

The connection of phytoplankton biomass in the Marguerite Bay polynya of the western Antarctic Peninsula to the Southern Annular Mode

Ning Jiang¹, Zhaoru Zhang^{1,2*}, Ruifeng Zhang^{1,2}, Chuning Wang¹, Meng Zhou^{1,2}

¹ School of Oceanography, Shanghai Jiao Tong University, Shanghai 200240, China

² Key Laboratory for Polar Science, Polar Research Institute of China, Ministry of Natural Resources, Shanghai 200136, China

Received 16 September 2022; accepted 3 February 2023

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Abstract

Antarctic coastal polynyas are biological hotspots in the Southern Ocean that support the abundance of high-trophic-level predators and are important for carbon cycling in the high-latitude oceans. In this study, we examined the interannual variation of summertime phytoplankton biomass in the Marguerite Bay polynya (MBP) in the western Antarctic Peninsula area, and linked such variability to the Southern Annular Mode (SAM) that dominated the southern hemisphere extratropical climate variability. Combining satellite data, atmosphere reanalysis products and numerical simulations, we found that the interannual variation of summer chlorophyll-*a* (Chl-*a*) concentration in the MBP is significantly and negatively correlated with the spring SAM index, and weakly correlated with the summer SAM index. The negative relation between summer Chl-*a* and spring SAM is due to weaker spring vertical mixing under a more positive SAM condition, which would inhibit the supply of iron from deep layers into the surface euphotic layer. The negative relation between spring mixing and spring SAM results from greater precipitation rate over the MBP region in positive SAM phase, which leads to lower salinity in the ocean surface layer. The coupled physical-biological mechanisms between SAM and phytoplankton biomass revealed in this study is important for us to predict the future variations of phytoplankton biomasses in Antarctic polynyas under climate change.

Key words: Marguerite Bay polynya, phytoplankton biomass, Southern Annular Mode, mixed layer depth, interannual variation

Citation: Jiang Ning, Zhang Zhaoru, Zhang Ruifeng, Wang Chuning, Zhou Meng. 2024. The connection of phytoplankton biomass in the Marguerite Bay polynya of the western Antarctic Peninsula to the Southern Annular Mode. *Acta Oceanologica Sinica*, 43(1): 35–47, doi: 10.1007/s13131-023-2201-y

1 Introduction

The Southern Ocean is widely recognized for modulating the global climate variability due to its active role in carbon uptake and cycling (Smith et al., 1997; Arrigo et al., 2000; Becquevort and Smith, 2001), heat exchange between the ocean and atmosphere (Budillon et al., 2000; Dare and Atkinson, 2000; Roberts et al., 2001) and the meridional overturning circulation (Marshall and Speer, 2012; Talley, 2011; Tamura et al., 2016). Considerable CO₂ uptake and heat exchange occur in the coastal polynyas of the Southern Ocean, which are areas with low sea ice coverage along the coastlines, generally controlled by offshore katabatic and synoptic winds (Bromwich et al., 1998; Massom et al., 1998). As polynyas receive more solar radiation than the other regions during the spring and summer seasons (Li et al., 2016), they become biological hotspots in the Southern Ocean (Arrigo and van Dijken, 2003; Montes-Hugo and Yuan, 2012), which have more than twice the average phytoplankton concentration in open wa-

ters around Antarctica (Arrigo et al., 2015). Consequently, polynyas are also areas with the highest populations of top trophic level species in the Southern Ocean (Karnovsky et al., 2007).

Phytoplankton biomass are closely coupled with physical processes in polynyas, which are in turn influenced by climate variations. The Southern Annular Mode (SAM) is the dominant mode of the southern hemisphere extratropical atmosphere variability, which accounts for 20%–30% of the variance of monthly sea-level pressure (SLP) variation south of 20°S (Hall and Visbeck, 2002; Lefebvre et al., 2004; Gupta and England, 2006). SAM is characterized by opposite geopotential height anomalies in the middle and high latitudes. In the past few decades, due to ozone depletion and rising greenhouse gas levels, SAM has been shifted toward its positive phase, as seen by negative anomalies in geopotential height over the polar cap and positive anomalies over the midlatitudes. This is accompanied by strengthening and poleward shift of the westerly jet (Thompson and Wallace, 2000;

Foundation item: The Key Research & Development Program of the Ministry of Science and Technology of China under contract No. 2022YFC2807601; the National Natural Science Foundation of China under contract Nos 41941008 and 41876221; the Fund of Shanghai Science and Technology Committee under contract Nos 20230711100 and 21QA1404300; the Impact and Response of Antarctic Seas to Climate Change funded by the Chinese Arctic and Antarctic Administration under contract No. IRASCC 1-02-01B; the National Key Research and Development Program of China under contract No. 2019YFC1509102; the Shanghai Pilot Program for Basic Research—Shanghai Jiao Tong University under contract No. 21TQ1400201.

*Corresponding author, E-mail: zrzhang@sjtu.edu.cn

Fyfe, 2003; Gillett and Thompson, 2003; Marshall, 2003; Arblaster and Meehl, 2006). Regional atmospheric systems also show a response, such as that the Amundsen Sea Low strengthens toward a more positive SAM phase (Turner et al., 2013; Li et al., 2021). Changes in the atmospheric circulations impose significant influences on the oceanic properties including ocean circulations, heat budget in the mixed layer, biogeochemical processes (Marini et al., 2011; Screen et al., 2010; Butler et al., 2007) as well as sea-ice fields (Pezza et al., 2012; Simpkins et al., 2012; Zhang et al., 2018).

A couple of previous studies have explored the temporal variations of primary productivity in Antarctic coastal polynyas. Arigo and van Dijken (2003) characterized phytoplankton dynamics in 37 Antarctic polynyas, suggesting interannual changes in the primary productivity and phytoplankton abundance in these regions. Li et al. (2016) examined the synchrony of spring phytoplankton blooms and light availability for 50 circum-Antarctic coastal polynyas using 18-years of satellite observations of sea ice and chlorophyll concentration. They discovered significant synchronicity between the blooms and light intensity in the majority of western Antarctic polynyas and moderate synchronicity in the eastern Antarctic polynyas. La and Park (2016) found a robust correlation between phytoplankton biomass in Antarctic coastal polynyas and the photosynthetically active radiation (PAR), which is in turn related to the cloud cover. Montes-Hugo and Yuan (2012) suggested significant correlations between the summer chlorophyll concentration in the Dumont d'Urville and western Ross Sea polynyas and SAM, while the mechanisms responsible for such relationship remain to be explored.

The western Antarctic Peninsula (WAP) region is one of the most productive areas in the Southern Ocean (Vernet et al., 2008; Huang et al., 2012; Ducklow et al., 2013), and experiences the most significant change in physical environments associated with climate variations (Hansen et al., 1999; Bromwich et al., 2012). SAM has been demonstrated to play a significant role in the interannual variations of ocean dynamical and ecosystem processes in this region (Dinniman et al., 2012; Saba et al., 2014; Zhang et al., 2020). Ecological responses to climate change are reflected in phytoplankton biomass (Montes-Hugo et al., 2009; Moreau et al., 2015) as well as in higher trophic levels (Atkinson et al., 2004; Saba et al., 2014; Steinberg et al., 2015). The Marguerite Bay polynya (MBP) has been found to be a biological hotspot in the WAP throughout austral spring and summer (Clarke et al., 2008). This study aims to reveal the relationship between summertime biological productivity in the MBP and SAM for 2001–2020, which has not been fully understood in previous works. The physical mechanisms for the relationship will be explored combining satellite observations and numerical simulation results.

2 Data and methods

2.1 Data

2.1.1 Satellite data

In this work, the phytoplankton productivity is indicated by the surface chlorophyll-*a* (Chl-*a*) concentration, which were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) Level-3 standard mapped dataset (<https://modis.gsfc.nasa.gov>) with a horizontal resolution of 9 km. September–November and December–February are defined as the austral spring and summer seasons, respectively. Summertime composite Chl-*a* data are used in this work, which is available since 2000.

The satellite sea surface temperature (SST) data used for model validation are also from MODIS, with the same temporal and spatial resolution as Chl-*a*. Daily sea ice concentration (SIC) data were retrieved from the Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, which are available at the National Snow and Ice Data Center (<https://nsidc.org/data/nsidc-0079/versions/3>) with a spatial resolution of 25 km.

2.1.2 Atmospheric data

This study employed monthly wind speed, surface air temperature (SAT), cloudiness and precipitation data from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) product, which has a horizontal resolution of $(1/4)^{\circ}$ by $(1/4)^{\circ}$. To quantify the variation of SAM, the Marshall seasonal SAM indices (SAMI) (Marshall, 2003) were used, which are derived from the anomaly in zonal pressure difference between six stations near 65°S and six stations near 40°S . Higher SAMI indicates a shift toward the positive SAM phase.

2.1.3 Ocean observations

Temperature and salinity data used to validate the modeling results were obtained from the long-term dataset collected by the Palmer Long-Term Ecological Research (Pal LTER; <https://ltern-et.edu/site/palmer-antarctica-lter/>). Pal LTER was established in 1991 with the goal of determining how annual sea ice variability influences the ecology of the WAP. In this work, only CTD samplings within the MBP vicinity in 2001–2020 (see the locations in Fig. 1) are extracted for comparison. Over the 20 years, The Pal LTER program had measurements in the MBP area in 12 years (2001–2005, 2007, 2008, 2011, 2014, 2015, 2017 and 2018; one station each year), mainly in the middle and late January. The CTD measurements are available at a vertical interval of about 1 m. Chl-*a* data were only collected at the stations in 2001, 2003, 2005, 2007, 2014, 2015 and 2018.

2.2 Numerical model

In this work, to explore the significant correlation between interannual variations of summer Chl-*a* and spring SAM, the examinations of ocean hydrological properties are necessary. As mentioned in Section 2.1, observational data in the MBP area were mainly collected in austral summer, and therefore ocean physical parameters (temperature, salinity, mixed layer depth (MLD), etc.) in spring cannot be obtained or analyzed. In addition, the sampling sites in summer were also sparse, and it is hard to determine the statistics of physical parameters over the polynya. As a result, we need to use physical parameters derived from numerical simulations to examine their interannual variability.

2.2.1 Model configuration

The numerical model employed in this study is based on the Regional Ocean Modeling System (ROMS), which is a primitive-equation, finite-difference model with a terrain-following vertical coordinate system (Haidvogel et al., 2008; Shchepetkin and McWilliams, 2009). The model domain straddles the Antarctic Peninsula, extending into the Scotia Sea from the Thurston Island in the southwest (Graham et al., 2016). The model has a horizontal resolution of 1.5 km, and 24 vertical layers with finer resolution towards both surface and bottom. The model includes a simple frazil ice model (Steele et al., 1989), coupled with a dynamic sea ice model (Budgell, 2005) that implements both sea ice thermodynamics and elastic-viscous-plastic dynamics (Hunke and Dukowicz, 1997; Mellor and Kantha, 1989; Häkkinen and Mellor, 1992). The model also includes the thermodynamics and

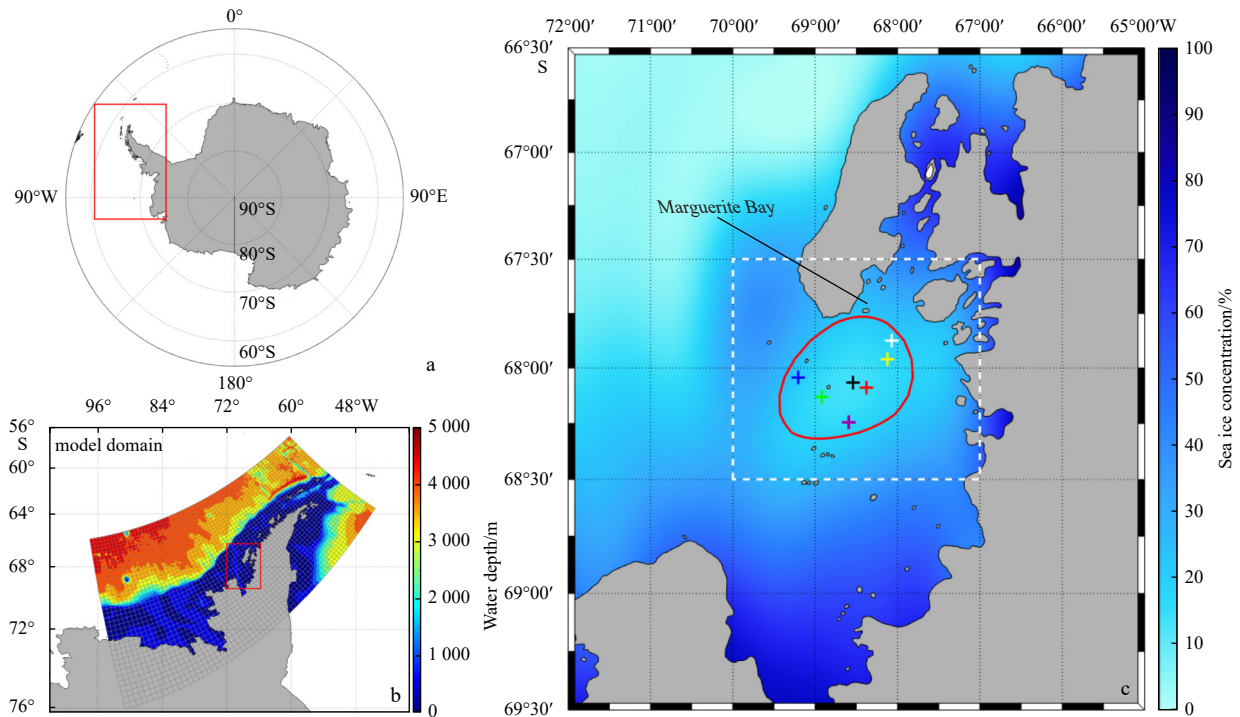


Fig. 1. Location of the numerical model domain in the Southern Ocean (red box) (a), location of the Marguerite Bay polynya area in the model domain (red box) (b), and distribution of the satellite-observed summer-mean sea ice concentration in the Marguerite Bay averaged over 2001–2020 (c). The white dashed rectangle represents the selected box enclosing the polynya, and the red line represents the 20% contour of sea ice concentration. The Pal LTER CTD sampling stations within the polynya area are shown by the plus markers (yellow: 2001; blue: 2002; black: 2003; red: 2004; green: 2005 and 2015; white: 2007, 2008, 2011 and 2017; purple: 2014 and 2018. Stations in different years labeled by the same color are very close to each other, but not at the exact locations). Temperature and salinity data were collected at all stations in the 12 years mentioned above, while Chl-*a* data were only collected in 2001, 2003, 2005, 2007, 2014, 2015 and 2018.

mechanical effects of static ice shelves (Holland and Jenkins, 1999; Dinniman et al., 2007).

Temperature and salinity on the lateral boundaries were nudged to a monthly mean climatology obtained from the combination of the World Ocean Atlas 2013 (WOA13) (Zweng et al., 2013) and the Monthly Isopycnal/Mixed-layer Ocean Climatology (MIMOC) (Schmidt et al., 2013). The Simple Ocean Data Assimilation (SODA v2.2.4) ocean reanalysis provided the velocity and sea surface height by determining the monthly mean climatology for each variable. Tidal forcing is omitted, and monthly SIC was obtained from the combination of Advanced Microwave Scanning Radiometer (AMSR-E) and Special Sensor Microwave Imager/Sounder (SSMIS) at a resolution of 6.25 km. Monthly mean ERA5 product from January 1995 to December 2020 is implemented as atmospheric forcing fields. The COARE 3.0 bulk flux algorithm was used to calculate the open sea surface heat and freshwater fluxes (Fairall et al., 2003).

The model was initialized in January 1995 with initial conditions from six-year spin-up simulations forced by the Antarctic Mesoscale Prediction Systems as described in Graham et al. (2016), and then integrated until December 2020. The model simulations from 2001 to 2020 were used to examine the interannual variability of physical environments (temperature, salinity, ocean mixing and stratification, sea ice freezing and melting, etc.) in the study area.

2.2.2 Model validation

The nonparametric Spearman rank order correlation (Spear-

man, 1904) analysis was used to compare the modelled and observed data (stations are shown in Fig. 1) in the MBP area for the years 2001–2020, and the comparison results are presented in the form of Taylor diagrams (Taylor, 2001). We compared the model outputs with data collected at the 12 stations (Fig. 1). Pointwise comparisons of modelled and observed temperature and salinity within the upper 100 m (basically the maximum range of mixed layer) are shown in Figs 2a and b, respectively. Significant correlations exist between the observed and modelled temperature ($r = 0.55, p < 0.01$) and between the observed and modelled salinity ($r = 0.88, p < 0.01$). The root-mean-square errors (RMSE) are 1.18°C for temperature and 0.52 for salinity, respectively. Figure 2c shows the comparison results between modelled and observed MLD, and the MLD values were calculated based on the CTD data from the 12 Pal LTER sampling stations using the method introduced in Section 2.3. The observed MLD values in January (Fig. 1) were relatively small, with an average value of 14.71 m. The modelled MLD values were similar to the observed data at the 12 sampling stations, with an average value of 16.25 m. Significant correlation also exists between the modelled and observed MLD ($r = 0.86, p < 0.01$), and RMSE is 3.61 m. The performance of the model in simulating spring and summer (the seasons focused on in this work) sea ice was evaluated by satellite data during 2001–2020, as shown in Figs 2d and e. Significant correlations exist between the modelled and observed spring SIC ($r = 0.46, p = 0.04$) as well as summer SIC ($r = 0.61, p < 0.01$), and RMSE are 19.43% and 22.48% respectively. Figure 2f presents

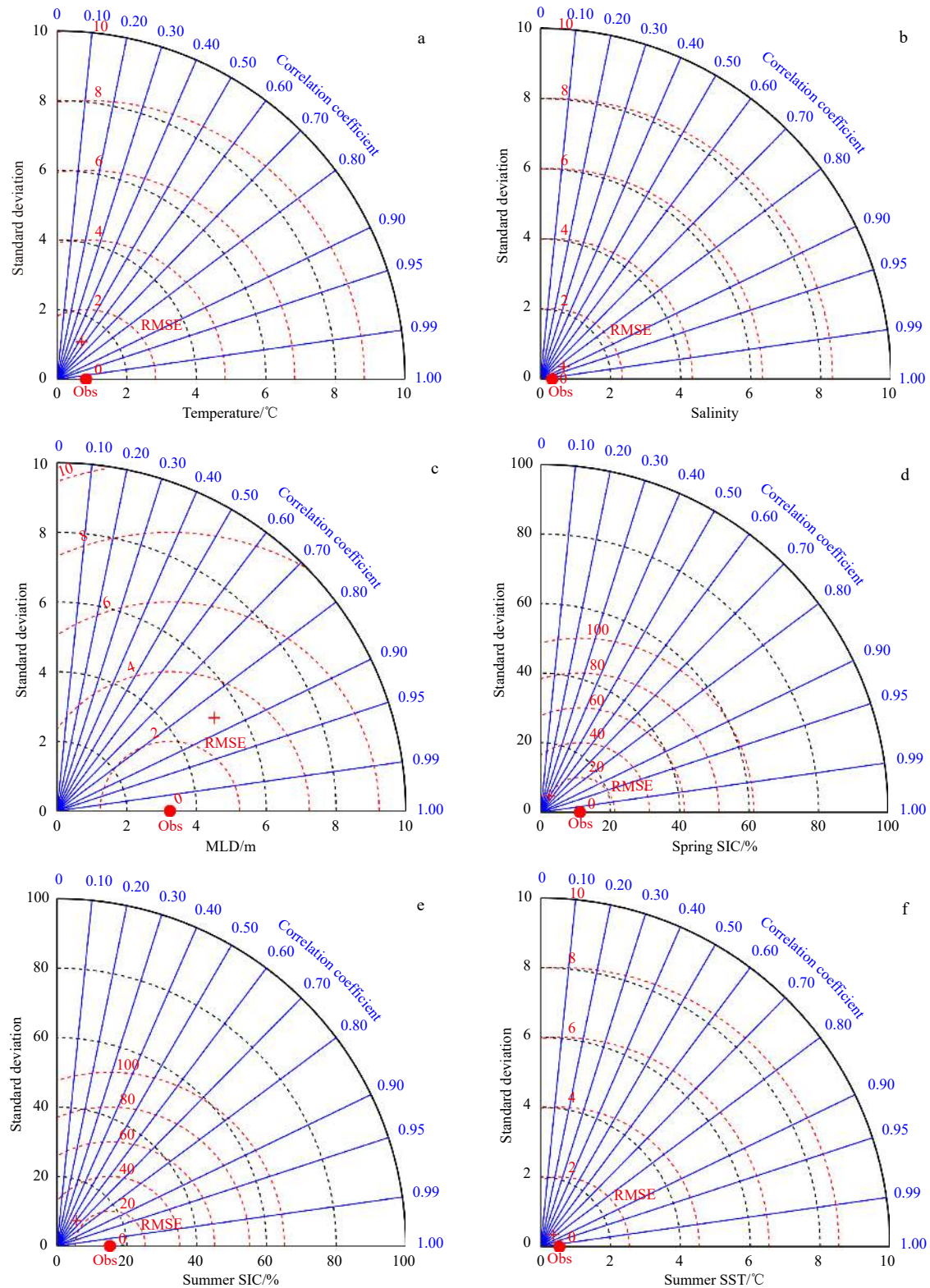


Fig. 2. Taylor diagrams of comparisons between modelled and observed physical parameters in the Marguerite Bay polynya. a. The comparison between modelled and observed temperature (from Pal LTER; Fig. 1). b. The comparison between modelled and observed salinity (from Pal LTER). c. The comparison between modelled and calculated mixed layer depth (MLD) based on temperature and salinity *in-situ* measurements. d. The comparison between modelled and satellite-observed spring sea ice concentration (SIC). e. The comparison between modelled and satellite-observed summer sea ice concentration. f. The comparison between modelled and satellite-observed summer sea surface temperature (SST). The red plus markers indicate the information of correlation coefficients, standard deviations and root mean square errors of the modeled data; the closer they are to the observations (Obs), the smaller the errors between the modeled and observed data are.

the comparison results between modelled and satellite-observed summer SST, with $r = 0.72$, $p < 0.01$ and RMSE of 0.44°C . There are only 4 years with available satellite spring SST data in the MBP region in these 20 years, so the modelled spring SST is not evaluated. We also compared the modelled SST and sea surface salinity (SSS) by observational data from the 12 Pal LTER stations, and found significant correlations between them (SST: $r = 0.61$, $p = 0.04$; SSS: $r = 0.64$, $p = 0.03$; not shown). RMSE are 1.62°C for SST and 0.67 for SSS, respectively. The satellite-observed SSS data are missing, so that we cannot use them to evaluate the performance of the model in simulating SSS. In addition, we showed the annual cycle of sea ice concentration from the model simulation and satellite observation in the MBP (Fig. 3),

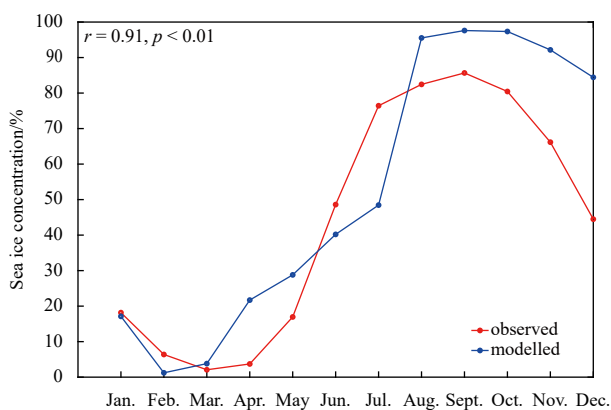


Fig. 3. The modelled and satellite-observed annual cycles of area-mean sea ice concentration in the Marguerite Bay polynya for the years 2001–2020. The correlation coefficient and p -value are shown.

and found that they have similar variation patterns ($r = 0.91$, $p < 0.01$). These results demonstrate the ability of the model in simulating the temporal-spatial variations of sea ice and hydrographic properties in the Marguerite Bay polynya.

2.3 Methods

To determine the location and extent of the MBP, we referred to 37 polynyas identified by Arrigo and vanDijken (2003) to first obtain a rectangular area enclosing the MBP. We then averaged the satellite-observed summer SIC in this rectangular area for 20 years, and defined the polynya as the area where the multi-year average SIC is lower than 20% as shown in Fig. 1. The MLD was defined as the depth at which the potential density (σ) exceeds the surface potential density (10 m) by 0.03 kg/m^3 (Dong et al., 2008). The nonparametric Spearman rank order correlation was used to quantify the relationship among Chl-*a*, physical variables and SAM.

3 Results

3.1 Chlorophyll concentration and seasonal SAM

The timeseries of satellite-observed summer Chl-*a* averaged over the MBP from 2001 to 2020 are shown in Fig. 4. Summer Chl-*a* concentration values ranged from 0.85 mg/m^3 to 3.68 mg/m^3 , with the maxima occurring in 2014 and the minima occurring in 2002. An examination of the correlations between the interannual variations of summer Chl-*a* and seasonal SAMI (Figs 4a, b and c) shows that Chl-*a* is only significantly related with the spring SAMI ($r = -0.52$, $p = 0.02$), and weakly correlated with the summer SAMI ($r = -0.42$, $p = 0.06$).

3.2 Factors linking the summer Chl-*a* and spring SAM

MLD is an indicator of the strength of ocean vertical mixing,

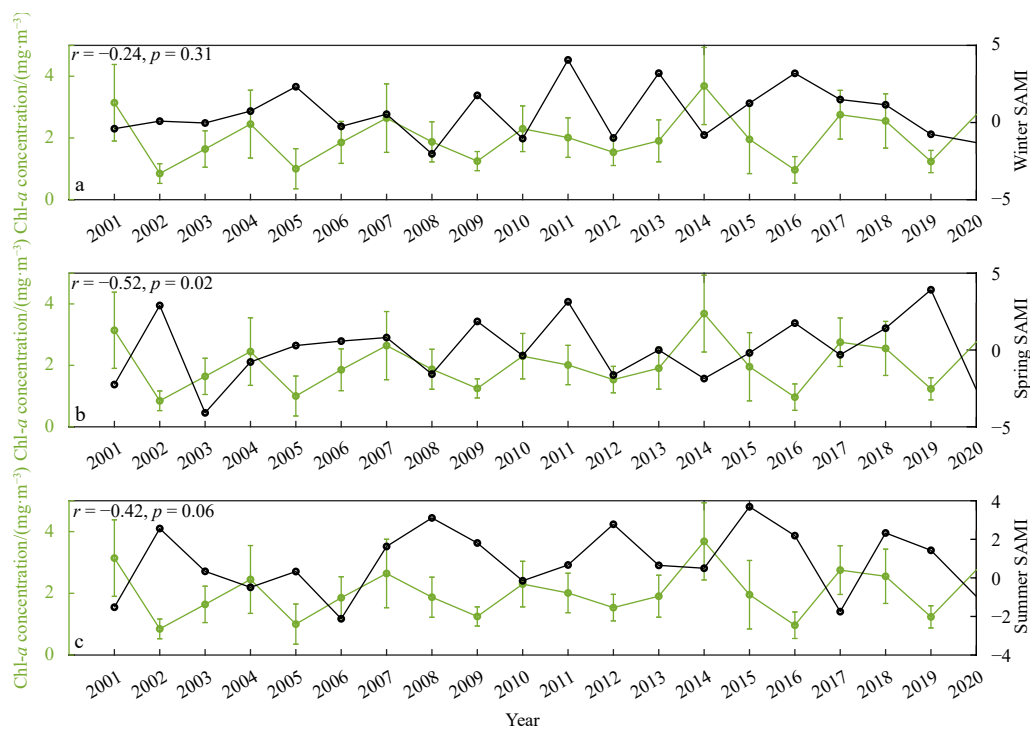


Fig. 4. Time series of the satellite-observed summer-mean chlorophyll-*a* (Chl-*a*) concentration averaged over the Marguerite Bay polynya (green lines) and the winter (a), spring (b), and summer (c) SAM indices (SAMI; black lines) for 2001–2020. The correlation coefficients, p -values, and standard deviations of Chl-*a* concentration (vertical bars) are shown.

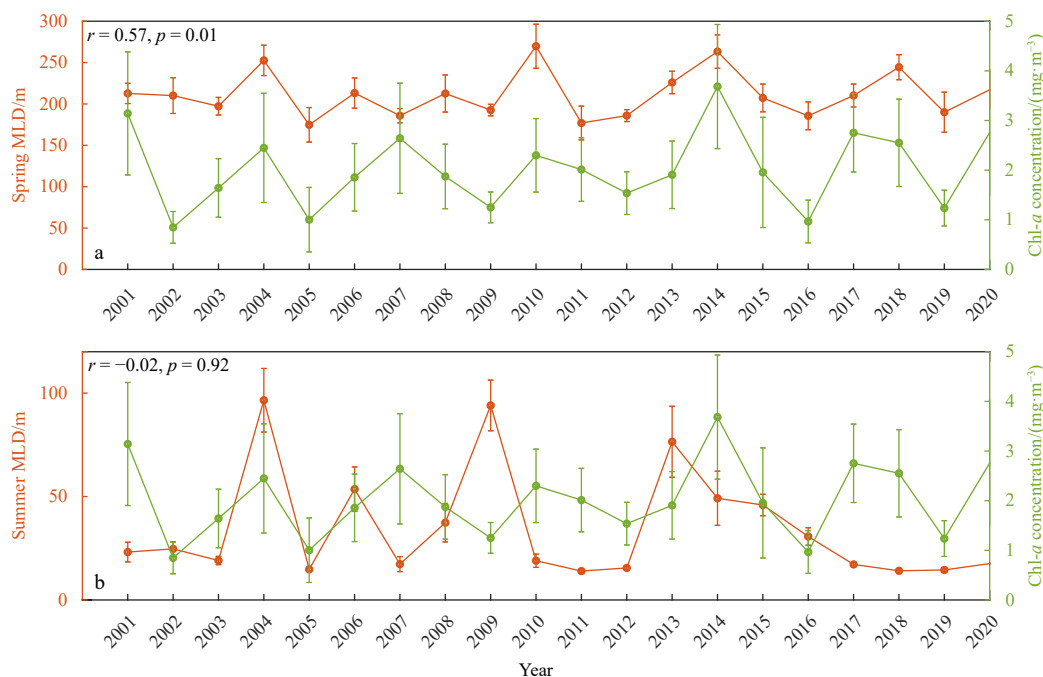


Fig. 5. Time series of the modelled spring (a) and summer (b) mean mixed layer depth (MLD) and summer-mean chlorophyll-*a* (Chl-*a*) concentration averaged over the Marguerite Bay polynya for 2001–2020. The correlation coefficients, *p*-values, and standard deviations (vertical bars) are shown.

and has crucial impacts on biological production in the Southern Ocean. The effect of MLD on phytoplankton biomass in the MBP is a trade-off between available light irradiance for the phytoplankton and nutrients supplied to the surface water. Figure 5 shows the timeseries of the modelled MLD averaged over the MBP during spring and summer and the summer Chl-*a* for 2001–2020. In all years, summer MLD values were generally lower than 100 m and mostly around 25 m. The summer Chl-*a* and summer MLD were not statistically correlated (as the temporal variation of MLD within summer is relatively small). In contrast, the MLD in spring is larger, and there exists a significant and positive correlation between the spring MLD and summer Chl-*a* ($r = 0.57$, $p = 0.01$), indicating that the stratification of water column in spring can affect the ecosystem production in summer.

To explore if spring MLD is the factor linking the variability of summer Chl-*a* and spring SAM, we examined the spring MLD patterns (Fig. 6) in 5 years of 2001–2020 with the highest spring SAMI (2002, 2009, 2011, 2016 and 2019) and 5 years with the lowest spring SAMI (2001, 2003, 2012, 2014 and 2020). Except for 2002 and 2012, there is a general trend of higher MLD in low-SAMI years compared to high-SAMI years. For the low-SAMI years, the polynya-averaged MLD ranged from 200 m to 270 m, except for 2012 when the value was around 185 m (Figs 6a–e). A large decrease of satellite-observed SIC happened in 2012 (2001: 82.44%; 2003: 88.49%; 2012: 74.19%; 2014: 85.09%; 2020: 84.38%), and lower SIC implies more sea ice melting, which would be accompanied by the strengthening of ocean stratification, resulting in the shallower spring MLD in 2012. The high-SAMI years exhibited lower MLD with the polynya-average values normally below 190 m except for 2002 when the MLD reached 210 m (Figs 6f–j). The interannual variation of spring MLD is significantly and negatively correlated with the spring SAMI ($r = 0.45$, $p = 0.05$; Fig. 6k).

3.3 Mechanisms for the relation between vertical mixing and SAM

Wind-driven vertical mixing and Ekman pumping can significantly alter the water column stratification and affect the distributions of nutrients and phytoplankton. However, in the MBP area, our results do not show significant relationship between the interannual variations of spring wind speed and spring MLD ($r = -0.23$ and $p = 0.32$; not shown). As such, the correlation between spring MLD and SAM should be connected by other processes, such as the surface heat fluxes and freshwater fluxes as examined below.

SST and SSS, which are respectively modulated by air-sea heat and freshwater fluxes, can be the driving factors for the interannual variation of vertical mixing in the MBP region. No significant correlation is found in our analysis between the modelled spring SST and spring MLD in the MBP ($r = 0.29$ and $p = 0.20$; not shown). On the contrary, the interannual variability of modelled polynya-averaged SSS is significantly and positively correlated with the variability of spring MLD ($r = 0.45$, $p = 0.05$; Fig. 7a), and both of them are positively correlated with the interannual variation of the modelled surface density ($r = 0.90$ and $p = 0.01$ for SSS, Fig. 7b; and $r = 0.47$ and $p = 0.03$ for MLD, Fig. 7c). This suggests that salinity change is the major driver of the surface density change that determines the temporal variation of MLD.

Sea ice freezing and melting can play an important role in the surface salinity change. However, when examining the interannual variations of the satellite-observed SIC and modelled sea ice production rate averaged over the MBP in spring, we found neither quantity is related to the interannual variability of spring SSS. We then examined the role of precipitation in the SSS variation, and found that the interannual variation of spring precipitation over the polynya is significantly and negatively correlated with the variation of spring SSS ($r = -0.54$, $p = 0.01$; Fig. 8a) as well as the spring SAMI ($r = 0.43$, $p = 0.05$; Fig. 8b). It is further

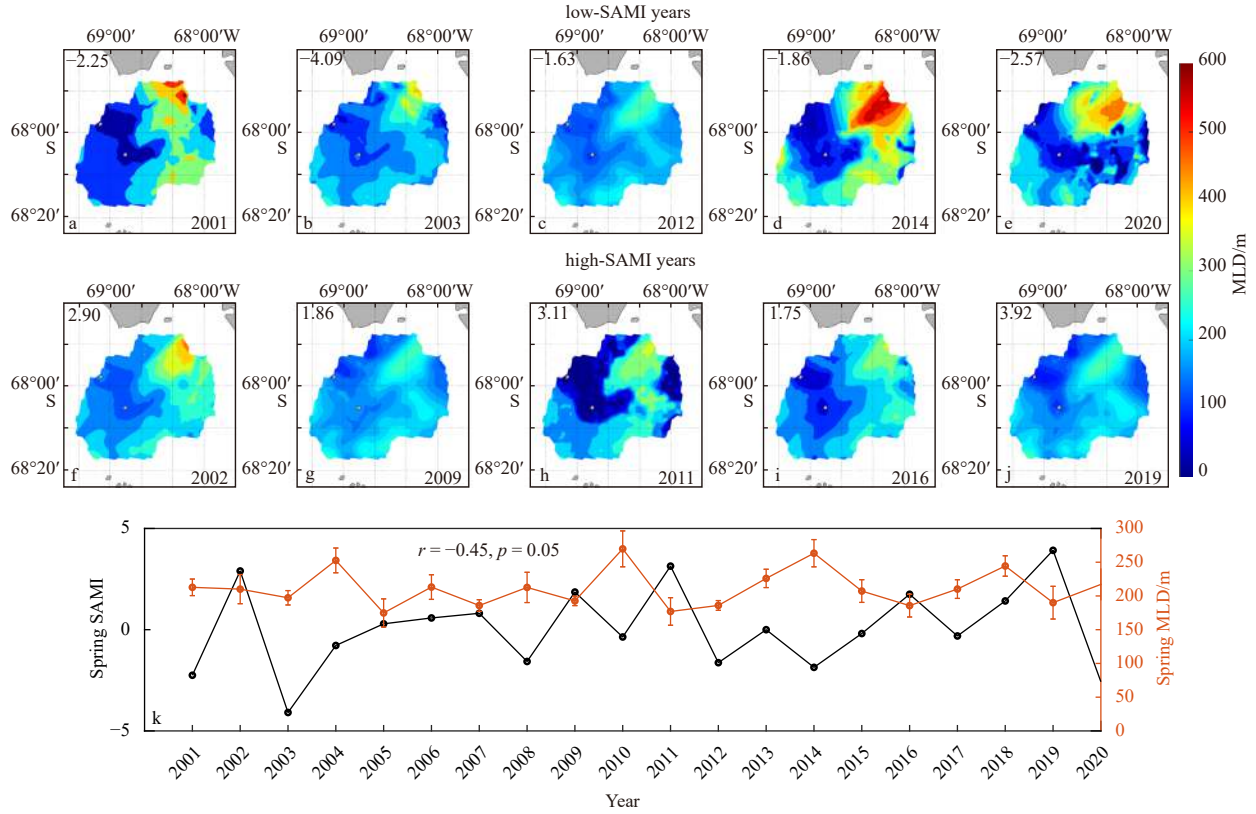


Fig. 6. Spatial distributions of the modelled spring-mean mixed layer depth (MLD) in the Marguerite Bay polynya during years with low spring SAM index (a–e) and high spring SAM index (f–j), and time series of spring SAM index and spring MLD in the MBP for 2001–2020 (k). In a–j, the SAM indices are labeled in the upper left corner of the panels. In k, the correlation coefficient, p -value, and standard deviations of MLD (vertical bars) are also shown.

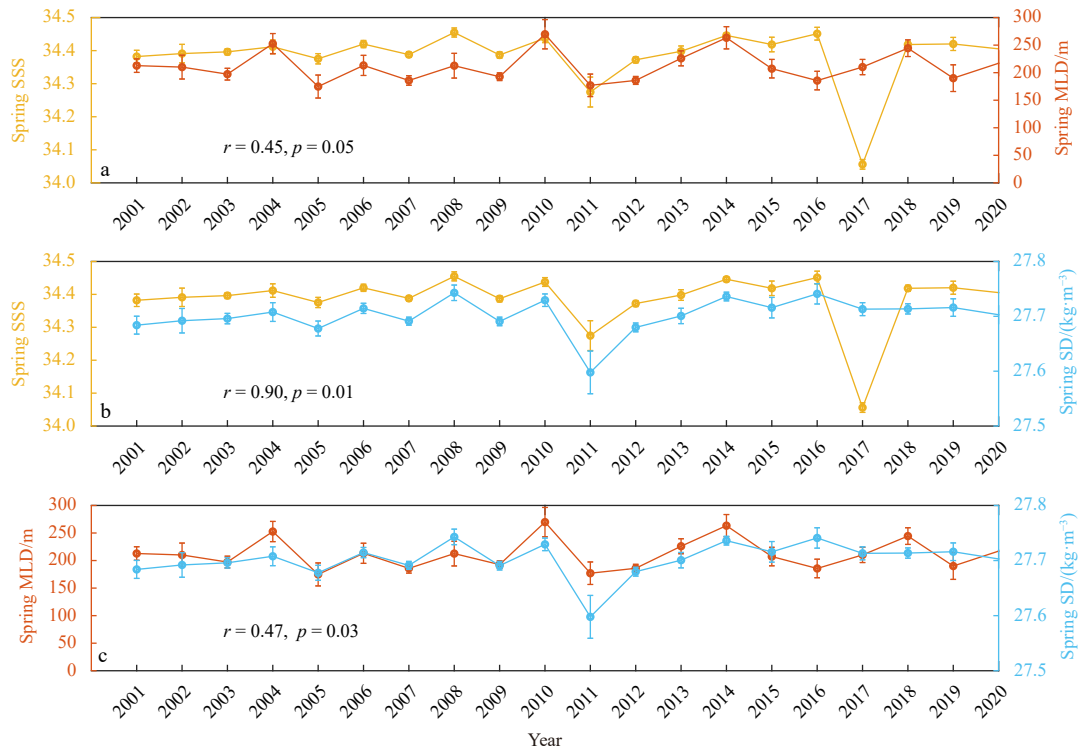


Fig. 7. Time series of the modelled spring-mean sea surface salinity (SSS) and mixed layer depth (MLD) (a), SSS and surface density (SD) (b), and MLD and surface density (c) in the Marguerite Bay polynya for 2001–2020. The correlation coefficients, p -values, and standard deviations (vertical bars) are shown.

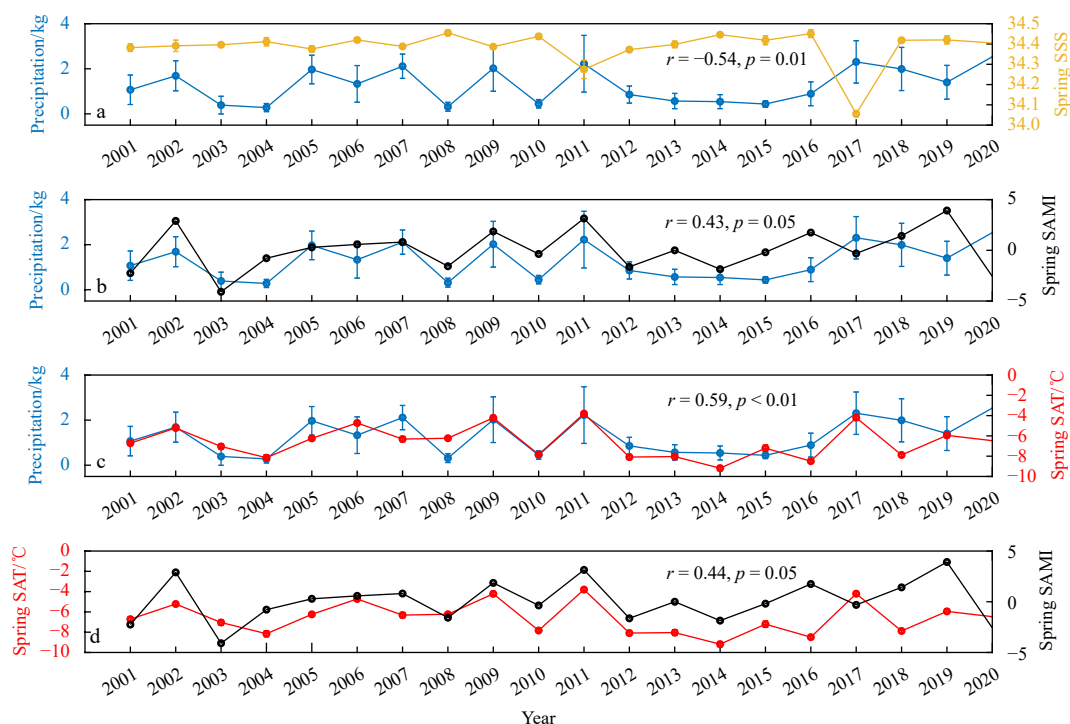


Fig. 8. Time series of spring-mean precipitation (from ERA5) and sea surface salinity (SSS; modelled) (a), precipitation and SAM index (SAMI) (b), precipitation and surface air temperature (SAT; from ERA5) (c), and SAT and SAMI (d) for the Marguerite Bay polynya during 2001–2020. The correlation coefficients, p -values, and standard deviations (vertical bars) are shown.

found that the variability of spring precipitation is closely related to that of spring SAT over the MBP ($r = 0.59$, $p < 0.01$; Fig. 8c), which is also significantly and positively correlated ($r = 0.44$, $p = 0.05$) with the spring SAMI (Fig. 8d). The reason for the relations of SAT and precipitation to SAM will be discussed in Section 4.

4 Discussion

4.1 The representation of surface Chl-*a* for the phytoplankton biomass

During the time period that our study focuses on, The Pal LTER program had Chl-*a* concentration measurements in the MBP area in 7 years (Fig. 1). The sampling time were mainly in middle and late January. The vertical profiles of Chl-*a* concentration at the sampling stations are shown in Fig. 9. The maximum value of Chl-*a* mostly occurred in the subsurface layer (5–15 m; except for 2014), and at several stations the surface Chl-*a* concentrations were close to the subsurface values. Also, Clarke et al. (2008) used the data collected at the Rothera Antarctic Time Series site (RATS; about 0.3° north of the MBP) and its nearby stations in the Marguerite Bay for 1997–2006 to study the vertical distribution of Chl-*a* concentration, finding that the Chl-*a* concentration at 15 m was strongly correlated with Chl-*a* concentration integrated over the upper 50 m and 100 m. Combining these facts, we consider the satellite-observed surface Chl-*a* concentration analyzed in this study as a good reflection of the MLD-averaged phytoplankton biomass in summer.

4.2 Light availability

Light limitation has been identified as a significant factor influencing the spring primary production in the Southern Ocean (Arrigo et al., 2010; Joy-Warren et al., 2019), which implies that if

the WAP was limited by light irradiance during spring, nutrient consumption would be reduced and more nutrients would be retained until summer. On the other hand, positive SAM is associated with depleted ozone cover over Antarctica (Arblaster and Meehl, 2006; Polvani et al., 2011), which may enhance the light irradiance reaching the sea surface (Hamre et al., 2008; Zhang et al., 2020). As such, spring SAM may control phytoplankton dynamics in the MBP in summer by regulating the local spring light conditions. However, the PAR data were severely missing in the MBP region, making it impossible to examine the relation between PAR and SAM. Revealing the role of light radiance in linking the phytoplankton biomass and SAM rely on long-term *in-situ* PAR data in the study area in the future.

4.3 Potential mechanisms for the positive relation between summer Chl-*a* and spring MLD

Iron (Fe) is a critical micronutrient for phytoplankton but is in short supply in the Southern Ocean (Measures et al., 2013; Annett et al., 2015; Jiang et al., 2019). The WAP is known as an important region of Fe source to the Southern Ocean, and both dissolved and particulate Fe are high on the WAP continental shelf (Ardelan et al., 2010; Measures et al., 2013; Annett et al., 2017). However, due to geographically varying inputs and abiotic or biological sinks, the WAP surface waters may not be uniformly replete with Fe. For example, Annett et al. (2017) found that low Fe concentrations (< 0.1 nmol/kg) were widespread in shelf surface waters, suggesting potential iron limitation of primary production in shelf waters. Heterogeneous Fe deficiency has also been postulated to explain the distributions of shelf primary production (Garibotti et al., 2003; Smith et al., 2008; Huang et al., 2012). An important Fe supply mechanism in the WAP region is that enhanced vertical mixing could entrain much Fe originating from sediments to the surface layers (Measures et al., 2013; Tagliabue

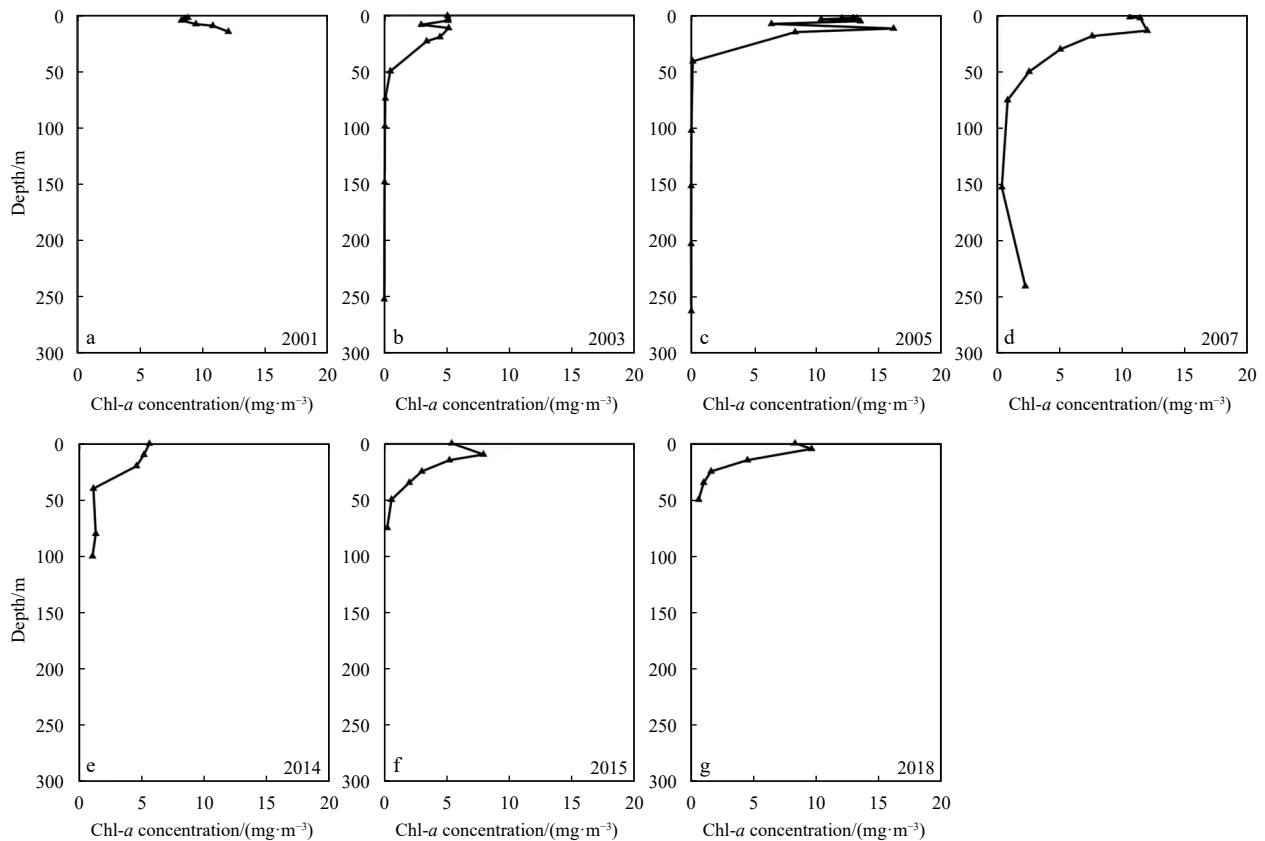


Fig. 9. The vertical profiles of chlorophyll-*a* (Chl-*a*) concentration at the 7 Pal LTER stations (Fig. 1) in 2001–2018.

et al., 2014). Mixing with deeper, Fe-replete water can mitigate the Fe limitation and enhance productivity in surface water. On the other hand, the upwelling of comparatively Fe-enriched modified Circumpolar Deep Water (mCDW) is one possible source of micronutrients for the WAP shelf euphotic zone (Planquette et al., 2013; Annett et al., 2015; Bown et al., 2017; Arrigo et al., 2017), and stronger mixing can entrain more CDW into the surface water and elevate the surface iron concentration.

Annett et al. (2015) examined the vertical distributions of dissolved Fe (dFe) based on data collected at RATS from December 2009 to March 2010, and found that a subsurface minimum was present at 50 m [$dFe = (3.8 \pm 0.3) \text{ nmol/kg}$], below which dFe increased to a maximum of $(9.5 \pm 0.3) \text{ nmol/kg}$ at 200 m which was the deepest water sampled. Bown et al. (2018) used the dFe samples collected at RATS and nearby sampling stations (11 in total) in the summer of 2013 and 2014 to reveal that the local dFe showing a monotonic increase from the surface to the bottom. On the other hand, the MLD at the RATS site showed the characteristics of deep in spring (40–100 m) and shallow in summer (0–20 m) (Clarke et al., 2008; Annett et al., 2015), which is consistent with the modelled seasonal variation of MLD (Fig. 10). Combining the vertical distribution of dFe and seasonal variation of MLD in the Marguerite Bay, there can be dFe limitation in the surface water of this area and dFe can be supplemented by strong vertical mixing of Fe-enriched deep water in spring.

Phytoplankton photosynthesis during spring preceding the summer season was not active due to the light limitation. Thus, Fe replenished via deep spring mixing was not utilized adequately and could accumulate. When it came to summer, Fe accumulated in spring was retained in the upper water due to the

lower MLD. With sufficient light and more Fe, summer primary production would increase significantly. The phytoplankton biomass produced in the spring season was also contributing to the Chl-*a* concentration during summer. As a result, the positive relationship between spring MLD and summer Chl-*a* may be explained as follows. During spring, higher MLD would enhance vertical mixing and supply more Fe from deep water rich in Fe to surface, which may retain in summer due to low productivity and Fe consumption in spring.

4.4 Surface air temperature and SAM

Positive relationship is found between the precipitation over the MBP and SAM in spring in Section 3.3. A shift of SAM towards its positive phase would result in the reinforcement and poleward shift of westerlies, which can bring more warm and moist air from the ocean to the Antarctic Peninsula continent and coastal regions. The Amundsen Sea Low is also found to be deepened during positive SAM phase, which will carry more warm air from lower latitudes to the WAP area (Gupta and England, 2006; Zhang et al., 2018). Both of the two processes mentioned above can result in warmer SAT over the MBP in positive SAM conditions and increase the precipitation rate, which ultimately weaken the vertical mixing and enhance phytoplankton biomass in summer.

4.5 Applicability of the coupled physical-biological processes related to SAM to Antarctic polynyas

This study finds a negative relationship between interannual variations of summer Chl-*a* in the MBP region and spring SAM. The impacts of SAM on Antarctic physical processes and phytoplankton biomass can vary across regions, depending on the loc-

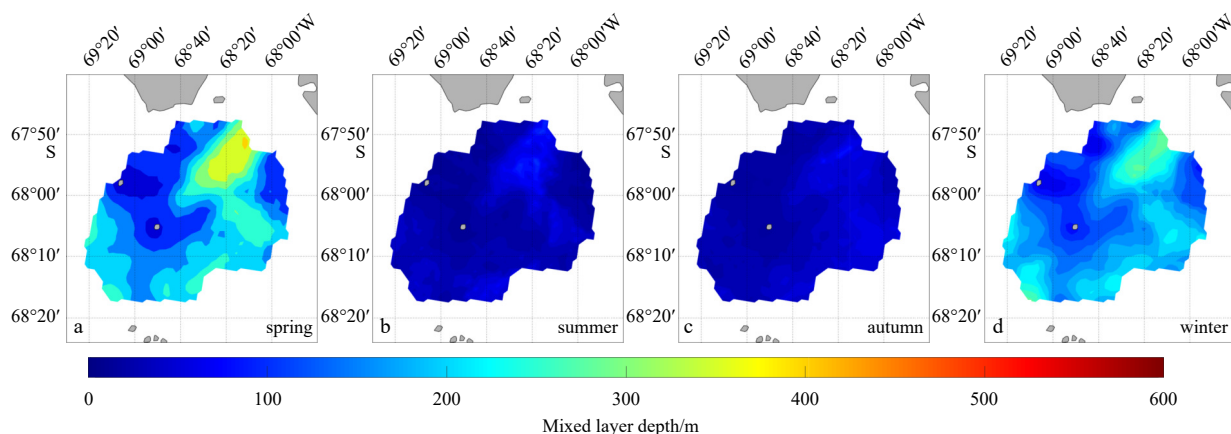


Fig. 10. The annual cycle of modelled mixed layer depth in the Marguerite Bay polynya for the years 2001–2020.

al topography and atmospheric circulation systems. For the western Antarctic Peninsula area, which are located at relatively low latitudes, the prevailing (background) winds are westerlies, and the enhancement in westerlies in positive SAM phase will increase the wind speed and generate stronger ocean vertical mixing, while also bringing more warm air from the ocean toward the Antarctic continent that increases precipitation and ocean stratification. The impact of SAM on the mixed layer depth in this region is the result of competition between wind-induced mixing and precipitation-induced stratification. For coastal polynyas at higher latitudes, such as in the East Antarctic where easterlies prevail, the poleward shift of westerlies in positive SAM phase will weaken the easterlies and thus the vertical mixing. The relationship between MLD and SAM and the impact on summer phytoplankton biomass are expected to be different and need to be examined using local data.

5 Conclusions

In this study, satellite observations, numerical simulations, and atmospheric reanalysis data were combined to reveal the relationship between phytoplankton biomass in the Marguerite Bay polynya during austral summer and the Southern Annular Mode based on data from 2001 to 2020. The interannual variation in Chl-*a* concentration in the study area is significantly and negatively correlated with spring SAM. The physical-ecological coupling mechanisms are summarized in Fig. 11. A shift toward the positive SAM phase in spring would be accompanied by strong northwesterlies over the MBP, which brought warm air from the lower latitudes to the study area. The atmospheric warming increases local precipitation rate, which reduces the sea surface salinity and enhances the stratification of the upper water column in spring. In such situation, less dissolved iron would be entrained from deep waters originating from sediments to sur-

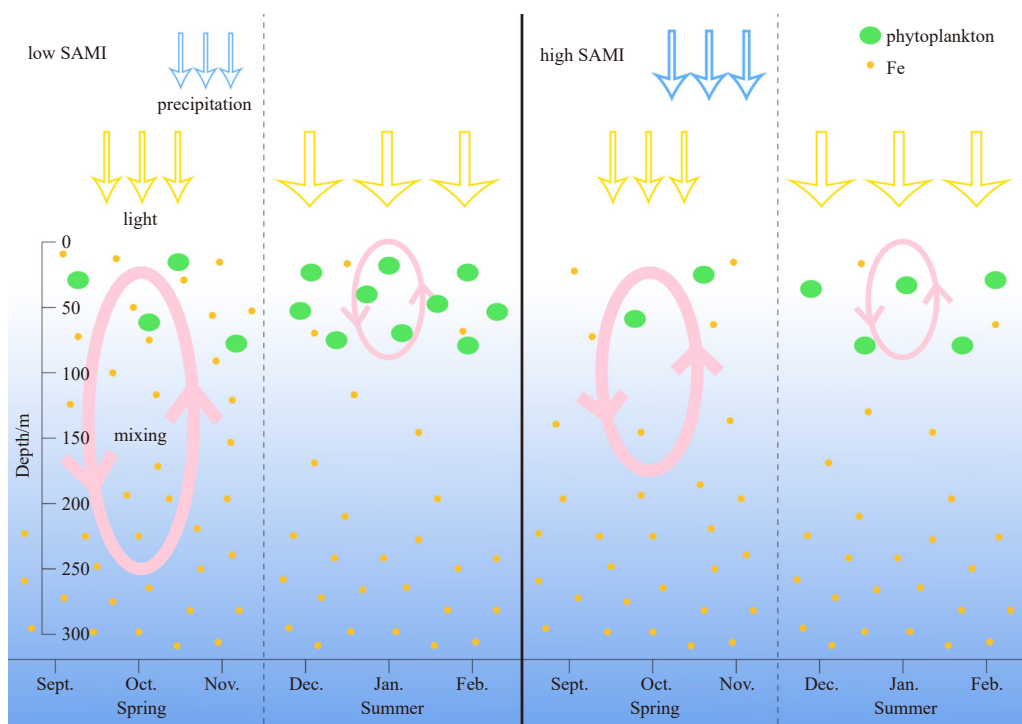


Fig. 11. Schematic for the mechanisms linking the interannual variations of summer phytoplankton biomass in the Marguerite Bay polynya and spring SAM. The yellow dots represent iron (Fe), and the green dots represent phytoplankton biomass.

face layers, and low Fe concentration would affect the primary production in summer. The relationship between phytoplankton biomass and SAM may vary in different regions of the Southern Ocean depending on the source of macronutrients and the competition in changes of vertical mixing induced by wind speed and precipitation associated with SAM. This study does not consider the top-down control on the interannual variation of phytoplankton biomass in the study area, and the significant correlation between physical parameters and Chl-*a* concentration revealed in this study suggests that the bottom-up control dominates the interannual variation of summer phytoplankton biomass in the MBP region. For other regions in the Southern Ocean the zooplankton predation may also be important in modulating the variations of phytoplankton biomass and may not be ignored, and studies of such impacts require long-term data of zooplankton biomass.

Acknowledgements

We thank Michael S. Dinniman with Old Dominion University and Jennifer A. Graham with Met Office Hadley Centre for providing the numerical model configurations, based on which we conducted the long-term simulations in this study. We also acknowledge the Shanghai Frontiers Science Center of Polar Science (SCOPS) for its support.

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