing season and high ANCP was also observed far north of Maud Rise in 2017–2018, where an early bloom followed widespread early sea ice retreat. This implies that early ice retreat elsewhere in the Southern Ocean could generate similar changes in bloom phenology, which has ramifications for primary productivity in the SIZ under anthropogenic climate change. For example, the B-SOSE model solution from 2013–2018 shows ANCP and ice-free days within the Weddell Sea SIZ to be significantly correlated ($r^2 = 0.68$, $p = 0.04$; Figure S9). However, further observational study of MIZ bloom phenology is needed to improve its presently poor representation in current-generation climate models (Hague & Vichi, 2018). Additionally, identifying the prevalence of fall blooms using satellite remote sensing

may prove difficult, as the chlorophyll observed by these four floats was primarily subsurface. These results highlight the importance of accounting for the vertical structure of Southern Ocean phytoplankton biomass, supporting other recent studies such as Carranza et al. (2018), which identified chlorophyll maxima below 20 m in about 25% of Southern Ocean float profiles.

In this study, we used SOCCOM autonomous biogeochemical floats to explore the intra-annual and inter-annual variability of phytoplankton blooms within the Weddell Sea SIZ. These data include the only in situ biogeochemical measurements from an open-ocean polynya event in the Weddell Sea (and, to our knowledge, the Southern Ocean). The appearance of an offshore polynya may trigger an early spring bloom, lengthen the growing season, and enhance carbon sequestration. This influence, however, can only be exerted if the polynya persists into spring, when light levels increase. We find enhanced chlorophyll levels at Maud Rise relative to the surrounding region in all years, irrespective of polynya formation. This study therefore shows that the local biological impacts attributable to mixing during offshore polynyas may be minimal, though offshore polynyas could still affect ocean carbon storage by altering the timing of bloom initiation or through air-sea gas exchange during deep convection (Bernardello et al., 2014). While major open-ocean polynya events at Maud Rise are rare (Campbell et al., 2019), our results demonstrating a double bloom structure following an early ice retreat may apply broadly to the SIZ and deserve further examination.

Data Availability Statement

The quality-controlled data from the 24 June 2019 SOCCOM snapshot are used in this analysis (http://doi.org/10.6075/J0GH9G8R). MODIS Aqua Level 3 binned chlorophyll *a* data at 9 km resolution are available from NASA (https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/). Bathymetry from the ETOPO1 Global Relief Model is available from NOAA (https://www.ngdc.noaa.gov/mgg/global/). NOAA/NSIDC Climate Data Record of passive microwave sea ice concentration is available online (https://nsidc.org/data/G02202). The B-SOSE Iteration 133 solution for 2013–2018 is publicly available (http://sose.ucsd.edu/).

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