Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL113717

Observation-Based Estimate of Net Community Production in Antarctic Sea Ice

Laura A. Dalman[1,2], Klaus M. Meiners[2,3,4], David N. Thomas[5], Florian Deman[6], Sophie Bestley[1,2,4], Sébastien Moreau[7], Kevin R. Arrigo[8], Karley Campbell[9], Matthew Corkill[1], Stefano Cozzi[10], Bruno Delille[11], Agneta Fransson[7], Alexander D. Fraser[1,2], Sian F. Henley[12], Julie Janssens[13], Delphine Lannuzel[1,2,4], David R. Munro[14,15], Daiki Nomura[16], Louisa Norman[17], Stathys Papadimitriou[18], Christina Schallenberg[2,19], Jean-Louis Tison[20], Martin Vancoppenolle[21], Pier van der Merwe[1], and François Fripiat[20]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia, [2]Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia, [3]Australian Antarctic Division, Department of Climate Change, Energy, the Environment and Water, Kingston, TAS, Australia, [4]Australian Centre for Excellence in Antarctic Science, University of Tasmania, Hobart, TAS, Australia, [5]Faculty of Biological & Environmental Sciences, University of Helsinki, Helsinki, Finland, [6]Analytical, Environmental, and Geo-Chemistry Department, Vrije Universiteit Brussel, Brussels, Belgium, [7]Norwegian Polar Institute, Tromsø, Norway, [8]Department of Earth System Science, Stanford University, Stanford, CA, USA, [9]Department of Arctic and Marine Biology, UiT the Arctic University of Norway, Tromsø, Norway, [10]CNR-ISMAR Istituto di Scienze Marine, Trieste, Italy, [11]Chemical Oceanography Unit, FOCUS, University of Liège, Liège, Belgium, [12]School of GeoSciences, University of Edinburgh, Edinburgh, UK, [13]CSIRO Environment, CSIRO National Collections and Marine Infrastructure, Hobart, TAS, Australia, [14]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA, [15]National Oceanic and Atmospheric Administration, Global Monitoring Laboratory, Boulder, CO, USA, [16]Hokkaido University, Hakodate, Japan, [17]School of Environmental Sciences, University of Liverpool, Liverpool, UK, [18]National Oceanography Centre, Southampton, UK, [19]CSIRO Environment, Hobart, TAS, Australia, [20]Department of Geosciences, Environment and Society, Université Libre de Bruxelles, Brussels, Belgium, [21]Sorbonne Université, LOCEAN-IPSL, CNRS/IRD/MNHN, Paris, France

Key Points:

- Based on depth-integrated organic carbon from 362 sea-ice cores, net community production of Antarctic ice algae is 26.8–32.9 Tg C yr^{-1}
- Sea-ice net community production is estimated to contribute at least 15%–18% to primary production in the sea-ice zone
- Surface, internal and bottom-ice communities contributed 33.3%, 30.6%, and 35.0%, respectively, to total depth-integrated organic carbon

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

L. A. Dalman,
laura.dalman@utas.edu.au

Citation:

Dalman, L. A., Meiners, K. M., Thomas, D. N., Deman, F., Bestley, S., Moreau, S., et al. (2025). Observation-based estimate of net community production in Antarctic sea ice. *Geophysical Research Letters*, *52*, e2024GL113717. https://doi.org/10.1029/2024GL113717

Received 10 DEC 2024
Accepted 27 FEB 2025

Abstract Antarctic sea ice is one of the largest biomes on Earth providing a critical habitat for ice algae. Measurements of primary production in Antarctic sea ice remain scarce and an observation-based estimate of primary production has not been revisited in over 30 years. We fill this knowledge gap by presenting a newly compiled circumpolar data set of particulate and dissolved organic carbon from 362 ice cores, sampled between 1989 and 2019, to estimate sea-ice net community production using a carbon biomass accumulation approach. Our estimate of 26.8–32.9 Tg C yr^{-1} accounts for at least 15%–18% of the total primary production in the Antarctic sea-ice zone, less than a previous observation-based estimate (63–70 Tg C yr^{-1}) and consistent with recent modeled estimates. The results underpin the ecological significance of sea-ice algae as an early season resource for pelagic food webs.

Plain Language Summary In the Southern Ocean, sea ice provides a habitat for sea-ice algae. These algae play an important role in Southern Ocean food webs by converting carbon dioxide into biomass via photosynthesis—a process known as primary production. Both simplistic calculations and elaborate production models suggest that sea-ice algae contribute a small but significant portion of Southern Ocean primary production in the sea-ice zone. However, direct measurements of primary production are rare, and observation-based estimates are limited. Here, we compiled a large data set of organic carbon in Antarctic sea ice, sampled between 1989 and 2019, to provide an updated estimate (reported as net community production) of how much organic carbon Antarctic sea ice algae are producing. These results show that sea-ice algae contribute at least 15%–18% of the total primary production in the Antarctic sea-ice zone. Future projections of algal activity in the Southern Ocean and its sea ice should take these results into account.

1. Introduction

The Antarctic sea-ice zone (i.e., the region of ocean that is seasonally covered by sea ice; Arrigo et al., 2008; Legendre et al., 1992; Saenz & Arrigo, 2014) in the Southern Ocean is where algae living within the ice can contribute significantly to overall primary production, particularly during the winter-to-spring transition (Arrigo

& Thomas, 2004). These microorganisms are a vital source of food for a diverse food web, including the abundant and commercially important Antarctic krill (*Euphausia superba*; Swadling et al., 2023). Sea-ice algae also provide other ecosystem services (Steiner et al., 2021) and contribute to the uptake of atmospheric carbon dioxide (CO_2) through photosynthesis (Campbell et al., 2017; Delille et al., 2014; Fransson et al., 2011; Henley et al., 2012). Thriving in liquid brine inclusions encased within sea ice, ice algae are adapted to extreme and variable conditions, including low light levels, cold temperatures, high brine salinities, fluctuating nutrient concentrations, and space constraints (Jones et al., 2022; Lim et al., 2023; Meiners et al., 2012).

During the winter-to-spring transition, ice algal communities initially face light limitation, with snow cover exerting substantial control through high albedo and low transmittance (Arndt et al., 2017; Campbell et al., 2015; van Leeuwe et al., 2022). As insolation increases, ice algal growth rapidly increases provided nutrients are sufficiently available (Fripiat et al., 2017; Henley et al., 2023; Lannuzel et al., 2016; van Leeuwe et al., 2022). Changes in snow and ice thickness and other properties such as temperature and salinity could significantly affect the timing (Stroeve et al., 2024), duration and magnitude (Arrigo & Sullivan, 1992; Vancoppenolle & Tedesco, 2017) of ice algal productivity as they control light, nutrient availability and algal physiology. A comprehensive understanding of sea-ice bio-physical coupling is essential to understand the seasonal development of ice algae and their contribution to Southern Ocean primary production.

The contribution of sea-ice algae to primary production depends on the reference used for the region. Literature-based values range over 10%–28% for the sea-ice zone and <1% if ice-free waters up to 50°S are included (1,300 to 1,949 Tg C yr^{-1}; Johnson et al., 2017; Arrigo et al., 2008). However, the ecological importance of ice algae surpasses these numbers. Ice algal production serves as a key energy (dietary carbon) conduit to higher trophic levels, contributing to the diets of Antarctic krill (larval and juvenile krill, ~88%; Kohlbach et al., 2017), sympagic amphipods (e.g., *Eusirus laticarpus*, 54%–67%), salps (e.g., *Salpa thompsoni*, 8%–40%), and copepods (e.g., *Calanus propinquus*, <50%; Kohlbach et al., 2018). Their presence is especially crucial during a temporal window when ice-algal production increases while water column production remains low, highlighting their importance notwithstanding their relatively low contribution to overall primary production (Arrigo et al., 2008; Veytia et al., 2021).

Despite ice algae's biogeochemical significance, measurements of primary production within Antarctic sea ice remain relatively scarce, which has limited knowledge on overall magnitude, spatial distribution, and temporal variability of sea-ice algal production. Intercomparison is complicated by varied approaches to estimate production, and whether they account for algal respiration (Net primary production, NPP), as well as grazing (Net Community Production, NCP), or rather focus on total carbon fixation independent of respiration (Gross Primary Production, GPP). Previous observation-based estimates using biomass accumulation, representing an estimate of NCP, have been derived but from a very limited number of ice cores (e.g., the estimate of 63–70 Tg C yr^{-1} from Legendre et al., 1992). To compensate for the lack of observations, biogeochemical models have been used to estimate sea-ice productivity, retrieving more conservative estimates of sea-ice algal production, primarily GPP, within the range of 15.5–35.7 Tg C yr^{-1} (Arrigo et al., 1997; Jeffery et al., 2020; Saenz & Arrigo, 2014).

In this study, we compiled a large data set of organic carbon measurements from sea-ice cores to provide an updated observation-based estimate of NCP (i.e., photosynthesis minus respiration) using a biomass accumulation approach adapted from Legendre et al. (1992). Here, production estimates are derived from in-situ measurements of particulate and dissolved organic carbon (POC, DOC), which are vertically integrated across the entire ice thickness. Using this data set, we estimate a daily rate of biomass change/production based on a Generalized Additive Model (GAM). The seasonal and vertical biogenic carbon distributions are described while also examining potential drivers of seasonal trends in ice algal NCP.

2. Materials and Methods

2.1. Data Set Compilation

The calculation of NCP from organic carbon is based on a new compilation of Antarctic sea-ice POC and DOC data. This compilation comprises 2,340 ice-core sections from 362 ice cores, which were collated from peer-reviewed publications, reports, and unpublished measurements from 20 voyages in Antarctic pack ice between 1989 and 2019. Pack ice refers to sea ice that drifts with ocean currents and winds. We focus on organic carbon from pack ice, which accounts for >80% of the total sea-ice coverage (Fraser et al., 2012), and upscale it to the entire sea-ice zone of the Southern Ocean (including landfast sea ice which is attached to the coast or between icebergs and remains stationary). Landfast sea ice (the remaining 4%–19% of the sea-ice extent) organic carbon production is typically higher than for pack ice, and our estimate is therefore conservative (Arrigo, 2017; Arrigo et al., 1995; Fraser et al., 2023; Meiners et al., 2018). The locations of the compiled ice cores are shown in Figure 1a, and a list of the campaigns and data sets can be found in Table S1 and Figure S1 in Supporting Information S1.

There are inevitable spatial and temporal biases in the data set. The data predominantly come from the Ross (39%) and Atlantic (35%) sectors, followed by the Bellingshausen/Amundsen sector (13%), and the Pacific sector (12%), with none from the Indian sector. Ice cores were primarily collected in spring (n = 171; 47%), with 110 from summer (30%), 65 from autumn (18%) and 16 from winter (4%, Figure 1b). Similar to sea-ice and snow thickness estimated from a compilation focusing on physical parameters by Worby et al. (2008; 0.87 ± 0.91 m and 0.16 ± 0.20 m, respectively; n = 23,373), the average ice thickness in our compilation was 0.82 ± 0.68 m ($n = 362$) and average snow depth was 0.18 ± 0.19 m ($n = 257$). Despite fewer data in winter, the data set captures the evolution and seasonal growth cycle of Antarctic sea ice (Figure S2 in Supporting Information S1). Environmental data retrieval and processing are detailed in Text S1 in Supporting Information S1.

2.2. Net Community Production Estimates

Our NCP estimates use proxies for biomass (i.e., POC and DOC), relying on inherent assumptions that a majority of carbon is sourced from primary production within the sea ice. A majority of the TOC in sea ice is often generated through in situ algal photosynthesis, and remain trapped in the brine channel network (Legendre et al., 1992). Several loss and gain factors in the system affect total carbon concentration (Meiners & Michel, 2017; Swadling et al., 2023), and thus the final estimate of NCP. A portion of organic carbon in sea ice is removed through grazing and export, in both POC and DOC forms; it is excluded from our NCP estimate. In addition, some biomass is allochthonous (i.e., introduced into sea ice through physical entrapment of particles during ice formation, sheltering animals and the exchange of brine with underlying seawater and its own organic matter; Spindler, 1994), which could result in overestimation of sea ice NCP, especially in autumn and winter. Contrary to the Arctic Ocean, we expect no riverine inputs that could contribute to the build up of organic carbon in sea ice in the Southern Ocean. While these factors introduce uncertainty into the derived estimates of NCP, we nonetheless take the following approach to use it as a proxy for productivity as in-situ measurements of production are limited to a very small number of studies (~10 studies summarized in Arrigo (2017)), and impossible to upscale at the scale of Antarctic sea ice.

For input for our NCP estimate, the integrated total organic carbon ($\mathrm{TOC_i}$) in sea ice was used, which is the sum of depth-integrated POC and DOC for each ice core. A GAM with a cyclic cubic regression spline was fitted to the $\mathrm{TOC_i}$ data to predict daily $\mathrm{TOC_i}$ and rates of change in $\mathrm{TOC_i}$. The daily change in $\mathrm{TOC_i}$ during the accumulation period was then multiplied by the median sea-ice area, calculated over a 30-year period, for each corresponding day of a median annual cycle (1989–2019; Figure 1). Carbon accumulation over the production period, defined as the period between minimum and maximum $\mathrm{TOC_i}$ as determined by the GAM, represents our conservative estimate of annual NCP in sea ice. Only positive daily changes in TOC were considered to focus on the productive phase when biomass is accumulating (Equation 1). Negative daily changes in TOC observed after the productive period likely indicate losses due to processes such as respiration, export and grazing.

$$\mathrm{NCP}\left(\mathrm{Tg\ C\ yr^{-1}}\right) = \sum_{d_{\min}}^{d_{\max}} \left(\Delta\mathrm{TOC_i}(d) \times \frac{A_i(d)}{\Delta t}\right) \text{ for } \Delta\mathrm{TOC_i} > 0 \tag{1}$$

where d represents day, A_i represents sea ice area and t is time.

For ice cores with missing (not collected) POC or DOC values, we assumed a ratio of POC to DOC to estimate the missing quantity and generate TOC. This ratio was calculated by taking the overall median (or seasonal) value of the ratios between POC and DOC from ice cores where both were available.

We used four approaches to estimate NCP from $\mathrm{TOC_i}$ data: (a) TOC only (no addition of estimated values), (b) TOC plus estimates of DOC where DOC was missing (n = 161 additional ice cores; $\mathrm{TOC_{DR}}$, DOC/POC ratio = 0.79 ± 1.63), (c) TOC plus estimates of DOC and POC (n = 36 additional ice cores; $\mathrm{TOC_{DPR}}$, POC/

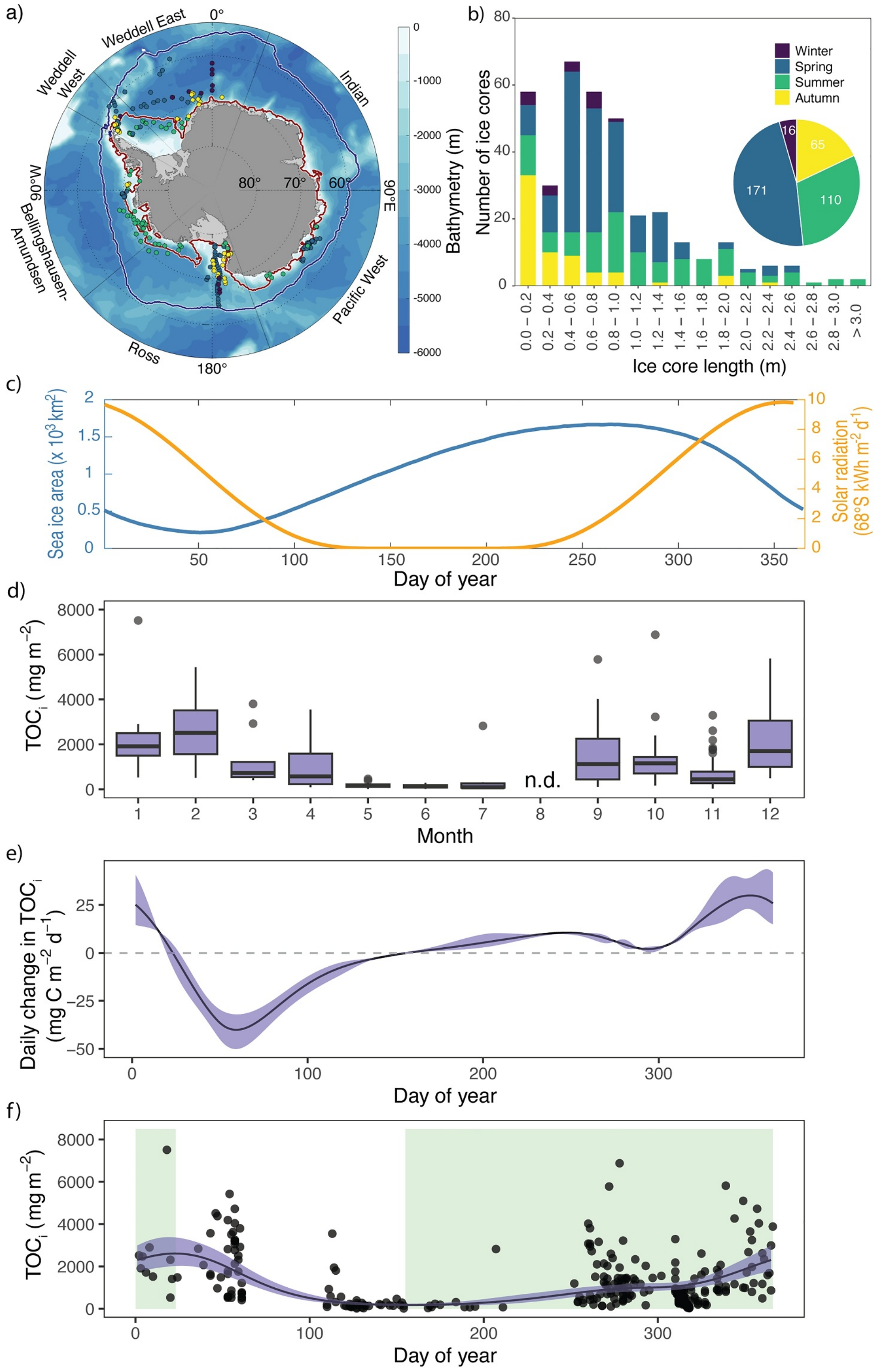

Figure 1. Map of sampling locations of collected ice cores colored by season (a) with median sea-ice edge at the sea-ice minimum (red) and maximum (blue) extent from daily NSIDC Climate Data Record data over the sampling period (1989–2019) shown as contours. Number of ice cores by core length (b) from all campaigns in each season. Pie graph summarizes the number of ice cores collected in each season (winter = June–August; spring = September–November; summer = December–February; autumn = March–May). Historical seasonal sea-ice area from 1989 to 2019 averaged (blue) and solar radiation at 68°S (orange; c). Boxplots of monthly integrated total organic carbon (TOC_i; raw data) over the year ("n.d." represents no data; d). The daily change of TOC_i predicted by the GAM over the year (e) from TOC_{DPSR} data, with purple shading indicating the associated error. Integrated TOC (TOC_i) over the year with GAM (TOC_{DPSR} data) overlayed (black line; f). The purple shading is the error associated with the GAM estimate of production, the green shading illustrates the production period (i.e., positive growth/accumulation).

Table 1
Antarctic Sea-Ice Primary Production Estimates Based on the Range of All Net Community Production (NCP) Data in Table S2 in Supporting Information S1

Study	Method	Type	Production (Tg C yr^{-1})
Bunt (1968)	Extrap. Obs. ($n = 4$)	NPP	<0.1
Heywood and Whitaker (1984)	Extrap. Obs. ($n \leq 5$)	NPP	50
Legendre et al. (1992)	Extrap. Obs. (n = n.a.)	NCP	63–70
Arrigo et al. (1997)	Model (static)	GPP	35.7
Saenz and Arrigo (2014)	Model (dynamic, sea ice state 2005–2006)	GPP	23.7
Jeffery et al. (2020)	Model (E3SM-BGC—historical)	NPP	15.5
Pinkerton and Hayward (2021)	Model (Satellite-based light index)	GPP	25
Wongpan et al. (2024)	Model (LIM1D, *landfast ice only)	GPP	2.8*
This study	**Extrap. Obs. (n = 362)**	**NCP**	**26.8–32.9**

Note. The abbreviations "n.a." and "Extrap. Obs." stand for not available (unreported) and extrapolated observations, respectively. The type refers to GPP (Gross Primary Production), NPP (Net Primary Production; NPP = GPP minus autotrophic respiration) and NCP (NCP = GPP minus autotrophic and heterotrophic respiration). The bold values in the last row emphasize the findings of this study in comparison to the previous studies.

DOC ratio = 1.26 ± 1.46), and (d) the seasonally varying DOC/POC ratio TOC_{DPSR} (Table S3 in Supporting Information S1). These scenarios were analyzed to check the variability of our estimates (Table S2 in Supporting Information S1). Unrealistic TOC values <400 mg m^{-2} between days 305–320 ($n = 17$) were excluded from the analysis to provide a more conservative result (Table S2 in Supporting Information S1). This was done because such TOC values are lower (median 240 mg m^{-2}, $n = 17$) than the expected values for spring (median = 774.5 mg m^{-2}, spring interquartile range = 332.7–1686.8 mg m^{-2}) and were thus considered as outliers within the seasonal cycle. These values were primarily associated with newly formed ice near the Ross Sea polynya (Arrigo et al., 2003).

3. Results and Discussion

3.1. Circum-Antarctic Estimate of Net Community Production

Our time-integrated analysis reveals a median ice algal NCP of 26.8 Tg C yr^{-1} based on the TOC_{DPSR} data (95% CI: 21.7–33.4 Tg C yr^{-1}; Table S2 in Supporting Information S1). The uncertainty range is supported by similar results from all four scenarios (with or without accounting for missing POC or DOC data), with NCP ranging between 26.8 and 32.9 Tg C yr^{-1} (Table 1, Table S2 in Supporting Information S1). However, our current NCP estimate inherently accounts for loss terms, specifically grazing and export, which remain insufficiently studied. Previous reports suggest in-ice grazing losses of ∼10% of available ice algal biomass in spring (Pakhomov & Perissinotto, 1996; Stretch et al., 1988), and the majority of export from ice via zooplankton fecal pellets prior to melt (Belcher et al., 2019; Schmidt et al., 2018), further highlighting that our estimates should be considered as conservative. Our estimate is half the production estimated by Legendre et al. (1992), which used a limited (unreported) number of ice cores and a biomass accumulation method similar to ours. The extrapolation of standing stock from a limited number of ice cores, where surface biomass was high and bottom communities were exclusively from fast ice, to the entire ice pack (Legendre et al., 1992), may have overestimated production. In contrast, the number and coverage of ice-core measurements is vastly increased in the current compilation, likely providing a more representative estimate. Despite the difference from Legendre et al. (1992), our estimate is in good agreement with previous model-based rates of 35 Tg C yr^{-1} (Arrigo et al., 1997) and 23.7 Tg C yr^{-1} (Saenz & Arrigo, 2014; Table 1). The former focused only on freeboard and infiltration communities and neglected algal growth in the bottom-ice, while the latter incorporated bottom (0.2 m from seawater interface) and interior (>0.2 m to surface) communities. The average daily rate of change in NCP, 10.5 mg C m^{-2} d^{-1} (0.01–30 mg C m^{-2} d^{-1}), calculated from the production period (Figure 1e) is in line with, but on the lower end of, in-situ rate measurements for springtime sea ice (0.5–140 mg C m^{-2} d^{-1}) collected primarily from productive landfast ice (Arrigo, 2017). For this comparison we excluded highly productive platelet ice values, yielding rates as high as 1250 mg C m^{-2} d^{-1} (Grossi et al., 1987).

Recent modeling work using an observation-based light index has provided an estimate of ice algal NPP for the Southern Ocean of 25 Tg C yr^{-1} over a 30-year period (1987–2017; Pinkerton & Hayward, 2021), which is similar to the one in this study despite using a different method (Table 1). Pinkerton and Hayward (2021) also used sea-ice algal production models (Jeffery et al., 2020; Saenz & Arrigo, 2014) to validate their light-based index against algal production. Jeffery et al. (2020) report NPP of 15.5 Tg C yr^{-1} (11–20 Tg C yr^{-1}) from the E3SMv1.1-BGC model and note that their model may underestimate sea-ice algal production in winter. Part of the inter-model NPP spread could be attributed to varying snow depth, as it affects light limitation; it could also be due to inter-model differences in ice volume, which provides an upper boundary to the domain over which ice algae can develop.

Our compilation shows the temporal development of ice algal production for the Southern Ocean (Figure 1). Under light-limiting conditions, low and stable TOC_i values occur during the winter months (May to July). With increasing solar insolation and relief of light limitation, TOC_i begins to increase notably from August to September, with the most rapid accumulation occurring in early spring (Figure 1). The daily change in production over time shows a seasonal pattern in the transition from net autotrophic production in early spring to net heterotrophy in late summer (Figure 1c). This shift reflects a seasonal depletion of biomass, possibly due to decreasing light (and lower algal growth rates), grazing and/or other loss processes like nutrient limitation and sea ice ablation which is not accounted for in the NCP estimate. It may also reflect the timing of a steep transition in ice age (i.e., old FYI and newly forming ice) which would have varying concentrations of TOC_i. Some comparatively low TOC_i values were recorded in November, mostly found in newly formed sea ice near the Ross Sea polynya, in a period expected to show a continuous increase in production. Low TOC_i in newly formed ice probably reflects sampling bias given the high spatial and temporal heterogeneity of ice algal biomass, community composition, and production (Campbell et al., 2017; Cimoli et al., 2020; Lim et al., 2023; Meiners et al., 2017), as well as in snow depth (Meiners et al., 2017), sea ice production and ice types (Arrigo et al., 2003). Another possible explanation is a seasonally varying impact of grazers on sea-ice algae (Kohlbach et al., 2017; Moreau et al., 2020). The overall seasonal cycle in TOC_i documented here is in agreement with previous macronutrient observations in sea ice, which are typically abundant in autumn and winter but can become depleted in spring/summer due to ice algal uptake (Fripiat et al., 2017; Henley et al., 2023), thus mirroring the production trends evident in this study. Notably, our findings indicate that production of ice algae begins 1 month earlier (in September) than under-ice phytoplankton (i.e., Arrigo et al., 2008, Briggs et al., 2018; Moreau et al., 2020; Hague & Vichi, 2021; McClish & Bushinsky, 2023), illustrating its significance in enhancing productivity during periods when pelagic production is minimal (Lenss et al., 2024), and providing an early season food source for grazers.

Our estimated NCP of 26.8 Tg C yr^{-1} for sea ice is approximately 2% of the most recent estimate of annual phytoplankton production in the Southern Ocean south of 50° S (1300 Tg C yr^{-1}; Johnson et al., 2017). When compared to a pelagic seasonal sea-ice zone production estimate of ~180.1 Tg C yr^{-1} (Arrigo et al., 2008), our observation-based NCP suggests that sea-ice algal production contributes at least 15%–18% (based on 26.8 to 32.9 Tg C yr^{-1}) to the seasonal ice zone production. However, given that the biomass accumulation method likely underestimates total ice algal production, this value represents a minimum contribution. Nevertheless, this study offers a benchmark NCP for models and future studies of change over time.

3.2. Distribution of Biomass

Vertically resolved data of organic carbon can inform on where algal carbon is accumulating within Antarctic sea ice. Both POC and DOC maintain consistent vertical distributions throughout winter and spring, with POC concentrations peaking in the bottom ice during these periods (Figures 2e and 2f). TOC is nearly equal in the three horizons, with the bottom section showing slightly higher values. Bottom-ice sections (bottom 33%) show the highest relative contribution to TOC_i (35.0%) in comparison to the interior (30.6%; middle 33%) and surface (33.3%; top 33%; Figure S3a and Table S4 in Supporting Information S1). While bottom-ice communities have been shown to be some of the most productive (Lim et al., 2023; Saenz & Arrigo, 2014), surface and interior communities make important contributions to biomass (i.e., TOC) accumulation in the current study, similar to results in Meiners et al. (2012). In contrast to Arctic sea ice, the consistent observation of biomass across the entire sea ice profile in this and other studies (e.g., Meiners et al., 2012) suggests that Antarctic sea-ice ecosystems are more uniformly distributed across the thickness of the ice.

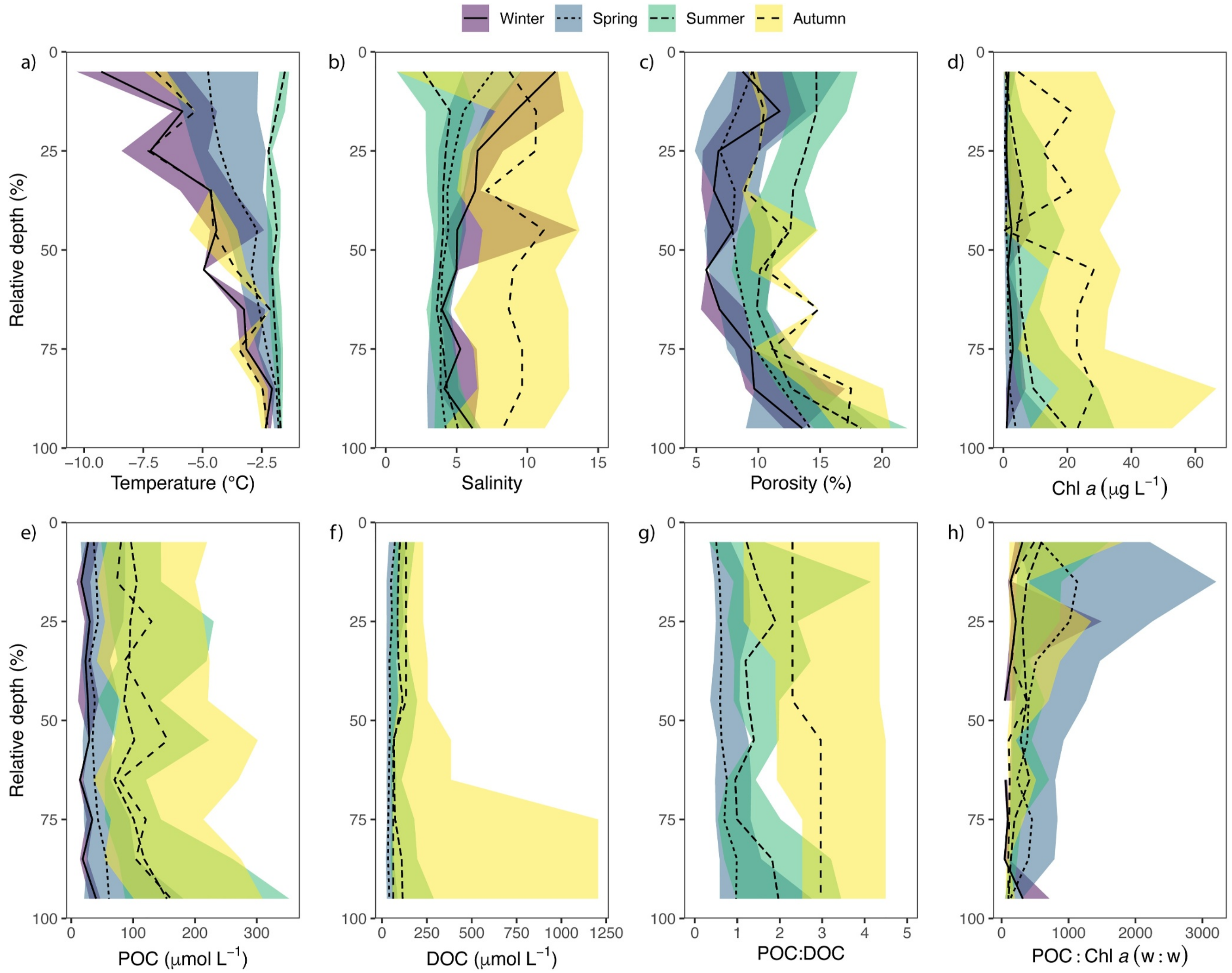

Figure 2. Seasonal distribution of environmental and biological parameters throughout the sea ice profiles. Profiles of temperature (°C; a), salinity (b), porosity (%; c), chlorophyll *a* (Chl *a*; d), particulate organic carbon (POC; e), dissolved organic carbon (DOC; f), POC:DOC ratio (g) and POC:Chl *a* ratio (h). Median concentrations are shown as dashed and solid lines with shaded regions indicating the interquartile range for each season.

Integrated Chl *a* was positively correlated with snow depth ($p < 0.001$, $\rho = 0.55$). The increase in Chl *a* may represent a photophysiological response to low light conditions, where cells increase Chl *a* per unit of carbon to maximize photosynthesis (e.g., Dalman et al., 2023). In addition, snow loading can induce surface flooding of ice floes creating favorable nutrient-replete habitat for surface and interior ice-algal communities (Meiners et al., 2017; Saenz & Arrigo, 2014).

The highest POC:Chl *a* ratios were within the surface, decreasing significantly toward the ice-ocean interface in both spring ($p < 0.001$, $\rho = -0.35$) and summer ($p < 0.001$, $\rho = -0.37$), with a slightly reversed trend for autumn ($p < 0.001$, $\rho = -0.47$). Autumn had consistently low ratios compared to spring and summer. The decrease in the POC:Chl *a* ratio from the surface to the bottom may be attributed to several factors, (a) more detritus within the surface and interior ice (van Leeuwe et al., 2022), (b) more prevalent photosynthetic communities in the bottom sections of ice, and/or (c) greater investment in Chl *a* per cell toward the bottom in response to low light (Arrigo et al., 2014; Dalman et al., 2023).

The POC:Chl *a* ratio for depth-integrated data increased from winter (median = 112.9, range: 14.8 to 4,347) to a peak in spring (median = 541.3, range: 8.9 to 137,554) followed by a decrease into summer (290.2, range: 23.3 to 13,747) and autumn (median = 140.1, range: 8.4 to 20,339). The strong increase from winter to spring may indicate that organic matter produced by photosynthesis is gradually channeled toward heterotrophic grazers, bacterial biomass and detritus over time. The continuous decrease toward summer and autumn may indicate light acclimation following similar patterns described in the vertical ice profile (van Leeuwe et al., 2022). Alternatively, bacterial remineralization of POC could be higher in summer, as warmer ice temperatures promote higher metabolism and organic matter consumption (Moreau et al., 2015) further reducing POC pools toward autumn.

The period of greatest organic carbon accumulation in the sea ice is between September and late January (Figures 1 and 2; Figure S5 in Supporting Information S1). The POC:DOC ratio increased over the growing season from spring (median = 0.85, range: 0.03 to 7.8) to summer (median = 2.03, range: 0.02 to 153), to autumn (median = 3.48, range: 0.63 to 8.76), suggesting a progressive accumulation of particulate over dissolved organic matter. This could indicate conversion of DOC into exopolymeric polymeric particles and gels (Underwood et al., 2013; Verdugo, 2012) or alternatively differential retention of POC over DOC during the melt season (Juhl et al., 2011). The only association between POC:DOC and ice depth was observed in spring ($p < 0.001$, $\rho = 0.197$), where the ratio increased toward the bottom-ice, emphasizing a favorable condition for ice algal growth accompanied by preferential loss of DOC from highly permeable ice layers (Juhl et al., 2011).

Sea-ice DOC in the Southern Ocean is thought to have an autochthonous origin (i.e., produced by in-situ photosynthesis; Smith et al., 1997; Norman et al., 2011; Stedmon et al., 2011). Indeed, this study observed a correlation between Chl *a* and DOC ($p < 0.001$, $\rho = 0.44$) suggesting ice algae as an important source for DOC. The correspondence between POC:PON and DOC:DON ratios (median = 9.9 and 8.7, respectively; Figure S5 in Supporting Information S1) further supports that most DOC derives from ice algae production (Amon et al., 2001; Norman et al., 2011; Smith et al., 1997; Stedmon et al., 2011; Thomas et al., 2001). However, a strong correlation between POC and DOC ($p < 0.001$, $\rho = 0.62$, Figure S6c in Supporting Information S1) indicates strong activity of breaking down ice algal POC into DOC through closely coupled microbial interactions. For nitrogen, PON correlates with POC ($p < 0.001$, $\rho = 0.88$) and DON with DOC ($p < 0.001$, $\rho = 0.72$), both overall and in each season (Figures S6a and S6b in Supporting Information S1).

The overall C:N ratio of particulate matter of 9.9 (Figure S5a in Supporting Information S1) is larger than the Redfield value of 6.6 (Martiny et al., 2013), which illustrates the progressive accumulation of carbon-rich organic matter over time (Henley et al., 2012), such as exopolymeric substances, lipids and fatty acids (Krembs et al., 2002; Meiners et al., 2004; Underwood et al., 2010) within the brine network (Figure S5 in Supporting Information S1). Alternatively, it can indicate an undersupply of nitrogen to meet production demands, leading to carbon-rich organic matter being formed as nitrogen is scarce (Cota & Sullivan, 1990; Fransson et al., 2011; Niemi et al., 2015). In addition, faster remineralization of N-bearing compounds relative to C-bearing organic compounds (e.g., Letscher & Moore, 2015) will increase the residual TOC:TON ratio (Figure S6 in Supporting Information S1 data). The observed trend of increasing C:N ratios with greater distance from the ice-water interface (Figures S5a and S5b in Supporting Information S1) further supports this accumulation over time of carbon-rich organic matter.

4. Conclusions

In this study, we present a comprehensive observation-based assessment of NCP in Antarctic sea ice. We estimate that it accounts for 26.8–32.9 Tg C yr^{-1} of primary production in the Southern Ocean, which aligns remarkably well with existing models that primarily report NPP rather than NCP itself and is consistent with in-situ production measurements. Our production estimate is conservative, as loss terms that would increase estimated production are not explicitly constrained for. Nevertheless, based on the documented vertical distribution of carbon within sea ice, this study highlights the interior and surface layers as important microhabitats for algal communities, likely enriching sea-ice algal production (contributing 29.3% and 31.8% to $\mathrm{TOC_i}$, respectively). Our observed initiation of biomass accumulation also shows ice-algal production early in the season, which underscores its crucial role in providing a highly concentrated carbon source for the food web before pelagic production dominates. Given the recent shift in the timing and extent of Antarctic sea ice (Himmich et al., 2024; Purich & Doddridge, 2023), the ice-algal phenology and its contribution to overall primary productivity of the Southern Ocean ecosystems is likely undergoing significant changes, with potential severe ramifications for Antarctic marine food webs.

Data Availability Statement

All data used in this study are publicly available or were obtained from published work. The compiled organic carbon concentration data set from Antarctic pack ice is available through Dalman et al. (2025) with CC-BY 4.0.

Acknowledgments
We thank all data contributors: Stephen Ackley, Amber Annett, Sylvie Becquevort, Frank Dehairs, Gerhard Dieckmann, Isabelle Dumont, Robert Dunbar, Luis Paulo Duprat, Raja Ganeshram, David Garrison, Letterio Guglielmo, Louis Legendre, Richard Rivkin, Arnout Roukaerts, Véronique Schoemann, Jacqueline Stefels and Nadja Steiner. This compilation is a product of the Biogeochemical Exchange Processes at Sea Ice Interfaces (BEPSII) community and SCOR Working Group 152 ECV-Ice. This project was supported through the Australian Antarctic Program Partnership (AAPP; project ID ASCI000002), an Australian Research Council (ARC) Special Research Initiative (SR200100008), and Australian Antarctic Science project #4635. LAD is supported by a University of Tasmania Graduate Research Scholarship and the AAPP. ADF and DL are funded by ARC Future Fellowships FT230100234 and FT190100688, respectively. SFH was supported by UK Natural Environment Research Council (NE/K010034/1). DN is supported by the Japan Society for the Promotion of Science (24H02341). SM is supported by the Research Council of Norway projects I-CRYME (335512), and iC3 (332635) and by European Union project WOBEC (350906). Belgian funding from ARC-CWB SIBCLIM, BELSPO BIGSOUTH (SD/CA05A) and F.R.S.-FNRS ISOGGAP (T-0268-16) projects. BD is supported by F.R.S-FNRS. The Oden Southern Ocean (OSO) Expedition 2008/09 was funded by the Swedish Science Council (VR) projects: DNR 2008–6226, 2008–6228, and 2009–2994. KC is supported by RCN project BREATHE (325405) and WOBEC. Open access publishing facilitated by University of Tasmania, as part of the Wiley - University of Tasmania agreement via the Council of Australian University Librarians.

References

Amon, R. M. W., Fitznar, H.-P., & Benner, R. (2001). Linkages among the bioreactivity, chemical composition, and diagenetic state of marine dissolved organic matter. *Limnology & Oceanography*, *46*(2), 287–297. https://doi.org/10.4319/lo.2001.46.2.0287

Arndt, S., Meiners, K. M., Ricker, R., Krumpen, T., Katlein, C., & Nicolaus, M. (2017). Influence of snow depth and surface flooding on light transmission through Antarctic pack ice. *Journal of Geophysical Research: Oceans*, *122*(3), 2108–2119. https://doi.org/10.1002/2016jc012325

Arrigo, K. R. (2017). In D. N. Thomas (Ed.), *Sea ice as a habitat for primary producers* (3rd ed.). Wiley-Blackwell. https://doi.org/10.1002/9781118778371.ch14

Arrigo, K. R., Brown, Z. W., Mills, M. M., Deming, J. W., & Tremblay, J.-É. (2014). Sea ice algal biomass and physiology in the Amundsen Sea, Antarctica. *Elementa: Science of the Anthropocene*, *2*. https://doi.org/10.12952/journal.elementa.000028

Arrigo, K. R., Dieckmann, G., Gosselin, M., Robinson, D. H., Fritsen, C., & Sullivan, C. W. (1995). High resolution study of the platelet ice ecosystem in McMurdo Sound, Antarctica: Biomass, nutrient and production profiles within a dense microgalgal bloom. *Marine Ecology Progress Series*, *127*, 255–268. https://doi.org/10.3354/meps127255

Arrigo, K. R., Robinson, D. H., Dunbar, R. B., Leventer, A. R., & Lizotte, M. P. (2003). Physical control of chlorophyll a, POC, and TPN distributions in the pack ice of the Ross Sea, Antarctica. *Journal of Geophysical Research*, *108*(C10). https://doi.org/10.1029/2001jc001138

Arrigo, K. R., & Sullivan, C. W. (1992). The influence of salinity and temperature covariation on the photophysiological characteristics of Antarctic sea ice microalgae. *Journal of Phycology*, *28*(6), 746–756. https://doi.org/10.1111/j.0022-3646.1992.00746.x

Arrigo, K. R., & Thomas, D. N. (2004). Large scale importance of sea ice biology in the Southern Ocean. *Antarctic Science*, *16*(4), 471–486. https://doi.org/10.1017/s0954102004002263

Arrigo, K. R., van Dijken, G. L., & Bushinsky, S. (2008). Primary production in the Southern Ocean, 1997–2006. *Journal of Geophysical Research*, *113*(C8). https://doi.org/10.1029/2007jc004551

Arrigo, K. R., Worthen, D. L., Lizotte, M. P., Dixon, P., & Dieckmann, G. (1997). Primary production in Antarctic sea ice. *Science*, *276*(5311), 394–397. https://doi.org/10.1126/science.276.5311.394

Belcher, A., Henson, S. A., Manno, C., Hill, S. L., Atkinson, A., Thorpe, S. E., et al. (2019). Krill faecal pellets drive hidden pulses of particulate organic carbon in the marginal ice zone. *Nature Communications*, *10*(1), 889. https://doi.org/10.1038/s41467-019-08847-1

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

Bunt, J. S. (1968). Microalgae of the Antarctic pack ice zone. In R. Currie (Ed.), *Symposium on Antarctic Oceanography* (pp. 198–218). W. Heffner & Sons Ltd.

Campbell, K., Mundy, C. J., Barber, D. G., & Gosselin, M. (2015). Characterizing the sea ice algae chlorophyll a –snow depth relationship over Arctic spring melt using transmitted irradiance. *Journal of Marine Systems*, *147*, 76–84. https://doi.org/10.1016/j.jmarsys.2014.01.008

Campbell, K., Mundy, C. J., Gosselin, M., Landy, J. C., Delaforge, A., & Rysgaard, S. (2017). Net community production in the bottom of first-year sea ice over the Arctic spring bloom. *Geophysical Research Letters*, *44*(17), 8971–8978. https://doi.org/10.1002/2017gl074602

Cimoli, E., Lucieer, V., Meiners, K. M., Chennu, A., Castrisios, K., Ryan, K. G., et al. (2020). Mapping the in situ microspatial distribution of ice algal biomass through hyperspectral imaging of sea-ice cores. *Scientific Reports*, *10*(1), 21848. https://doi.org/10.1038/s41598-020-79084-6

Cota, G. F., & Sullivan, C. W. (1990). Photoadaptation, growth and production of bottom ice algae in the Antarctic. *Journal of Phycology*, *26*(3), 399–411. https://doi.org/10.1111/j.0022-3646.1990.00399.x

Dalman, L., Meiners, K. M., Thomas, D., Deman, F., Moreau, S., Arrigo, K., et al. (2025). Circumpolar compilation of organic carbon data from Antarctic pack ice [Dataset]. *Australian Antarctic Data Centre*. https://doi.org/10.26179/et5t-zv87

Dalman, L. A., Schallenberg, C., Fraser, A. D., Bestley, S., Yang, E. J., Clementson, L., & Meiners, K. M. (2023). Bio-optical properties of algal communities in Antarctic pack ice during spring. *Journal of Marine Systems*, *240*, 103890. https://doi.org/10.1016/j.jmarsys.2023.103890

Delille, B., Vancoppenolle, M., Geilfus, N. X., Tilbrook, B., Lannuzel, D., Schoemann, V., et al. (2014). Southern ocean CO_2 sink: The contribution of the sea ice. *Journal of Geophysical Research: Oceans*, *119*(9), 6340–6355. https://doi.org/10.1002/2014jc009941

Fransson, A., Chierici, M., Yager, P. L., & Smith, W. O. (2011). Antarctic sea ice carbon dioxide system and controls. *Journal of Geophysical Research*, *116*(C12), C12035. https://doi.org/10.1029/2010jc006844

Fraser, A. D., Massom, R. A., Michael, K. J., Galton-Fenzi, B. K., & Lieser, J. L. (2012). East Antarctic Landfast Sea ice distribution and variability, 2000–2008. *Journal of Climate*, *25*(4), 1137–1156. https://doi.org/10.1175/jcli-d-10-05032.1

Fraser, A. D., Wongpan, P., Langhorne, P. J., Klekociuk, A. R., Kusahara, K., Lannuzel, D., et al. (2023). Antarctic Landfast Sea Ice: A review of its physics, biogeochemistry and ecology. *Reviews of Geophysics*, *61*(2). https://doi.org/10.1029/2022rg000770

Fripiat, F., Meiners, K., Vancoppenolle, M., Papadimitriou, S., Thomas, D. N., Ackley, S. F., et al. (2017). Macro-nutrient concentrations in Antarctic pack ice; overall patterns and overlooked processes. *Elementa: Science of the Anthropocene*, *5*(13). https://doi.org/10.1525/journal.elementa.217

Grossi, S. M., Kottmeier, S. T., Moe, R. L., Taylor, G. T., & Sullivan, C. W. (1987). Sea ice microbial communities. VI. Growth and primary production in bottom ice under graded snow cover. *Marine Ecology Progress Series*, *35*, 153–164. https://doi.org/10.3354/meps035153

Hague, M., & Vichi, M. (2021). Southern ocean biogeochemical Argo detect under-ice phytoplankton growth before sea ice retreat. *Biogeosciences*, *18*(1), 25–38. https://doi.org/10.5194/bg-18-25-2021

Henley, S. F., Annett, A. L., Ganeshram, R. S., Carson, D. S., Weston, K., Crosta, X., et al. (2012). Factors influencing the stable carbon isotopic composition of suspended and sinking organic matter in the coastal Antarctic sea ice environment. *Biogeosciences*, *9*(3), 1137–1157. https://doi.org/10.5194/bg-9-1137-2012

Henley, S. F., Cozzi, S., Fripiat, F., Lannuzel, D., Nomura, D., Thomas, D. N., et al. (2023). Macronutrient biogeochemistry in Antarctic land-fast sea ice: Insights from a circumpolar data compilation. *Marine Chemistry*, *257*, 104324. https://doi.org/10.1016/j.marchem.2023.104324

Heywood, R. B., & Whitaker, T. M. (1984). The Antarctic marine flora. In R. M. Laws (Ed.), *Antarctic Ecology* (pp. 373–419). Academic Press.

Himmich, K., Vancoppenolle, M., Stammerjohn, S., Bocquet, M., Madec, G., Sallée, J. B., & Fleury, S. (2024). Thermodynamics drive post-2016 changes in the Antarctic sea ice seasonal cycle. *Journal of Geophysical Research: Oceans*, *129*(8). https://doi.org/10.1029/2024jc021112

Jeffery, N., Maltrud, M. E., Hunke, E. C., Wang, S., Wolfe, J., Turner, A. K., et al. (2020). Investigating controls on sea ice algal production using E3SMv1.1-BGC. *Annals of Glaciology*, *61*(82), 51–72. https://doi.org/10.1017/aog.2020.7

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

Jones, E. M., Henley, S. F., van Leeuwe, M. A., Stefels, J., Meredith, M. P., Fenton, M., & Venables, H. J. (2022). Carbon and nutrient cycling in Antarctic Landfast Sea ice from winter to summer. *Limnology & Oceanography*, *68*(1), 208–231. https://doi.org/10.1002/lno.12260

Juhl, A. R., Krembs, C., & Meiners, K. M. (2011). Seasonal development and differential retention of ice algae and other organic fractions in first-year Arctic sea ice. *Marine Ecology Progress Series*, *436*, 1–16. https://doi.org/10.3354/meps09277

Kohlbach, D., Graeve, M., Lange, B. A., David, C., Schaafsma, F. L., van Franeker, J. A., et al. (2018). Dependency of Antarctic zooplankton species on ice algae-produced carbon suggests a sea ice-driven pelagic ecosystem during winter. *Global Change Biology*, *24*(10), 4667–4681. https://doi.org/10.1111/gcb.14392

Kohlbach, D., Lange, B. A., Schaafsma, F. L., David, C., Vortkamp, M., Graeve, M., et al. (2017). Ice algae-produced carbon is critical for overwintering of Antarctic Krill Euphausia superba. *Frontiers in Marine Science*, *4*. https://doi.org/10.3389/fmars.2017.00310

Krembs, C., Eicken, H., Junge, K., & Deming, J. W. (2002). High concentrations of exopolymeric substances in Arctic winter sea ice: Implications for the polar ocean carbon cycle and cryoprotection of diatoms. *Deep Sea Research Part I: Oceanographic Research Papers*, *49*(12), 2163–2181. https://doi.org/10.1016/S0967-0637(02)00122-X

Lannuzel, D., Chever, F., van der Merwe, P. C., Janssens, J., Roukaerts, A., Cavagna, A.-J., et al. (2016). Iron biogeochemistry in Antarctic pack ice during SIPEX-2. *Deep Sea Research Part II: Topical Studies in Oceanography*, *131*, 111–122. https://doi.org/10.1016/j.dsr2.2014.12.003

Legendre, L., Ackley, S. F., Dieckmann, G., Gulliksen, B., Horner, R. A., Hoshiai, T., et al. (1992). Ecology of sea ice biota. *Polar Biology*, *12*(3–4), 429–444. https://doi.org/10.1007/BF00243114

Lenss, M., Moreau, S., Hattermann, T., Wiktor, J., Różańska, M., Claeys, P., et al. (2024). Phytoplankton bloom distribution and succession driven by sea-ice melt in the Kong Håkon VII Hav. *Elementa: Science of the Anthropocene*, *12*(1). https://doi.org/10.1525/elementa.2023.00122

Letscher, R. T., & Moore, J. K. (2015). Preferential remineralization of dissolved organic phosphorus and non-Redfield DOM dynamics in the global ocean: Impacts on marine productivity, nitrogen fixation, and carbon export. *Global Biogeochemical Cycles*, *29*(3), 325–340. https://doi.org/10.1002/2014gb004904

Lim, S. M., van Dijken, G. L., & Arrigo, K. R. (2023). Spatial and interannual variability of Antarctic Sea ice bottom algal habitat, 2004–2019. *Journal of Geophysical Research: Oceans*, *128*(9). https://doi.org/10.1029/2023jc020055

Martiny, A., Pham, C., Primeau, F. W., Vrugt, J. A., Moore, J. K., Levin, S. A., & Lomas, M. W. (2013). Strong latitudinal patterns in the elemental ratios of marine plankton and organic matter. *Nature Geoscience*, *6*(4), 279–283. https://doi.org/10.1038/ngeo1757

McClish, S., & Bushinsky, S. M. (2023). Majority of southern ocean seasonal sea ice zone bloom net community production precedes total ice retreat. *Geophysical Research Letters*, *50*(20). https://doi.org/10.1029/2023gl103459

Meiners, K., Brinkmeyer, R., Granskog, M. A., & Lindfors, A. (2004). Abundance, size distribution and bacterial colonization of exopolymeric particles in Antarctic sea ice (Bellingshausen Sea). *Aquatic Microbial Ecology*, *35*, 283–296. https://doi.org/10.3354/ame035283

Meiners, K. M., Arndt, S., Bestley, S., Krumpen, T., Ricker, R., Milnes, M., et al. (2017). Antarctic pack ice algal distribution: Floe-scale spatial variability and predictability from physical parameters. *Geophysical Research Letters*, *44*(14), 7382–7390. https://doi.org/10.1002/2017gl074346

Meiners, K. M., & Michel, C. (2017). In D. N. Thomas (Ed.), *Dynamics of nutrients, dissolved organic matter and exopolymers in sea ice* (3rd ed.). Wiley-Blackwell. https://doi.org/10.1002/9781118778371.ch17

Meiners, K. M., Vancoppenolle, M., Carnat, G., Castellani, G., Delille, B., Delille, D., et al. (2018). Chlorophyll-a in Antarctic Landfast Sea Ice: A first synthesis of historical ice core data. *Journal of Geophysical Research: Oceans*, *123*(11), 8444–8459. https://doi.org/10.1029/2018jc014245

Meiners, K. M., Vancoppenolle, M., Thanassekos, S., Dieckmann, G. S., Thomas, D. N., Tison, J. L., et al. (2012). Chlorophyll a in Antarctic sea ice from historical ice core data. *Geophysical Research Letters*, *39*(21). https://doi.org/10.1029/2012gl053478

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), 3108. https://doi.org/10.1038/s41467-020-16931-0

Moreau, S., Vancoppenolle, M., Delille, B., Tison, J. L., Zhou, J., Kotovitch, M., et al. (2015). Drivers of inorganic carbon dynamics in first-year sea ice: A model study. *Journal of Geophysical Research: Oceans*, *120*(1), 471–495. https://doi.org/10.1002/2014jc010388

Niemi, A., Michel, C., Deming, J. W., & Thomsen, L. (2015). Temporal and spatial variability in sea-ice carbon:nitrogen ratios on Canadian Arctic shelves. *Elementa: Science of the Anthropocene*, *3*. https://doi.org/10.12952/journal.elementa.000078

Norman, L., Thomas, D. N., Stedmon, C. A., Granskog, M. A., Papadimitriou, S., Krapp, R. H., et al. (2011). The characteristics of dissolved organic matter (DOM) and chromophoric dissolved organic matter (CDOM) in Antarctic sea ice. *Deep Sea Research Part II: Topical Studies in Oceanography*, *58*(9–10), 1075–1091. https://doi.org/10.1016/j.dsr2.2010.10.030

Pakhomov, E., & Perissinotto, R. (1996). Antarctic neritic krill euphausia crystallorophias: Spatio-temporal distribution, growth and grazing rates. *Deep Sea Research Part I: Oceanographic Research Papers*, *43*(1), 59–87. https://doi.org/10.1016/0967-0637(95)00094-1

Pinkerton, M. H., & Hayward, A. (2021). Estimating variability and long-term change in sea ice primary productivity using a satellite-based light penetration index. *Journal of Marine Systems*, *221*, 103576. https://doi.org/10.1016/j.jmarsys.2021.103576

Purich, A., & Doddridge, E. W. (2023). Record low Antarctic sea ice coverage indicates a new sea ice state. *Communications Earth & Environment*, *4*(1), 314. https://doi.org/10.1038/s43247-023-00961-9

Saenz, B. T., & Arrigo, K. R. (2014). Annual primary production in Antarctic sea ice during 2005–2006 from a sea ice state estimate. *Journal of Geophysical Research: Oceans*, *119*(6), 3645–3678. https://doi.org/10.1002/2013jc009677

Schmidt, K., Brown, T. A., Belt, S. T., Ireland, L. C., Taylor, K. W. R., Thorpe, S. E., et al. (2018). Do pelagic grazers benefit from sea ice? Insights from the Antarctic sea ice proxy $IPSO_{25}$. *Biogeosciences*, *15*(7), 1987–2006. https://doi.org/10.5194/bg-15-1987-2018

Smith, R. E. H., Gosselin, M., Kudoh, S., Robineau, B., & Taguchi, S. (1997). DOC and its relationship to algae in bottom ice communities. *Journal of Marine Systems*, *11*(1–2), 71–80. https://doi.org/10.1016/S0924-7963(96)00029-2

Spindler, M. (1994). Notes on the biology of sea ice in the Arctic and Antarctic polar biology. *Polar Biology*, *14*(5), 319–324. https://doi.org/10.1007/BF00238447

Stedmon, C. A., Thomas, D. N., Papadimitriou, S., Granskog, M. A., & Dieckmann, G. S. (2011). Using fluorescence to characterize dissolved organic matter in Antarctic sea ice brines. *Journal of Geophysical Research*, *116*(G3), G03027. https://doi.org/10.1029/2011jg001716

Steiner, N. S., Bowman, J., Campbell, K., Chierici, M., Eronen-Rasimus, E., Falardeau, M., et al. (2021). Climate change impacts on sea-ice ecosystems and associated ecosystem services. *Elementa: Science of the Anthropocene*, *9*(1), 00007. https://doi.org/10.1525/elementa.2021.00007

Stretch, J. J., Hamner, P. P., Hamner, W. M., Michel, W. C., Cook, J., & Sullivan, C. W. (1988). Foraging behavior of antarctic krill Euphasia superba on sea ice microalgae. *Marine Ecology Progress Series*, *44*, 131–139. https://doi.org/10.3354/meps044131

Stroeve, J. C., Veyssiere, G., Nab, C., Light, B., Perovich, D., Laliberté, J., et al. (2024). Mapping potential timing of ice algal blooms from satellite. *Geophysical Research Letters*, *51*(8). https://doi.org/10.1029/2023gl106486

Swadling, K. M., Constable, A. J., Fraser, A. D., Massom, R. A., Borup, M. D., Ghigliotti, L., et al. (2023). Biological responses to change in Antarctic sea ice habitats. *Frontiers in Ecology and Evolution*, *10*. https://doi.org/10.3389/fevo.2022.1073823

Thomas, D. N., Kattner, G., Engbrodt, R., Giannelli, V., Kennedy, H., Haas, C., & Dieckmann, G. S. (2001). Dissolved organic matter in Antarctic sea ice. *Annals of Glaciology*, *33*, 297–303. https://doi.org/10.3189/172756401781818338

Underwood, G. J., Aslam, S. N., Michel, C., Niemi, A., Norman, L., Meiners, K. M., et al. (2013). Broad-scale predictability of carbohydrates and exopolymers in Antarctic and Arctic sea ice. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(39), 15734–15739. https://doi.org/10.1073/pnas.1302870110

Underwood, G. J. C., Fietz, S., Papadimitriou, S., Thomas, D. N., & Dieckmann, G. S. (2010). Distribution and composition of dissolved extracellular polymeric substances (EPS) in Antarctic sea ice. *Marine Ecology Progress Series*, *404*, 1–19. https://doi.org/10.3354/meps08557

Vancoppenolle, M., & Tedesco, L. (2017). Numerical models of sea ice biogeochemistry. In *Sea ice* (pp. 492–515). https://doi.org/10.1002/9781118778371.ch20

van Leeuwe, M. A., Fenton, M., Davey, E., Rintala, J.-M., Jones, E. M., Meredith, M. P., & Stefels, J. (2022). On the phenology and seeding potential of sea-ice microalgal species. *Elementa: Science of the Anthropocene*, *10*(1). https://doi.org/10.1525/elementa.2021.00029

Verdugo, P. (2012). Marine microgels. *Annual Review of Marine Science*, *4*(1), 375–400. https://doi.org/10.1146/annurev-marine-120709-142759

Veytia, D., Bestley, S., Kawaguchi, S., Meiners, K. M., Murphy, E. J., Fraser, A. D., et al. (2021). Overwinter sea-ice characteristics important for Antarctic krill recruitment in the southwest Atlantic. *Ecological Indicators*, *129*, 107934. https://doi.org/10.1016/j.ecolind.2021.107934

Wongpan, P., Meiners, K. M., Vancoppenolle, M., Fraser, A. D., Moreau, S., Saenz, B. T., et al. (2024). Gross primary production of Antarctic Landfast Sea ice: A model-based estimate. *Journal of Geophysical Research: Oceans*, *129*(10), e2024JC021348. https://doi.org/10.1029/2024JC021348

Worby, A. P., Geiger, C. A., Paget, M. J., Van Woert, M. L., Ackley, S. F., & DeLiberty, T. L. (2008). Thickness distribution of Antarctic sea ice. *Journal of Geophysical Research*, *113*(C5). https://doi.org/10.1029/2007jc004254

References From the Supporting Information

Augstein, E., Bagriansev, N., & Sschenke, H.-W. (1991). Die expedition Antarktis VIII/1-2, 1989 mit der Winter Weddell Gyre study der Forschungsschiffe Polarstern and Akademik Federov. *Berichte zum Polarfurschung*, *84*, 134.

Becquevort, S., Dumont, I., Tison, J. L., Lannuzel, D., Sauvée, M. L., Chou, L., & Schoemann, V. (2009). Biogeochemistry and microbial community composition in sea ice and underlying seawater off East Antarctica during early spring. *Polar Biology*, *32*(6), 879–895. https://doi.org/10.1007/s00300-009-0589-2

Dumont, I., Schoemann, V., Lannuzel, D., Chou, L., Tison, J. L., & Becquevort, S. (2009). Distribution and characterization of dissolved and particulate organic matter in Antarctic pack ice. *Polar Biology*, *32*(5), 733–750. https://doi.org/10.1007/s00300-008-0577-y

Duprat, L., Corkill, M., Genovese, C., Townsend, A. T., Moreau, S., Meiners, K. M., & Lannuzel, D. (2020). Nutrient distribution in East Antarctic summer sea ice: A potential iron contribution from glacial basal melt. *Journal of Geophysical Research: Oceans*, *125*(12). https://doi.org/10.1029/2020jc016130

Herborg, L. M., Thomas, D. N., Kennedy, H., Haas, C., & Dieckmann, G. S. (2004). Dissolved carbohydrates in Antarctic sea ice. *Antarctic Science*, *13*(2), 119–125. https://doi.org/10.1017/s0954102001000190

Hulatt, C. J., & Thomas, D. N. (2010). Dissolved organic matter (DOM) in microalgal photobioreactors: A potential loss in solar energy conversion? *Bioresource Technology*, *101*(22), 8690–8697. https://doi.org/10.1016/j.biortech.2010.06.086

Janssens, J., Meiners, K. M., Tison, J.-L., Dieckmann, G., Delille, B., Lannuzel, D., et al. (2016). Incorporation of iron and organic matter into young Antarctic sea ice during its initial growth stages. *Elementa: Science of the Anthropocene*, *4*. https://doi.org/10.12952/journal.elementa.000123

Kauko, H. M., Assmy, P., Peeken, I., Różańska-Pluta, M., Wiktor, J. M., Bratbak, G., et al. (2022). First phytoplankton community assessment of the Kong Håkon VII Hav, Southern Ocean, during austral autumn. *Biogeosciences*, *19*(23), 5449–5482. https://doi.org/10.5194/bg-19-5449-2022

Kennedy, H., Thomas, D. N., Kattner, G., Haas, C., & Dieckmann, G. (2002). Particulate organic matter in antarctic summer sea ice: Concentration and stable isotopic composition. *Marine Ecology Progress Series*, *238*, 1–13. https://doi.org/10.3354/meps238001

Meier, W. N., Fetterer, F., Windnagel, A. K., & Stewart, J. S. (2021). *NOAA/NSIDC climate data record of passive microwave sea ice concentration, version 4*. National Snow and Ice Data Center. https://doi.org/10.7265/efmz-2t65

Meiners, K. M., Norman, L., Granskog, M. A., Krell, A., Heil, P., & Thomas, D. N. (2011). Physico-ecobiogeochemistry of East Antarctic pack ice during the winter-spring transition. *Deep Sea Research Part II: Topical Studies in Oceanography*, *58*(9–10), 1172–1181. https://doi.org/10.1016/j.dsr2.2010.10.033

Miller, L. A., Fripiat, F., Else, B. G. T., Bowman, J. S., Brown, K. A., Collins, R. E., et al. (2015). Methods for biogeochemical studies of sea ice: The state of the art, caveats, and recommendations. *Elementa: Science of the Anthropocene*, *3*. https://doi.org/10.12952/journal.elementa.000038

Munro, D. R., Dunbar, R. B., Mucciarone, D. A., Arrigo, K. R., & Long, M. C. (2010). Stable isotope composition of dissolved inorganic carbon and particulate organic carbon in sea ice from the Ross Sea, Antarctica. *Journal of Geophysical Research*, *115*(C9). https://doi.org/10.1029/2009jc005661

Papadimitriou, S., Thomas, D. N., Kennedy, H., Haas, C., Kuosa, H., Krell, A., & Dieckmann, G. S. (2007). Biogeochemical composition of natural sea ice brines from the Weddell Sea during early austral summer. *Limnology & Oceanography*, *52*(5), 1809–1823. https://doi.org/10.4319/lo.2007.52.5.1809

Roukaerts, A., Cavagna, A.-J., Fripiat, F., Lannuzel, D., Meiners, K. M., & Dehairs, F. (2016). Sea-ice algal primary production and nitrogen uptake rates off East Antarctica. *Deep Sea Research Part II: Topical Studies in Oceanography*, *131*, 140–149. https://doi.org/10.1016/j.dsr2.2015.08.007

Thomas, D. N., Lara, R. J., Haas, C., Schnack-Schiel, S. B., Dieckmann, G., Kattner, G., et al. (1998). Biological soup within decaying slimmer sea ice in the Amundsen Sea, Antarctica. *Antarctic Research Series*, 161–171. https://doi.org/10.1029/AR073p0161 van der Merwe, P., Lannuzel, D., Nichols, C. A. M., Meiners, K., Heil, P., Norman, L., et al. (2009). Biogeochemical observations during the winter–spring transition in East Antarctic sea ice: Evidence of iron and exopolysaccharide controls. *Marine Chemistry*, *115*(3–4), 163–175. https://doi.org/10.1016/j.marchem.2009.08.001

Vancoppenolle, M., Madec, G., Thomas, M., & McDougall, T. J. (2019). Thermodynamics of sea ice phase composition revisited. *Journal of Geophysical Research: Oceans*, *124*(1), 615–634. https://doi.org/10.1029/2018jc014611