Majority of Southern Ocean seasonal sea ice bloom net community production precedes total ice retreat

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Key points

- Majority of net community production during the Southern Ocean spring ice zone bloom occurs prior to full sea ice retreat
- Highest rates of daily net community production occur during active sea ice retreat and may be due to iron delivery or low grazing rates
- Highest observed bloom net community production is tied to early sea ice retreat and/or proximity to topographic features

Abstract

The Southern Ocean Seasonal Sea Ice Zone (SSIZ) is characterized by the development of spring phytoplankton blooms following retreating sea ice. Until recently, assessing SSIZ bloom carbon export has been limited by a lack of under ice observations. Here, we relate the timing of phytoplankton growth to the drawdown of surface nutrients and sea ice cover and estimate spring bloom net community production (bNCP) using biogeochemical profiling float observations. The onset of biological production follows initial sea ice breakup with 64% of bNCP under partial sea ice cover. Estimates of bNCP range from <1 to >4 mol C m^{-2} bloom^{-1}, with earlier sea ice breakup associated with higher bNCP, and the highest bNCP where micronutrient supply is likely enhanced by topographic-driven mixing. These results indicate that satellite-derived export estimates will underestimate bNCP in the SSIZ and have implications for future carbon export in a changing Southern Ocean sea ice regime.

Plain Language Summary

Sea ice around the Southern Ocean expands during the fall/winter and retreats each spring/summer. Massive spring blooms of phytoplankton are observed around the retreating sea ice edge, but observations of these blooms are limited by ice cover and difficult ocean conditions such that quantification of their biological impact has been difficult. In this study we use year-round data from profiling floats that measure oxygen, nitrate, chlorophyll fluorescence, and particulate backscatter. We use these data to determine that the spring phytoplankton bloom begins just after sea ice breaks up and the majority of organic matter that is produced but not consumed is generated before total sea ice retreat. This indicates that commonly used satellite observations miss most of the bloom period. We also found that the greatest organic matter production occurred in regions

of early sea ice retreat or near sea-floor features. We explored the potential role of phytoplankton growth limitation by micronutrients, such as iron, and consumption by grazing zooplankton, finding it likely that these drove the patterns of organic matter production seen in this study. These results indicate that changes in sea ice timing and magnitude due to climate change will likely impact biological production in the Southern Ocean.

Introduction

The Seasonal Sea Ice Zone (SSIZ) encompasses the roughly 16 million km^2 Southern Ocean region between the winter maximum and summer minimum sea ice extent. Winter sea ice formation inhibits light availability and air-sea gas exchange in the surface ocean and deepens the mixed layer through cooling and brine rejection. In spring, sea ice rapidly retreats and freshens the surface ocean, creating shallow mixed layers and increased light levels in surface waters. Elevated regions of chlorophyll identified in ocean color observations suggest phytoplankton blooms occur over a third of the SSIZ each spring (Fitch & Moore, 2007). The initiation of blooms in the SSIZ has been attributed to an increase in light levels, sea ice melt induced surface stratification, release of sea-ice algae, and/or increased iron supply from melting ice following sea ice retreat (Ardyna et al., 2017; Walker O. Smith & Comiso, 2008; Walker O. Smith & Nelson, 1985; Taylor et al., 2013a). However, a lack of under ice, multi-year, and basin wide observations has hindered a clear understanding of how sea ice impacts phytoplankton blooms and the associated nutrient and inorganic carbon drawdown. Recent record minima in Antarctic Sea ice extent and anomalously early sea ice retreats in 2017 and 2022 (Parkinson, 2019; Wang et al., 2022) underline the need to understand the link between sea ice retreat and biological processes in the Southern Ocean.

Estimates of net primary production (NPP) from satellite ocean color observations (Arrigo et al., 2008; Moore & Abbott, 2000), extrapolated from discrete sampling efforts (Buesseler et al., 2003; W. O. Smith & Nelson, 1986), and a biogeochemically coupled circulation model (Taylor et al., 2013b) find that the sea ice impacted Southern Ocean contributes between as little as 4% to as much as 15% of total Southern Ocean NPP. Estimates of NPP and prior research on bloom drivers in the SSIZ from ship surveys and satellite observations are constrained to the ice-free portion of the year. Recent deployment of profiling floats equipped with biogeochemical sensors, primarily by the Southern Ocean Carbon and Climate Observations and modeling project (Johnson, Plant, Coletti, et al., 2017), has enabled a more complete characterization of SSIZ blooms and associated NCP through under ice observations. Novel observations of chlorophyll fluorescence and particulate backscatter from biogeochemical profiling floats have provided new understanding of SSIZ bloom phenology, indicating that phytoplankton biomass begins to accumulate from September to October, prior to sea ice melt detection and several months prior to ice free conditions in January and February (L. A. Arteaga et al., 2020; Hague & Vichi, 2020; Horvat et al., 2022; Uchida et al., 2019).

However, the biogeochemical impact of SSIZ phytoplankton blooms on mixed layer carbon and nutrient cycling, especially during the under-ice season, and their broader role in the total Southern Ocean carbon cycle is unclear. Net community production (NCP) describes the fraction of primary production that is not respired at the surface and can be exported into the ocean interior. Prior estimates of NCP in the SSIZ are sparse in spatial and temporal extent and recent estimates from biogeochemical profiling floats using the seasonal change in mixed layer nitrate or mesopelagic oxygen concentration indicate a wide potential range in the magnitude of SSIZ NCP (1-3.5 mol C m^{-2} yr^{-1}) (L. A. Arteaga et al., 2019; von Berg et al., 2020; Johnson, Plant, Dunne, et al., 2017). Here we link seasonal changes in phytoplankton biomass to NCP throughout the SSIZ from 2015-2021 to determine the link between sea ice breakup, nutrient drawdown and NCP.

Results

Timing of declining sea ice cover, phytoplankton biomass, and nutrient drawdown

We compare Southern Ocean Carbon and Climate Observation and Modeling float observations of salinity, nitrate, oxygen, float derived phytoplankton carbon (C_p), chlorophyll (Chl), and calculated mixed layer depth to along-track sea ice concentration and surface radiative flux. Data are from 31 floats, measuring 64 bloom periods from July 2015 to March 2021 (Fig. 1). We focus the analysis from July to March of each year, during which time mixed layer phytoplankton carbon, chlorophyll, and oxygen concentrations increase from their annual minima to maxima and mixed layer nitrate concentration and salinity decrease from annual maxima to minima (representative winter to summer period illustrated in Fig. 2). We use mixed layer mean values to investigate the order of events, which also allows close comparison with satellite-derived timing studies of surface ocean properties.

Changes in salinity, satellite SIC and an initial oxygen increase all can be used to independently identify the onset of sea ice melt and initial exposure of previously isolated water to atmospheric gases and increased light. We determine initial sea ice breakup timing using an average of these three proxies to minimize individual uncertainties. Total sea ice retreat is used to refer to the first day of sea ice free conditions and is determined from satellite SIC. We estimate growth initiation from both phytoplankton carbon (GI_{Cp}) and chlorophyll (GI_{Chl}) and compare these to the date of a decrease in mean mixed layer nitrate concentrations to identify the timing between phytoplankton biomass increase from near zero values in peak winter and the draw down of surface nutrients and inorganic carbon due to biological growth.

Figure 2. Seasonal relationships between mixed layer properties and sea ice. Example float (WMO 5904471) winter to summer timeseries with mixed layer mean oxygen (orange), nitrate (red), phytoplankton carbon (blue), and chlorophyll (green) concentrations **(a.)** and mixed layer mean salinity, mixed layer depth, mixed layer median light **(b.)** with satellite SIC in shaded blue for both (SIC scale on bottom panel only). Symbols indicate the day of $GI_{Chl,Cp}$ or when nitrate, oxygen, or salinity thresholds are exceeded. **(c.)** Relationships between date of sea ice breakup relative to nitrate decrease and GI_{Cp} date. The day of year of nitrate decrease (red circles) and GI_{Cp} (blue triangles) vs. sea ice breakup day for all 64 float seasons analyzed. Colored lines indicate 20-day bin means ± 1 standard deviation. Symbols lying above the solid gold 1:1 line in the unshaded region indicate mixed layer nitrate decrease and GI_{Cp} after sea ice breakup.

The initial increase in mixed layer oxygen coincides with a decrease in mixed layer salinity and SIC, indicating sea ice breakup and invasion of atmospheric oxygen, and the onset of sea ice decrease (Fig. 2). The onset of sea ice breakup occurs 17 ± 12 days before the mixed layer nitrate decreases and 17 ± 18 days before growth initiation from phytoplankton carbon (GI_{Cp}) (Fig. 2c). GI_{Chl} occurs 7 ± 23 days before estimated sea ice breakup and does not show a consistent relationship with mixed layer nitrate decrease or growth initiation from phytoplankton carbon, though GI_{Chl} is almost always earlier. GI_{Chl} occurs 23 ± 23 days earlier than initial mixed layer nitrate decrease and 23 ± 21 days before GI_{Cp}. The longest delay between GI_{Chl} and GI_{Cp}/nitrate decrease is 76 and 80 days, respectively, which occurred early (~September), approximately two months before sea ice breakup (Fig. S2). While GI_{Cp} and mixed layer nitrate decrease almost always occur after initial sea ice breakup, the lag between sea ice breakup and GI_{Cp} and mixed layer nitrate decrease is greater earlier in the season (mid-September) than later (mid-November) (Fig. 2c).

SSIZ bloom net community production

NCP is calculated from nitrate drawdown down to the depth of the wintertime maximum MLD to include production or respiration immediately beneath the mixed layer and in order to determine the net transport of carbon from the surface ocean to depth, rather than redistribution of carbon within the upper ocean that will be seasonally re-exposed to the atmosphere (Bushinsky & Emerson, 2018; Johnson, Plant, Dunne, et al., 2017; Text S4). Daily NCP begins to be positive coincident with mixed layer decreases in nitrate and increases in phytoplankton carbon (Fig. S3) and continues to increase as the ice concentrations decline from near 100% sea ice concentration to open water (Fig. 3a). On average 64% of the NCP associated with the seasonal sea ice zone blooms, bloom NCP (bNCP), occurs under partial sea ice cover (Fig. 3a), and higher daily NCP is observed prior to total sea ice retreat (Fig. 3b). Cumulative bNCP peaks between January and April.

While observations of higher NCP between sea ice break up and total sea ice retreat are consistent throughout all 64 float years, bNCP magnitude spanned a wide range of <1 to >4 mol C m^{-2} $bloom^{-1}$. In order to identify possible drivers of the wide range in SSIZ bNCP, we test the relationship between bNCP and timing of sea ice breakup, length of productive period (defined as the period between minimum and maximum cumulative NCP), cumulative mixed layer depth radiation adjusted for SIC, days with SIC < 15%, and duration of shallow mixed layers. Variability in cumulative bNCP is related to the timing of sea ice breakup (r^2=0.27, P<.001), with higher bNCP found when sea ice breakup occurs earlier, and lower bNCP when sea ice breakups later in the year (Fig. 4). On average, bNCP is 1 mol C m^{-2} $bloom^{-1}$ higher in floats where sea ice retreat begins on or before mid-October (day 290, 19 occurrences) than after early November (day 310, 20 occurrences). The higher bNCP with earlier breakup is not attributable to an increase duration of nitrate drawdown, as the duration of nitrate drawdown is only weakly linearly related to the magnitude of bNCP (r^2=.105, *P*=.009) (Fig. S4). Rather, the higher bNCP of floats which observe early sea ice retreat is associated with higher daily NCP rates, as well as higher mixed layer phytoplankton carbon concentrations following sea ice breakup (Fig. 4b, Fig. S5). Prior to total sea ice retreat, the floats that observe early sea ice breakup and higher daily NCP have lower light availability compared to observations with late sea ice breakup (Fig 4b).

Discussion

Biomass increases and NCP initiation

The onset of rapid phytoplankton biomass increase and nutrient drawdown occurs approximately two weeks after initial sea ice breakup (Fig. 2), suggesting that small openings in sea ice relieve light limitation and trigger biological production and associated biologically derived net community production in the SSIZ. Net autotrophy begins well before either total sea ice retreat or the 10-15% SIC contour commonly used to define the retreating sea ice edge in previous work assessing SSIZ blooms from ship surveys or satellite ocean color products (e.g., (Ardyna et al., 2017; Arrigo et al., 2008)). Onset of NCP following sea ice breakup is consistent with observations in the Arctic of increased phytoplankton biomass near leads and unconsolidated ice and correlations between chlorophyll, backscatter and sea ice thickness, and presence of leads in the Southern Ocean (Assmy et al., 2017; Bisson & Cael, 2021).

Our observed timing of growth initiation and the transition to net autotrophy confirms recent findings that production begins well prior to total sea ice retreat (L. A. Arteaga et al., 2020; Hague & Vichi, 2020; Horvat et al., 2022; Uchida et al., 2019). However, despite the increases in chlorophyll observed weeks to months before initial sea ice breakup, we do not find any indication of biological production sufficient to influence surface nutrient and carbon concentrations until after sea ice breakup. Increases in chlorophyll (GI_{Chl}) prior to sea ice breakup are not concurrent with GI_{Cp} or an observable decrease in nitrate (Fig. S2). The initial increases in chlorophyll concentration are very small, and even when GI_{Chl} occurs months before sea ice opening, mixed layer chlorophyll concentrations remain very low until sea ice breakup begins. The difference in GI_{Cp} and GI_{Chl} timing are largely due to a high sensitivity of GI_{Chl} to very small changes in chlorophyll concentration. If instead a 0.035 mg m^{-3} chlorophyll concentration threshold is used based on the 0.2 μmol kg^{-1} nitrate concentration threshold and a chl:N ratio of 1.75 (Moreau et al., 2020), growth initiation inferred from chlorophyll has a similar timing as both GI_{Cp} and nitrate decrease (Fig. S2). The significant difference between identifying phytoplankton growth initiation using the rate based GI_{Chl} or a chlorophyll concentration threshold based on meaningful biogeochemical changes affects interpretation of drivers of phytoplankton growth, and indicates the advantage of using backscatter and nitrate data in addition to chlorophyll to understand seasonal changes in phytoplankton biomass in the SSIZ. This is especially true considering inherent uncertainties involved in using chlorophyll fluorescence to estimate chlorophyll concentrations and the near zero chlorophyll and phytoplankton concentrations in winter.

Previous hypotheses suggest that SSIZ blooms are stimulated by shallow mixed layers and increased light following sea ice retreat. Our results suggest sea ice breakup, rather than near total or total sea ice retreat, appears to relieve winter light limitation, even while SIC is still near the winter maximum. During the remainder of the bloom period we do not find evidence for light as the primary limiting factor affecting magnitude of total SSIZ bNCP. The cumulative available light in the mixed layer, duration of ice-free days, or duration of shallow mixed layers explain very little to no variation in the magnitude or duration of bNCP (Fig S4). In contrast, coastal and coastal polynya Antarctic sea ice blooms have been shown to be primarily light limited (Joy-Warren et al., 2019; Park et al., 2017), suggesting different mechanisms may control primary and net community production in the SSIZ and in ice impacted coastal environments.

Drivers of higher daily NCP under actively retreating sea ice

Iron is known to limit phytoplankton growth in the Southern Ocean and iron from sea ice melt has previously been proposed to fuel SSIZ blooms (Croot et al., 2004; Delphine Lannuzel et al., 2008). Iron in sea ice is an order of magnitude greater than in surface waters, such that sea ice melt acts as a short-lived iron source (D. Lannuzel et al., 2016) and phytoplankton growth in the sea ice impacted Southern Ocean is strongly stimulated by additional iron (Alderkamp et al., 2019; Viljoen et al., 2018; Vives et al., 2022). Both grazing pressure and Fe limitation are thought to increase through the bloom season in the SSIZ (Moreau et al., 2020). In the present study, higher daily NCP rates occur while sea ice is still melting relative to the open water period, which leads to the majority of bNCP taking place under partial sea ice cover. The higher under-ice NCP is consistent with sea ice melt supplying micronutrients to the upper ocean and stimulating phytoplankton growth, which then decreases after total sea ice retreat.

Declining NCP rates as the season progresses (Fig. 3) may also result from increased grazing and/or shifts in phytoplankton community composition. Krill are effective grazers of phytoplankton blooms following sea ice retreat and have been observed to diminish phytoplankton populations within hours (GranÍi et al., 1993; Lancelot et al., 1991; Mengesha et al., 1998) and can significantly control NCP (Ishii et al., 2002). Community composition shifts linked to the sea ice environment have been shown to explain a high portion of variability in NCP in the West Antarctic

Peninsula, with more diverse plankton communities and higher NCP found when sea ice concentration was higher during the summer sampling month (Lin et al., 2021). Iron limitation, grazing, and community composition may all interact to drive the observed decrease in NCP following total sea ice retreat. Phytoplankton communities are observed to shift from *Phaeocystis Antarctica* to diatom communities throughout the season in response to increasing iron limitation (Ryan-Keogh & Smith, 2021; Wright & van den Enden, 2000), while krill have been shown to more effectively graze diatoms than and selectively graze diatoms over *Phaeocystis* (Davidson et al., 2010; Haberman et al., 2003). Ecological modeling work suggests that the seasonal shift of *Phaeocystis* and diatoms south of 60°S is controlled by temperature and iron, and the relative importance of each to carbon cycling is also determined by biomass loss rates (Nissen & Vogt, 2020).

Bloom NCP magnitude variability

In addition to higher daily NCP rates during active sea ice retreat at a given location in the SSIZ, estimated bNCP is higher when sea ice breaks up earlier relative to when sea ice breaks up later in the year (Figs. 3c & 4a). This relationship cannot be primarily explained by a difference in available light, as daily NCP rates are relatively higher even while estimated light is lower when sea ice breaks up earlier in the year (Fig. 4b). We postulate that increased daily NCP associated with anomalously early sea ice breakup could be due a greater lag between initial phytoplankton biomass increases and grazer (predominately krill) biomass increases when sea ice breaks up earlier in the year. Later sea ice breakup may reduce the lag, if zooplankton follow the sea ice southward, which is consistent with observations of high krill abundances near the sea ice edge in

January and February, and southward krill migration over the season in the North Antarctic Peninsula (Brierley et al., 2022; Loeb & Santora, 2015).

The highest estimated bNCP (> 3.5 mol C m^{-2} $bloom^{-1}$) occurs in two regions; near Maud Rise and east of the Antarctic Peninsula (Fig. 1). Models of iron distribution within the Southern Ocean SSIZ and available in situ dissolved iron data (Laufkötter et al., 2018; Person et al., 2021; Tagliabue et al., 2012) indicate relatively high iron near the Eastern Antarctic peninsula. Flow topography interactions can enhance upwelling of deep waters throughout the Southern Ocean (Tamsitt et al., 2017) and specifically near Maud Rise (Bersch et al., 1992), and anomalous deep mixing has been observed near Maud Rise in 2016 and 2017 prior to the opening of open ocean polynyas (Campbell et al., 2019). This topographic-induced mixing could result in additional iron supply to support the highest bNCP values.

Spatial or interannual differences in micronutrient supply from sea ice melt may additionally explain some of the variance in bNCP, but this is currently difficult to assess as the dynamics and spatiotemporal variability of iron supply from melting sea ice are still not well constrained. Furthermore, we did not evaluate how the upper ocean processes that result in anomalously early sea ice break up or iceberg production could otherwise impact iron fertilization and subsequently bNCP. New proxies for iron limitation have been developed in the pelagic Southern Ocean (Schallenberg et al., 2022) and the coastal Ross Sea (Ryan-Keogh & Smith, 2021) and the addition of radiometers on under ice floats could allow for investigation of spatio-temporal patterns of iron limitation throughout the SSIZ.

Estimates of NCP or carbon export in the SSIZ that use NPP derived from satellite ocean color (~1-1.5 mol C m^{-2} yr^{-1}) (L. Arteaga et al., 2018; Li et al., 2021) are lower than estimates in this study. The fact that the majority (64%) of NCP associated with the SSIZ blooms occurs before sea ice retreat is complete, suggests that estimates of NCP relying solely on satellite observations miss a significant portion of SSIZ bNCP and may not adequately capture spatial or temporal variations in NCP in the SSIZ. This is consistent with a prior modeling study that found that spring blooms began when SIC fell below 90% coverage and under ice NPP accounted for two thirds of the NPP in the marginal ice zone (MIZ, a subset of the SSIZ with actively retreating sea ice (Taylor et al., 2013a). These modeled under ice blooms yielded higher estimates of MIZ contribution to total Southern Ocean NPP south of 30°S (15%) than estimates from satellite ocean color observations (~4%) (Arrigo et al., 2008; Moore & Abbott, 2000; Taylor et al., 2013a). In the Southern Ocean south of 50°S, higher carbon export is estimated from inverse modeling and spring/summer climatological nitrate budgets relative to satellite derived methods, which could in part be in part explained by carbon export prior to full sea ice retreat (Maccready & Quay, 2001; Schlitzer, 2002). The estimates of NCP in this study focus solely on the bloom period and are therefore comparable in timing to satellite-based NCP estimates. The amount of organic carbon respired in winter should to be assessed in future work, as annual NCP estimated from one float in the Ross Sea indicated a near balance between positive spring bloom NCP offset by subsequent winter remineralization (Briggs et al., 2018).

Conclusions

The recent availability of under ice observations throughout the SSIZ has enabled examination of timing, mechanisms of bloom onset, and NCP associated with SSIZ blooms. By constraining the onset of biological production with nutrient data and matching this timing to estimates of sea ice breakup we find that biological production resulting in significant nutrient and carbon uptake in surface waters is not observed prior to initial sea ice breakup regardless of latitude or incoming surface radiation. NCP estimates reveal that the majority of bNCP occurs as sea ice is actively melting, and the highest bNCP occurs in regions with potentially increased micronutrient delivery due to topographic features. This provides the first in-situ evidence that the SSIZ may contribute a far larger proportion of total Southern Ocean carbon export than had previously been observed, consistent with a few modeling studies.

The onset of phytoplankton biomass increase and nutrient drawdown occurs as sea ice first breaks up (~October), considerably before blooms have previously been observed by satellite ocean color and field surveys (~Jan-Feb). The lack of correlation between higher bNCP and cumulative light availability or duration of a shallow mixed layer provides new insight suggesting micronutrient availability, community composition, and/or grazing pressure are more important factors influencing SSIZ blooms and associated carbon export. The timing of sea ice breakup can explain a portion of the overall variance in total bNCP, which we suggest may result from earlier sea ice breakup leading to greater decoupling of phytoplankton growth and grazing loss. Our results indicate that future changes in sea ice seasonality, consolidation, and extent will all affect the timing and magnitude of SSIZ phytoplankton blooms and biogeochemistry, yet these changes are not likely to be predicted based on changes in light availability alone.

Open Research: Data and Code Availability

Float data used was downloaded from the SOCCOM project. The May 2021 quarterly snapshot dataset is used in this analysis and is available at doi.org/10.6075/J0T43SZG.

Mean surface downward short-wave radiation flux was downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store https://doi.org/10.24381/cds.f17050d7 (Hersbach et al., 2020). The results contain modified Copernicus Climate Change Service information 2020. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4 (G02202) is available for download at https://doi.org/10.7265/efmz-2t65.

The International Bathymetric Chart of the Southern Ocean v2 digital bathymetric model is available for download at https://doi.org/10.1594/PANGAEA.937574.

Code used for the analysis is available for download at https://doi.org/10.5281/zenodo.7192130.

Author Contributions

S. McClish conducted the data analysis and writing of the manuscript. S. Bushinsky contributed to the data analysis and manuscript preparation.

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References

Ardyna, M., Claustre, H., Sallée, J. B., D'Ovidio, F., Gentili, B., van Dijken, G., et al. (2017). Delineating environmental control of phytoplankton biomass and phenology in the Southern Ocean. *Geophysical Research Letters*, *44*(10), 5016–5024. https://doi.org/10.1002/2016GL072428

Arrigo, K. R., van Dijken, G. L., & Bushinsky, S. (2008). Primary production in the Southern Ocean, 1997-2006. *Journal of Geophysical Research*, *113*(C08004), doi:10.1029/2007JC004551. https://doi.org/10.1029/2007JC004551

Arteaga, L., Haëntjens, N., Boss, E., Johnson, K. S., & Sarmiento, J. L. (2018). Assessment of Export Efficiency Equations in the Southern Ocean Applied to Satellite-Based Net Primary Production. *Journal of Geophysical Research: Oceans*, *123*(4), 2945–2964. https://doi.org/10.1002/2018JC013787

Arteaga, L. A., Pahlow, M., Bushinsky, S. M., & Sarmiento, J. L. (2019). Nutrient Controls on Export Production in the Southern Ocean. *Global Biogeochemical Cycles*, *33*(8), 942–956. https://doi.org/10.1029/2019GB006236

Arteaga, L. A., Boss, E., Behrenfeld, M. J., Westberry, T. K., & Sarmiento, J. L. (2020). Seasonal modulation of phytoplankton biomass in the Southern Ocean. *Nature Communications*. https://doi.org/10.1038/s41467-020-19157-2

Assmy, P., Fernández-Méndez, M., Duarte, P., Meyer, A., Randelhoff, A., Mundy, C. J., et al. (2017). Leads in Arctic pack ice enable early phytoplankton blooms below snow-covered sea ice. *Scientific Reports*, *7*(September 2016), 1–9. https://doi.org/10.1038/srep40850

von Berg, L., Prend, C. J., Campbell, E. C., Mazloff, M. R., Talley, L. D., & Gille, S. T. (2020). Weddell Sea Phytoplankton Blooms Modulated by Sea Ice Variability and Polynya Formation. *Geophysical Research Letters*, *47*(11), 1–12. https://doi.org/10.1029/2020GL087954

Bersch, M., Becker, G. A., Frey, H., & Koltermann, K. P. (1992). Topographic effects of the Maud Rise on the stratification and circulation of the Weddell Gyre. *Deep Sea Research Part A, Oceanographic Research Papers*, *39*(2), 303–331. https://doi.org/10.1016/0198-0149(92)90111-6

Bisson, K. M., & Cael, B. B. (2021). How Are Under Ice Phytoplankton Related to Sea Ice in the Southern Ocean? *Geophysical Research Letters*, *48*(21), 1–9. https://doi.org/10.1029/2021gl095051

Brierley, A. S., Fernandes, P. G., Brandon, M. A., Armstrong, F., Millard, N. W., McPhail, S. D., et al. (2022). *Antarctic Krill Under Sea Ice:Elevated Abundance in aNarrow Band Just South ofIce Edge*. *13. G. R. Sarson, Philos. Trans. R. Soc. London Ser. A* (Vol. 24). Academic Press. Retrieved from https://www.science.org

Briggs, E. M., Martz, T. R., Talley, L. D., Mazloff, M. R., & Johnson, K. S. (2018). Physical and Biological Drivers of Biogeochemical Tracers Within the Seasonal Sea Ice Zone of the Southern Ocean From Profiling Floats. *Journal of Geophysical Research: Oceans*, *123*(2), 746–758. https://doi.org/10.1002/2017JC012846

Buesseler, K. O., Barber, R. T., Dickson, M.-L., Hiscock, M. R., Moore, J. K., & Sambrotto, R. (2003). The effect of marginal ice-edge dynamics on production and export in the Southern Ocean along 1701W. *Deep-Sea Research II*, *50*, 579–603. https://doi.org/10.1016/S0967-0645(02)00585-4

Bushinsky, S. M., & Emerson, S. R. (2018). Biological and physical controls on the oxygen cycle in the Kuroshio Extension from an array of profiling floats. *Deep-Sea Research Part*

I: Oceanographic Research Papers, *141*(January), 51–70. https://doi.org/10.1016/j.dsr.2018.09.005

Campbell, E. C., Wilson, E. A., Moore, G. W. K., Riser, S. C., Brayton, C. E., Mazloff, M. R., & Talley, L. D. (2019). Antarctic offshore polynyas linked to Southern Hemisphere climate anomalies. *Nature*, *570*(7761), 319–325. https://doi.org/10.1038/s41586-019-1294-0

Croot, P. L., Andersson, K., Öztürk, M., & Turner, D. R. (2004). The distribution and speciation of iron along 6°E in the Southern Ocean. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *51*(22–24), 2857–2879. https://doi.org/10.1016/j.dsr2.2003.10.012

Davidson, A. T., Scott, F. J., Nash, G. v., Wright, S. W., & Raymond, B. (2010). Physical and biological control of protistan community composition, distribution and abundance in the seasonal ice zone of the Southern Ocean between 30 and 80°E. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *57*(9–10), 828–848. https://doi.org/10.1016/j.dsr2.2009.02.011

Dorschel, B., Hehemann, L., Viquerat, S., Warnke, F., Dreutter, S., Tenberge, Y. S., et al. (2022). The International Bathymetric Chart of the Southern Ocean Version 2. *Scientific Data*, *9*(1). https://doi.org/10.1038/s41597-022-01366-7

Fitch, D. T., & Moore, J. K. (2007). Wind speed influence on phytoplankton bloom dynamics in the Southern Ocean Marginal Ice Zone. *Journal of Geophysical Research: Oceans*, *112*(8), 1–13. https://doi.org/10.1029/2006JC004061

GranÍi, E., Granéli, W., Rabbani, M. M., Daugbjerg, N., Fransz, G., Roudy, J. C., & Alder, V. A. (1993). The influence of copepod and krill grazing on the species composition of phytoplankton communities from the Scotia Weddell sea - An experimental approach. *Polar Biology*, *13*(3), 201–213. https://doi.org/10.1007/BF00238930

Haberman, K. L., Quetin, L. B., & Ross, R. M. (2003). Diet of the Antarctic krill (Euphausia superba Dana): I. Comparisons of grazing on Phaeocystis antarctica (Karsten) and Thalassiosira antarctica (Comber). *Journal of Experimental Marine Biology and Ecology*, *283*(1–2), 79–95. https://doi.org/10.1016/S0022-0981(02)00466-5

Hague, M., & Vichi, M. (2020). Southern Ocean BGC-Argo Detect Under Ice Phytoplankton Growth Before Sea Ice Retreat. *Biogeosciences Discussions*, 1–22. https://doi.org/10.5194/bg-2020-257

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Horvat, C., Bisson, K., Seabrook, S., Cristi, A., & Matthes, L. C. (2022). Evidence of phytoplankton blooms under Antarctic sea ice. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.942799

Ishii, M., Inoue, H. Y., & Matsueda, H. (2002). Net community production in the marginal ice zone and its importance for the variability of the oceanic pCO2 in the Southern Ocean south of Australia. *Deep Sea Research Part II: Topical Studies in Oceanography*, *49*(9–10), 1691–1706. https://doi.org/10.1016/S0967-0645(02)00007-3

Johnson, K. S., Plant, J. N., Dunne, J. P., Talley, L. D., & Sarmiento, J. L. (2017). Annual nitrate drawdown observed by SOCCOM profiling floats and the relationship to annual net community production. *Journal of Geophysical Research: Oceans*, *122*(8), 6668–6683. https://doi.org/10.1002/2017JC012839

Johnson, K. S., Plant, J. N., Coletti, L. J., Jannasch, H. W., Sakamoto, C. M., Riser, S. C., et al. (2017). Biogeochemical sensor performance in the SOCCOM profiling float array. *Journal* *of Geophysical Research: Oceans*, *122*(8), 6416–6436. https://doi.org/10.1002/2017JC012838

Joy-Warren, H. L., van Dijken, G. L., Alderkamp, A. C., Leventer, A., Lewis, K. M., Selz, V., et al. (2019). Light Is the Primary Driver of Early Season Phytoplankton Production Along the Western Antarctic Peninsula. *Journal of Geophysical Research: Oceans*, *124*(11), 7375–7399. https://doi.org/10.1029/2019JC015295

Lancelot, C., Billen, G., Veth, C., Becquevort, S., & Mathot, S. (1991). Modelling carbon cycling through phytoplankton and microbes in the Scotia—Weddell Sea area during sea ice retreat. *Marine Chemistry*, *35*(1–4), 305–324. https://doi.org/10.1016/S0304-4203(09)90024-X

Lannuzel, D., Vancoppenolle, M., Merwe, P. van der, Jong, J. de, Meiners, K. M., Nishioka, et al. (2016). Iron in sea ice: Review and new insights. https://doi.org/10.12952/journal.elementa.000130

Lannuzel, Delphine, Schoemann, V., de Jong, J., Chou, L., Delille, B., Becquevort, S., & Tison, J. L. (2008). Iron study during a time series in the western Weddell pack ice. *Marine Chemistry*, *108*(1–2), 85–95. https://doi.org/10.1016/j.marchem.2007.10.006

Laufkötter, C., Stern, A. A., John, J. G., Stock, C. A., & Dunne, J. P. (2018). Glacial Iron Sources Stimulate the Southern Ocean Carbon Cycle. *Geophysical Research Letters*, *45*(24), 13,377-13,385. https://doi.org/10.1029/2018GL079797

Li, Z., Lozier, M. S., & Cassar, N. (2021). Linking Southern Ocean Mixed-Layer Dynamics to Net Community Production on Various Timescales. *Journal of Geophysical Research: Oceans*, *126*(10), 1–14. https://doi.org/10.1029/2021JC017537

Lin, Y., Moreno, C., Marchetti, A., Ducklow, H., Schofield, O., Delage, E., et al. (2021). Decline in plankton diversity and carbon flux with reduced sea ice extent along the Western Antarctic Peninsula. *Nature Communications*, *12*(1), 1–9. https://doi.org/10.1038/s41467-021-25235-w

Loeb, V. J., & Santora, J. A. (2015). Climate variability and spatiotemporal dynamics of five Southern Ocean krill species. *Progress in Oceanography*, *134*, 93–122. https://doi.org/10.1016/j.pocean.2015.01.002

Maccready, P., & Quay, P. (2001). *Biological export flux in the Southern Ocean estimated from a climatological nitrate budget*. *Deep-Sea Research II* (Vol. 48).

Mengesha, S., Dehairs, F., Fiala, M., Elskens, M., & Goeyens, L. (1998). Seasonal variation of phytoplankton community structure and nitrogen uptake regime in the Indian Sector of the Southern Ocean. *Polar Biology*, *20*(4), 259–272. https://doi.org/10.1007/s003000050302

Moore, J. K., & Abbott, M. R. (2000). Phytoplankton chlorophyll distributions and primary production in the Southern Ocean. *Journal of Geophysical Research: Oceans*, *105*(C12), 28709–28722. https://doi.org/10.1029/1999jc000043

Moreau, S., Boyd, P. W., & Strutton, P. G. (2020). Remote assessment of the fate of phytoplankton in the Southern Ocean sea-ice zone. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-16931-0

Nissen, C., & Vogt, M. (2020). Factors controlling the competition between <i>Phaeocystis</i> and diatoms in the Southern Ocean. *Biogeosciences Discussions*, (January), 1–39.

Park, J., Kuzminov, F. I., Bailleul, B., Yang, E. J., Lee, S. H., Falkowski, P. G., & Gorbunov, M. Y. (2017). Light availability rather than Fe controls the magnitude of massive phytoplankton bloom in the Amundsen Sea polynyas, Antarctica. *Limnology and Oceanography*, *62*(5), 2260–2276. https://doi.org/10.1002/lno.10565

Parkinson, C. L. (2019). A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(29), 14414–14423. https://doi.org/10.1073/pnas.1906556116

Person, R., Vancoppenolle, M., Aumont, O., & Malsang, M. (2021). Continental and Sea Ice Iron Sources Fertilize the Southern Ocean in Synergy. *Geophysical Research Letters*, *48*(23), 1–9. https://doi.org/10.1029/2021GL094761

Ryan-Keogh, T. J., & Smith, W. O. (2021). Temporal patterns of iron limitation in the Ross Sea as determined from chlorophyll fluorescence. *Journal of Marine Systems*, *215*, 103500. https://doi.org/10.1016/j.jmarsys.2020.103500

Schallenberg, C., Strzepek, R. F., Bestley, S., Bozena, W., & Trull, and T. W. (2022). Iron limitation drives the globally extreme Fluorescence/Chlorophyll ratios of the Southern Ocean. *Geophysical Research Letters*, *49*(12). https://doi.org/doi: 10.1029/2021GL097616

Schlitzer, R. (2002). Carbon export fluxes in the Southern Ocean: Results from inverse modeling and comparison with satellite-based estimates. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *49*(9–10), 1623–1644. https://doi.org/10.1016/S0967-0645(02)00004-8

Smith, W. O., & Nelson, D. M. (1986). Importance of ice edge phytoplankton production in the Southern Ocean. *Bioscience*, *36*(4), 251–257. https://doi.org/10.2307/1310215

Smith, Walker O., & Comiso, J. C. (2008). Influence of sea ice on primary production in the Southern Ocean: A satellite perspective. *Journal of Geophysical Research: Oceans*, *113*(5), 1–19. https://doi.org/10.1029/2007JC004251

Smith, Walker O., & Nelson, D. M. (1985). Phytoplankton bloom produced by a receding ice edge in the ross sea: Spatial coherence with the density field. *Science*, *227*(4683), 163–166. https://doi.org/10.1126/science.227.4683.163

Tagliabue, A., Mtshali, T., Aumont, O., Bowie, A. R., Klunder, M. B., Roychoudhury, A. N., & Swart, S. (2012). A global compilation of dissolved iron measurements: Focus on distributions and processes in the Southern Ocean. *Biogeosciences*, *9*(6), 2333–2349. https://doi.org/10.5194/bg-9-2333-2012

Tamsitt, V., Drake, H. F., Morrison, A. K., Talley, L. D., Dufour, C. O., Gray, A. R., et al. (2017). Spiraling pathways of global deep waters to the surface of the Southern Ocean. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-00197-0

Taylor, M. H., Losch, M., & Bracher, A. (2013a). On the drivers of phytoplankton blooms in the Antarctic marginal ice zone: A modeling approach. *Journal of Geophysical Research: Oceans*, *118*(1), 63–75. https://doi.org/10.1029/2012JC008418

Taylor, M. H., Losch, M., & Bracher, A. (2013b). On the drivers of phytoplankton blooms in the Antarctic marginal ice zone: A modeling approach. *Journal of Geophysical Research: Oceans*, *118*(1), 63–75. https://doi.org/10.1029/2012JC008418

Uchida, T., Balwada, D., Abernathey, R., Prend, C. J., Boss, E., & Gille, S. T. (2019). Southern Ocean Phytoplankton Blooms Observed by Biogeochemical Floats. *Journal of Geophysical Research: Oceans*, *124*(11), 7328–7343. https://doi.org/10.1029/2019JC015355

Viljoen, J. J., Philibert, R., van Horsten, N., Mtshali, T., Roychoudhury, A. N., Thomalla, S., & Fietz, S. (2018). Phytoplankton response in growth, photophysiology and community structure to iron and light in the Polar Frontal Zone and Antarctic waters. *Deep-Sea*

Research Part I: Oceanographic Research Papers, *141*(May), 118–129. https://doi.org/10.1016/j.dsr.2018.09.006

Wang, J., Luo, H., Yang, Q., Liu, J., Yu, L., Shi, Q., & Han, B. (2022). An Unprecedented Record Low Antarctic Sea-ice Extent during Austral Summer 2022. *Advances in Atmospheric Sciences*. https://doi.org/10.1007/s00376-022-2087-1

Wright, S. W., & van den Enden, R. L. (2000). Phytoplankton community structure and stocks in the East Antarctic marginal ice zone (BROKE survey, January-March 1996) determined by CHEMTAX analysis of HPLC pigment signatures. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *47*(12–13), 2363–2400. https://doi.org/10.1016/S0967-0645(00)00029-1

References From the Supporting Information

Arteaga, L. A., Pahlow, M., Bushinsky, S. M., & Sarmiento, J. L. (2019). Nutrient Controls on Export Production in the Southern Ocean. *Global Biogeochemical Cycles*, *33*(8), 942–956. https://doi.org/10.1029/2019GB006236

Behrenfeld, M. J., & Boss, E. S. (2018). Student's tutorial on bloom hypotheses in the context of phytoplankton annual cycles. *Global Change Biology*. Blackwell Publishing Ltd. https://doi.org/10.1111/gcb.13858

de Boyer Montégut, C. (2004). Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology. *Journal of Geophysical Research*, *109*(C12), C12003. https://doi.org/10.1029/2004JC002378

Britton, C. M., & Dodd, J. D. (1976). Relationships of photosynthetically active radiation and shortwave. *Agricultural Meteorology* (Vol. 17).

Castellani, G., Schaafsma, F. L., Arndt, S., Lange, B. A., Peeken, I., Ehrlich, J., et al. (2020). Large-Scale Variability of Physical and Biological Sea-Ice Properties in Polar Oceans. *Frontiers in Marine Science*, *7*(August), 1–22. https://doi.org/10.3389/fmars.2020.00536

Elipot, S., & Gille, S. T. (2009). *Ekman layers in the Southern Ocean: spectral models and observations, vertical viscosity and boundary layer depth*. *Ocean Sci* (Vol. 5). Retrieved from www.ocean-sci.net/5/115/2009/

Graff, J. R., Westberry, T. K., Milligan, A. J., Brown, M. B., Dall'Olmo, G., van Dongen-Vogels, V., et al. (2015). Analytical phytoplankton carbon measurements spanning diverse ecosystems. *Deep-Sea Research Part I: Oceanographic Research Papers*, *102*, 16–25. https://doi.org/10.1016/j.dsr.2015.04.006

Haëntjens, N., Boss, E., & Talley, L. D. (2017). Revisiting Ocean Color algorithms for chlorophyll a and particulate organic carbon in the Southern Ocean using biogeochemical floats. *Journal of Geophysical Research: Oceans*, *122*(8), 6583–6593. https://doi.org/10.1002/2017JC012844

Hedges, J. I., Baldock, J. A., Gélinas, Y., Lee, C., Peterson, M. L., & Wakeham, S. G. (2002). *The biochemical and elemental compositions of marine plankton: A NMR perspective* (pp. 47–63). https://doi.org/10.1016/S0304-4203(02)00009-9

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Ishii, M., Inoue, H. Y., & Matsueda, H. (2002). Net community production in the marginal ice zone and its importance for the variability of the oceanic pCO2 in the Southern Ocean south of Australia. *Deep Sea Research Part II: Topical Studies in Oceanography*, *49*(9–10), 1691–1706. https://doi.org/10.1016/S0967-0645(02)00007-3

Maurer, T. L., Plant, J. N., & Johnson, K. S. (2021). Delayed-Mode Quality Control of Oxygen, Nitrate, and pH Data on SOCCOM Biogeochemical Profiling Floats. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.683207

Meier, W. N. , F. F. A. K. W. and J. S. S. (2021). NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4 . Boulder, Colorado USA: National Snow and Ice Data Center.

Morel, A., Huot, Y., Gentili, B., Werdell, P. J., Hooker, S. B., & Franz, B. A. (2007). Examining the consistency of products derived from various ocean color sensors in open ocean (Case 1) waters in the perspective of a multi-sensor approach, *111*, 69–88. https://doi.org/10.1016/j.rse.2007.03.012

Papadimitriou, S., Kennedy, H., Norman, L., Kennedy, D. P., Dieckmann, G. S., & Thomas, D. N. (2012). The effect of biological activity, CaCO3 mineral dynamics, and CO2 degassing in the inorganic carbon cycle in sea ice in late winter-early spring in the Weddell Sea, Antarctica. *Journal of Geophysical Research: Oceans*, *117*(8), 1–12. https://doi.org/10.1029/2012JC008058

Verdy, A., & Mazloff, M. R. (2017). A data assimilating model for estimating Southern Ocean biogeochemistry. *Journal of Geophysical Research: Oceans*, *122*(9), 6968–6988. https://doi.org/10.1002/2016JC012650

Westberry, T., Behrenfeld, M. J., Siegel, D. A., & Boss, E. (2008). Carbon-based primary productivity modeling with vertically resolved photoacclimation. *Global Biogeochemical Cycles*, *22*(2). https://doi.org/10.1029/2007GB003078

Figure 1. **Mean float positions during spring bloom and associated net community production**. Ocean bathymetry (International Bathymetric chart of the Southern Ocean (IBSCO) version 2(Dorschel et al., 2022) overlayed with circular markers indicating float positions during spring nitrate minimum. Marker colors correspond to the magnitude of bNCP calculated from integrated upper ocean nitrate changes during each spring bloom.

Figure 2. Seasonal relationships between mixed layer properties and sea ice. Example float (WMO 5904471) winter to summer timeseries with mixed layer mean oxygen (orange), nitrate (red), phytoplankton carbon (blue), and chlorophyll (green) concentrations **(a.)** and mixed layer mean salinity, mixed layer depth, mixed layer median light **(b.)** with satellite SIC in shaded blue for both (SIC scale on bottom panel only). Symbols indicate the day of $GI_{Chl,Cp}$ or when nitrate, oxygen, or salinity thresholds are exceeded. **(c.)** Relationships between date of sea ice breakup relative to nitrate decrease and GI_{Cp} date. The day of year of nitrate decrease (red circles) and GI_{Cp} (blue triangles) vs. sea ice breakup day for all 64 float seasons analyzed. Colored lines indicate 20-day bin means ± 1 standard deviation. Symbols lying above the solid gold 1:1 line in the unshaded region indicate mixed layer nitrate decrease and GI_{Cp} after sea ice breakup.

Figure 3. Relationship between calculated NCP and sea ice cover. **a)** Average cumulative fraction of total bNCP for all floats (solid line) with respect to total sea ice retreat (dashed vertical

line) and ± 1 std deviation (shaded region). **b)** Probability histogram of daily NCP rates 50 days before (green) and 50 days after (pink) total sea ice retreat date.

Figure 4. Relationship between NCP and timing of sea ice breakup. (**a.)** bNCP is negatively correlated (red line, P<.001) with date of sea ice breakup. (**b.)** Differences between 10-day binned mean daily NCP (purple line) and light availability (blue line) for early sea ice breakup and late sea ice breakup observations (before mid-October, day 290) minus late (after early November, day 310). Floats with observations of early sea ice breakup had higher daily NCP prior to total sea ice retreat despite lower light availability prior to total sea ice retreat.