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LETTER

Sea-ice loss accelerates carbon cycling and enhances seasonal extremes of acidification in the Arctic Chukchi Sea

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Scientific Significance Statement

The Arctic Chukchi Sea shelf (CSS) is a prominent site for the biological drawdown of atmospheric carbon dioxide, which can subsequently be transported to the deep sea in the Arctic Ocean. The efficiency of carbon export is influenced by seasonal seaice formation and retreat: longer period of sea-ice opening results in shorter carbon retention time and reduced carbon export due to rapid recycling of organic matter. However, this process is poorly understood due to lack of observations. Here, we present three sets of late- vs. early-summer reoccupations along the same transect in the CSS. We unveil distinct spatial patterns of carbonate chemistry and subsurface acidification between the southern CSS and northern CSS. In the sCSS, degradation of biologically produced organic matter has occurred rapidly and caused subsurface acidification since early summer due to earlier sea-ice retreat; however, no such phenomenon is observed in the northern region. As Arctic warming continues in the future, these conditions are expected to persist, further diminishing carbon export capacity and exacerbating seasonal acidification.

Abstract

The Chukchi Sea shelf (CSS) is a highly productive region in the Arctic Ocean and it is highly efficient for absorbing atmospheric carbon dioxide and exporting and retaining carbon in the deep sea. However, with global warming, the carbon retention time in CSS may decrease, leading to less efficient carbon export. Here, we investigate the seasonal variability of carbonate chemistry in CSS using three sets of late- vs. early-summer reoccupations of the same transect. Our findings demonstrate substantially increased and rapid degradation of biologically produced organic matter and therefore acidification over time in the southern CSS due to earlier sea-ice retreat, resulting in significantly shorter carbon retention time. In sharp contrast, no increased

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degradation has been observed in the northern CSS where photosynthesis has just commenced. In the future, climate change would further diminish the carbon export capacity and exacerbate seasonal acidification not only within CSS but also across other polar coastal oceans.

Human activities have released significant amounts of carbon dioxide (CO₂) into the atmosphere (Friedlingstein et al. 2022) with 30% of the anthropogenic CO_2 being absorbed by the ocean (Gruber et al. 2019). The Arctic Ocean plays a crucial role as a sink for atmospheric CO₂ (Cai et al. 2010; Bates et al. 2011; Ouyang et al. 2020, 2022a), resulting in decreases in pH and aragonite saturation state (Ω_{arag}) , known as ocean acidification (OA) (Doney et al. 2009; Yamamoto-Kawai et al. 2009; Qi et al. 2022a,b). As a critical inflow continental shelf sea connecting the North Pacific Ocean and Arctic Ocean, the Chukchi Sea accounts for onethird of carbon sink in the Arctic Ocean primarily through biological drawdown of CO₂ (Arrigo et al. 2010; Pipko et al. 2015; Ouyang et al. 2020). In conjunction with brine production during sea-ice formation, carbon-rich waters containing organic and inorganic forms exit from the shelf into the deep Arctic basin at intermediate depths to sustain carbon sink capacity on the shelf while also inducing significant subsurface acidification (Bates 2006; Anderson et al. 2010; Qi et al. 2017). Consequently, the Chukchi Sea shelf (CSS) remains a hotspot for CO₂ uptake, transport, storage, and acidification.

Since the late 1990s, the CSS has undergone significant climate changes, including earlier and rapid sea-ice retreat associated with warming (Wang and Overland 2009; Parkinson and Comiso 2013) and increased inflow of nutrient-rich Pacific waters (Torres-Valdés et al. 2013; Woodgate 2018). These have resulted in a > 90% enhancement of primary production on the CSS (Lewis et al. 2020), which subsequently stimulated oceanic CO₂ uptake and mitigated the increase in anthropogenic CO₂ emissions (Ouyang et al. 2020; Tu et al. 2021). However, this increasing biological-driven carbon sink in the surface ocean comes at a cost of severe subsurface acidification occurring 2-3 times faster than that projected from atmospheric CO₂ increase due to rapid recycling of organic matter to CO₂ (Bates et al. 2009; Qi et al. 2022b). Previous studies have observed seasonal acidification on the CSS during summer and autumn (Bates et al. 2013; Mathis and Questel 2013), with nearly 40% of bottom water exhibiting aragonite undersaturation (Yamamoto-Kawai et al. 2016). This process occurs on seasonal or even shorter timescales (Bates et al. 2009, 2013; Qi et al. 2020) but significant gaps remain in understanding its development due to lack of observations. The seasonal evolution of sea-ice introduces additional complexity to this highly dynamic system. On the one hand, seaice retreat during warm seasons alleviates light limitation and removes the physical barrier to air-sea CO₂ exchange, thereby facilitating pronounced seasonal uptake of CO₂ (Mathis and Questel 2013); on the other hand, sea-ice formation during

cold seasons generates dense shelf water that transports carbon toward deep sea for longer-term sequestration (Bates 2006; Anderson et al. 2010). Another previously overlooked aspect is that under climate change, prolonged open-water periods in the warming Arctic Ocean (Crawford et al. 2021) create conditions for CO_2 released from rapidly remineralized organic matter to be returned back into the atmosphere before winter sea ice re-closes over the sea surface. Collectively, we postulate that the interplay among these aforementioned processes may lead to subsurface acidification and reduced efficiency of carbon transport and storage. Nevertheless, this phenomenon remains poorly constrained and requires urgent examination.

To test this hypothesis, we investigate the short-term variations of dissolved inorganic carbon (DIC), pH, Ω_{arag} , and associated variables based on data collected from the forward (late July to early August) and return (late August to early September) voyages during the Chinese Arctic Research Expedition (CHINARE) in 2008, 2010, 2014, 2016, and 2018. Furthermore, we further quantitatively evaluate the development of carbonate chemistry and seasonal acidification from the southern to northern CSS, which exhibit divergent spatial patterns during the study period.

Methods

Cruise description

All samples were collected on the RV *Xuelong* during the CHINARE cruises in 2008, 2010, 2014, 2016, and 2018 (Fig. 1; Chen et al. 2023). A repeated transect along the 169°W has been surveyed during the five cruises, the forward voyage (Leg 1) from late July to early August represents the early summer situation, and the return voyage (Leg 2) from late August to early September represents the late summer situation (*see* details in Fig. 1; Table S1). The CSS was geographically divided into the southern CSS (sCSS; south of 70°N) and the northern CSS (nCSS; north of 70°N) based on submarine topography (following, e.g., Weingartner et al. 2005).

The discrete samples from CHINARE cruises were collected by using a rosette equipped with 24 Niskin bottles (12 liters) and a Sea-Bird 9/11 plus Conductivity, Temperature, Depth instrument. The DIC and TA samples were stored in 250-mL borosilicate glass bottles and preserved, and saturated mercuric chloride solution was injected to halt biological activity. All samples were analyzed within 8 weeks after collection. DIC was measured via acidification and subsequent quantification of released CO_2 by a non-dispersive infrared CO_2 analyzer (Apollo SciTech DIC analyzer). TA was measured using the open-cell Gran titration method (Apollo SciTech Alkalinity analyzer). Both DIC and TA were measured multiple times

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Fig. 1. The sampling stations in the Chukchi Sea from 2008 to 2018. The daily SIC is obtained from the National Snow and Ice Data Center.

 $(N \ge 3)$ until the repeatability better than 0.1% (± 2 μ mol kg⁻¹). The accuracies of the TA and DIC measurements were determined by routine analysis of certified reference materials provided by A. G. Dickson, Scripps Institution of Oceanography.

The DO samples were immediately analyzed on board using the spectrophotometric method based on Winkler titration with a precision of $\pm 1 \,\mu$ mol kg⁻¹ (Bryan et al. 1976; Ouyang et al. 2022*b*). Nutrient samples were measured using a Continuous Flow Analyzer (Skalar San⁺⁺) based on standard colorimetric methods (Grasshoff et al. 1999; Zhuang et al. 2022), and data were from Zhuang et al. (2022). Analytical precision was $\pm 2\%$ for both NO₃⁻ + NO₂⁻ and PO₄³⁻ and was $\pm 2.5\%$ for Si(OH)₄.

Calculation of carbonate system parameters and apparent oxygen utilization

pH (in total scale) and Ω_{arag} were calculated using the Matlab version of CO2SYS v1.1 (Van Heuven et al., 2011) with inputs of DIC and TA. Carbonate dissociation constants were taken from Roy et al. (1993), K_{sp} from Mucci (1983), Kso₄ from Dickson (1990), and total boron from Lee et al. (2010). Using the error propagation approach developed by Orr et al. (2018), we further estimated the uncertainties of calculated pH and Ω_{arag} (0.05 and 0.06, respectively).

The salinity-normalized DIC (nDIC) was calculated following Friis et al. (2003); we derived the following equation to describe the relationship between nDIC and DIC:

$$nDIC = \frac{DIC - DIC_{s=0}}{S} \times S_{ref} + DIC_{s=0}$$
(1)

where $\text{DIC}_{s=0}$ is determined based on the intercept of conservative mixed DIC calculated using the end-member mixing model at a salinity of 0, which yields values of 307 μ mol kg⁻¹. *S*_{ref} is the average salinity of 31.8 during the observation period.

The apparent oxygen utilization (AOU), a proxy to indicate the biological effects, was calculated by subtracting the observed oxygen concentration from its saturation value:

$$AOU = O_{2,sat} - O_{2,obs}$$
(2)

where O_{2rsat} is the saturated oxygen concentration and O_{2robs} is the observed DO concentration. O_{2rsat} was calculated following Garcia and Gordon (1992, 1993).

Calculation of "days since ice retreat"

The term of "days since ice retreat (DSR)" was developed from DeGrandpre et al. (2020) and Qi et al. (2022*a*). DSR represents a timescale concept from when sea-ice concentration (SIC) drops below 15%. A positive (negative) DSR implies that the day of field observation is later (earlier) than the day of ice retreat (the 1st day of SIC < 15% during the seasonal cycle of sea-ice).

SIC data are obtained from NASA National Snow and Ice Data Center Distributed Active Archive Center (https://nsidc.org/data/nsidc-0079/versions/3). This data product is derived from the Scanning Multichannel Microwave Radiometer on the Nimbus-7 satellite and the Special Sensor Microwave/ Imager on the Defense Meteorological Satellite Program's -F8, -F11, -F13, -F15, -F16, -F17, and -F18 satellites. Data are gridded on the polar stereographic grid (25 × 25 km).

Decomposition of factors causing acidification

pH and Ω_{arag} in the Chukchi Sea are affected by several processes, including temperature change, air–sea gas exchange, mixing of different water masses (e.g., seawater, sea-ice meltwater, and river water), and biological CO₂ uptake and respiration. We decomposed the variations of pH and Ω_{arag} into multiple components to investigate the main drivers (Ouyang et al. 2020; Qi et al. 2022*b*):

$$\Delta pH = \Delta pH_t + \Delta pH_g + \Delta pH_m + \Delta pH_b \tag{3}$$

$$\Delta\Omega_{arag} = \Delta\Omega_{arag,t} + \Delta\Omega_{arag,g} + \Delta\Omega_{arag,m} + \Delta\Omega_{arag,b}$$
(4)

where ΔpH and $\Delta \Omega_{arag}$ represent total changes of pH and Ω_{arag} , respectively. Subscripts "t, g, m, and b" represent changes induced by thermal effect, air–sea CO₂ gas exchange, water mixing, and biological activity (i.e., photosynthesis and respiration). Detailed description of calculation of each term on the right-hand side of Eqs. 3 and 4 is given in Supporting Information Text S1.

Comparing difference between forward and return voyages

To statistically compare the vertical profiles of pH, Ω_{arag} , and other associated variables between the forward (Leg 1) and return (Leg 2) voyages, we employed the generalized additive models (GAMs; Zuur et al. 2009; Wood 2017; van Rij et al. 2019), which provide insights into the overall vertical distribution pattern and confidence intervals. The absence of overlap in the 95% confidence intervals justifies significant differences observed between Leg 1 and Leg 2.

Results

Contrasting environmental settings between forward and return voyages

The CSS is primarily composed of the relatively warm Alaska Coastal Water (ACW) and Chukchi Summer Water (CSW), ice-melt water (Early- and Late-season Melt Water, ESMW and LSMW), and the relatively cold and dense Pacific Winter Water (PWW) (Gong and Pickart 2015; Supporting Information Fig. S2; Text S2). The forward (Leg 1) and return (Leg 2) voyages offer an opportunity for investigating the seasonal acidification of subsurface waters and its relationship with the seasonal evolution of sea ice. From late July to early September, the surveyed region north of 70°N transitioned from being seasonally ice-covered to ice-free, while the region south of 70°N remained consistently ice-free throughout the observation period (Fig. 1). Accordingly, both the ACW and CSW water masses (characterized by higher pH > 8.0 and Ω_{arag} > 1.25) extended further northward and displaced the original PWW water mass (characterized by low pH < 7.9 and Ω_{arag} < 1) at depth of 20–50 m until reaching $72^{\circ}N$ (Supporting Information Fig. S3); the LSMW displaced ESMW in surface layers on the nCSS. Due to spatial inconsistencies in water

mass distribution and sea-ice melting patterns, significant differences were observed in carbonate chemistry and the progression of subsurface acidification between the sCSS and nCSS.

Seasonal progression of carbonate chemistry on the sCSS and nCSS $% \left(\mathcal{L}^{2}\right) =\left(\mathcal{L}^{2}\right) \left(\mathcal{L}^{2}\right) \left($

On the sCSS, a significant increase in salinity-normalized DIC disequilibrium (nDIC_{dise}; salinity-normalization eliminates the influence of melt-induced dilution, and disequilibrium term refers to the deviation of nDIC from its atmospheric equilibrium value) was observed from Leg 1 to Leg 2, accompanied by subsequent decreases in pH and Ω_{arag} (Fig. 2; Supporting Information Figs. S4-S7). The values of nDIC_{dise} shifted from negative to near zero (sometimes even positive) (Supporting Information Fig. S7), indicating the occurrence of atmospheric CO₂ uptake and a transition in carbonate chemistry from pronounced biological CO₂ drawdown toward organic matter recycling that could potentially result in CO₂ release back into the atmosphere (see quantification in the following texts). As a consequence, for most of the water depths, nDIC_{dise} values during Leg 2 were significantly larger than those during Leg 1 (Supporting Information Fig. S7), pH and Ω_{arag} during Leg 2 were significantly lower than those during Leg 1 (Fig. 2). For repeated surveys of the same transect in the same year, the water column-averaged pH significantly decreased from Leg 1 to Leg 2 from 8.13 ± 0.11 to 8.03 ± 0.12 in 2008, and from 8.20 ± 0.10 to 8.04 ± 0.10 in 2010; likewise, Ω_{arag} significantly decreased from 1.78 ± 0.41 to 1.59 ± 0.59 in 2008 and from 2.03 ± 0.39 to 1.55 ± 0.36 in 2010 (Fig. 2). For individual survey of the same transect in different years (i.e., forward survey in 2014 vs. return survey in 2018 as shown in Fig. 2c,f), we have detrended the interannual changes in pH and Ω_{arag} throughout the water column between 2014 and 2018, with the rates of each water mass (shown in Supporting Information Fig. S2) as reported by Qi et al. (2022b). The detrended results also exhibited similar signals indicating pronounced remineralization and subsurface acidification. From late July-early August to late August-early September, pH and Ω_{arag} in the Chukchi Sea exhibited a declining trend of -0.0030 ± 0.0006 and $-0.0079 \pm 0.0030 d^{-1}$, respectively, which is approximately 2-12 times higher than that observed during the winter/spring to summer transition (Supporting Information Table S2; Bates et al. 2009, 2013). Furthermore, stations near Hope Valley displayed an accelerated acidification rate with a decline rate of Ω_{arag} equaling $-0.0152 \pm 0.0087 \text{ d}^{-1}$, consistent with findings reported by Yamamoto-Kawai et al. (2016).

However, the rapid seasonal progression of carbon cycling and subsurface acidification was not observed on the nCSS during the observation. The replacement of originally acidified PWW with warmer and more productive ACW, CSW and ice melt waters from Leg 1 to Leg 2 (Supporting Information Fig. S3) resulted in a relieved acidification status. The shift in



Fig. 2. Vertical profile of pH and its relationship with sea-ice retreat status in the Chukchi Sea. The left panel (**a**–**c**) is for the sCSS and the right panel (**d**–**f**) is for the nCSS. Data obtained from Leg 1 (circle) and Leg 2 (triangle) are fitted by GAMs, with colormaps representing days since ice retreat. The dashed lines with shadows (Leg 1: blue line; Leg 2: red line) represent the predicted means and 95% confidence intervals by the GAMs. Significant differences between the two legs are justified by the lack of overlap of the 95% confidence intervals. Data points are colored by values of DSR.

 $nDIC_{dise}$ toward more negative during Leg 2 corresponded to changes induced by biological uptake (Supporting Information Fig. S7). Meanwhile, the water column-averaged pH and



Fig. 3. The decomposition of changes in (a) pH and (b) Ω_{arag} from Leg 1 to Leg 2 into contributions from thermal effect, physical mixing, air-sea gas exchange, and biological effect.

 $\Omega_{\rm arag}$ increased from 1.27–1.31 and 8.03–8.04 to 1.49–1.50 and 8.06–8.07, respectively. The pH and $\Omega_{\rm arag}$ of the water column exhibit an increase at rates of 0.0018 ± 0.0013 and 0.0093 ± 0.0048, respectively (Supporting Information Table S2). We hypothesized that the dissimilar acidification patterns observed in sCSS and nCSS are attributed to variances in sea-ice melting status and their associated biogeochemical responses.

Discussion

Seasonal sea-ice melt drives the spatial inconsistency in carbonate chemistry

Utilizing the DSR as a temporal reference (*see* Methods) for each cruise reveals a significant correlation between sea-ice and carbonate chemistry. On the sCSS, Leg 1 took place at the seasonal ice-free period, indicated by a DSR of 40–50 d. During this period, biological photosynthesis had already occurred for a couple of months due to alleviated light limitation (as indicated by AOU reaching up to $-100 \,\mu$ mol kg⁻¹, negative nDIC_{dise}, and depleted nutrients in surface layer; Supporting Information Figs. S7–S13). On the other hand, Leg 2 occurred with a longer DSR of over 80 d when organic matter produced since Leg 1 had quickly recycled and remineralized into CO₂ (as indicated by nDIC_{dise} and AOU

0.50 • 2008; sCSS 2008; nCSS • 2010: sCSS 2010: nCSS 2014/2016; nCSS 2014/2016; sCSS 0.25 -0.2397 x-0.0836 $R^2 = 0.64$ Hq∆ -0.25 (a) -0.50 -2.00-1.000.00 1.00 2.00 2.00 1.00 -0.8120 x-0.1990 $\Delta\Omega_{\rm arag}$ $R^2 = 0.65$ -1.00(b) -2.00-1.000.00 1.00 2.00 -2.00 ΔPO_4^{3-}

Fig. 4. The relationship between (**a**) ΔpH and ΔPO_4^{3-} , (**b**) $\Delta \Omega_{arag}$ and ΔPO_4^{3-} during the observation period. ΔpH , $\Delta \Omega_{arag}$, and ΔPO_4^{3-} refer to the difference in each variable from Leg 1 to Leg 2.

changing from negative values toward positive; Supporting Information Figs. S7, S8), leading to acidification of subsurface waters (Fig. 2; Supporting Information Fig. S6). In contrast, the observation on the nCSS began at the stage of seasonal ice melting (DSR ranging from -20 to 0 d, SIC reached up to 60%) when photosynthesis process was at its initial stage. From Leg 1 to Leg 2, there was an increase in biological uptake of CO₂ which elevated subsurface pH and Ω_{arag} at 20–50 m depth, exhibiting a distinct pattern compared to sCSS (Fig. 2; Supporting Information Fig. S6).

It is also noteworthy that $\Delta NO_3^{-1}/\Delta PO_4^{-3}$ from Leg 1 to Leg 2 is significantly lower than the classical Redfield ratio of 16 : 1 (Supporting Information Figs. S1, S11, S12), particularly at depths shallower than 20 m, indicating the occurrence of



Fig. 5. Schematic illustrating the progression of seasonal carbon cycling and acidification across the CSS during summer. The change in the length and thickness of the arrows indicate enhancement or attenuation of a certain process.

denitrification which utilized nitrate (Yamamoto-Kawai et al. 2006; Chang and Devol 2009; Piper et al. 2016). However, this denitrification process seems to be compensated for at depths greater than 30 m through sediment resuspension and degradation (Barrett et al. 2023).

Biogeochemical controls for rapid seasonal carbon cycling and subsurface acidification

To test our hypothesis, we conducted further quantitative evaluations on the seasonal progression of pH and Ω_{arag} changes across the CSS. The decomposition reveals that the thermal effect only contributes marginally to variation in pH and contributes negligibly to variation in Ω_{arag} (Fig. 3; similar to Wu et al. 2021). From sCSS to nCSS, thermal effect accounts for 29% and 10% of decreases in pH, respectively. Specifically, a rise in seawater temperature by $\sim 2^{\circ}$ C from Leg 1 to Leg 2 resulted in a decrease in pH of 0.03 ± 0.01 and 0.06 ± 0.02 , as well as an increases in Ω_{arag} of 0.02 ± 0.01 and 0.03 ± 0.01 on the sCSS and nCSS, respectively (see Supporting Information Text S1 for details). By employing a three end-member mixing model (see Supporting Information Texts S1, S2; Table S3), we quantified the influence from mixing of Pacific water, sea-ice meltwater, and river runoff; however, it was determined that physical mixing had negligible impact on both pH and Ω_{arag} (Fig. 3).

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The air–sea CO_2 gas exchange should also be taken into consideration. During the observation, sea surface pCO_2 consistently showed undersaturation with respect to atmospheric CO_2 , indicating a continuous absorption of CO_2 that would trigger acidification. Based on methods described in Supporting Information Text S1, we determined that the influx of atmospheric CO_2 resulted in decreases of Ω_{arag} by ~ 0.1 , and pH by ~ 0.03 (Fig. 3). The effect of air–sea CO_2 gas exchange was moderate, but it was still relatively smaller compared with the biological effect.

Lastly, we took into account potential biological contributions to the observed variability. The rate of primary production would increase when sea-ice thins and melts as lightlimitation decreases (Arrigo et al. 2008, 2017; Brown and Arrigo 2012; Arrigo and van Dijken 2015). In sCSS, subsurface waters with AOU > 0 and enriched nutrients greatly expanded from Leg 1 to Leg 2 (Supporting Information Figs. S8-S10). We used phosphate concentration as a proxy to calculate the biological-driven changes in the carbonate system (see Supporting Information Text S1). An increase in phosphate concentration by $0.15 \pm 0.06 \,\mu\text{mol}\,\text{kg}^{-1}$ caused decreases in pH and Ω_{arag} by 0.11 ± 0.03 and 0.30 ± 0.12 , respectively (see also Fig. 4). In contrast, expanded subsurface waters with AOU < 0 and nutrient consumption were found in nCSS from Leg 1 to Leg 2 (Supporting Information Figs. S8-S10). A decrease in phosphate concentration by $0.46 \pm 0.14 \,\mu \text{mol kg}^{-1}$ caused increases in pH and Ω_{arag} by 0.07 ± 0.05 and $0.35\pm0.19,$ respectively (see also Fig. 4). Taken together, the biological processes accounted for about 48-197% of changes in pH, 51-120% in Ω_{arag} on sCSS and nCSS, respectively, playing a predominant role in rapidly driving the carbon cycling (Figs. 3, 4). The seasonal acidification was reinforced by gas exchange and biology in sCSS while counteracted by biology in nCSS (Fig. 3).

Conclusions

Based on 5 years of repeated cruise data along the same transact, we have observed drastic seasonal variability in carbonate chemistry and subsurface acidification in sCSS, occurring earlier and exhibiting faster turnover rates compared to previous studies (Supporting Information Table S2); surprisingly, no such phenomenon was found in nCSS. Using the DSR as a temporal reference, our findings are linked to the status of sea-ice melt and its associated biogeochemical responses. From August to September, the rapid acidification in the sCSS was induced by an earlier onset of ice melting, with compounding effects from air-sea CO₂ exchange and organic matter recycling. These results suggest that the differential timing of sea-ice opening and retreat between the southern and northern regions sets apart their respective behaviors regarding carbon retention time and subsurface acidification progression.

As the Arctic warms (Rantanen et al. 2022), the duration of open water period is extending, with sea-ice opening occurring earlier in both the sCSS (shifting from July in 2000 to June in 2020) and nCSS (shifting from August in 2000 to June in 2020) (Supporting Information Figs. S14–S16). Moreover, there has been an increase in regions within the summer Chukchi Sea that are completely devoid of sea ice. Consequently, it can be reasonably inferred that these climatic changes will lead to an earlier hotspot for biological CO_2 uptake, followed by rapid recycling and subsequent release of absorbed carbon back into the atmosphere before winter sea ice acts as a barrier. The prolonged period of sea-ice opening introduces complexity to the carbon cycle, weakens carbon export capacity and exacerbates subsurface acidification (Fig. 5), posing a significant threat to ecosystem functions that warrants ongoing observations and modeling predictions.

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Conflict of Interest

None declared.

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