· Review ·
**Advances in Polar Science**
doi: 10.13679/j.advps.2022.0022
March 2023 Vol. 34 No. 1: 5-16

# Temporal and spatial variation characteristics of Antarctic sea ice and the causes of its record decline during 2015–2016: a review

YANG Yingyue[1], LIU Hailong[1,2,3*] & WANG Xidong[4,5,6]

[1] School of Oceanography, Shanghai Jiao Tong University, Shanghai 200030, China;
[2] Polar Research Institute of China, Shanghai 200136, China;
[3] Key Laboratory for Polar Science, MNR, Polar Research Institute of China, Shanghai 200136, China;
[4] Key Laboratory of Marine Hazards Forecasting, MNR, Hohai University, Nanjing 210024, China;
[5] College of Ocean, Hohai University, Nanjing 210098, China;
[6] Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519082, China

**Received 12 September 2022; accepted 9 January 2023; published online 31 March 2023**

**Abstract** Satellite observations over the past four decades have shown that the long-term trend of Antarctic sea ice extent (SIE) is opposite to the trend of sea ice extent in the Arctic. Arctic sea ice extent continues to decline while Antarctic SIE is generally on the rise except for a dramatic decline in 2015–2016. Based on the 40-year climatology from 1981 to 2020, Antarctic SIE anomaly in December 2016 is $-2.1\times10^6$ $km^2$, reaching the minimum since 1979. There are many studies on the cause of this record decline. This present review summarizes the spatial and temporal characters of Antarctic sea ice and recaps major findings on the causes of record decline in 2015–2016 from the perspective of direct thermodynamic and dynamic process of atmosphere and ocean as well as the modulation of climate modes. Finally, the challenges and key scientific problems to be solved in the future of Antarctic sea ice research are presented.

**Keywords** **Antarctic sea ice, sea ice extent, sea ice concentration, climate variability**

**Citation:** Yang Y Y, Liu H L, Wang X D. Temporal and spatial variation characteristics of Antarctic sea ice and the causes of its record decline during 2015–2016: a review. Adv Polar Sci, 2023, 34(1) 5-16, doi: 10.13679/j.advps.2022.0022

## 1 Introduction

Sea ice can not only regulate heat and mass exchange between atmosphere and ocean (Raphael, 2003; Massom and Stammerjohn, 2010), but also influence the temperature and salinity of sea water by melting and freezing, further impacting on ocean circulation (Aagaard and Carmack, 1989; Kirkman and Bitz, 2011). Moreover, sea ice plays an important role in the global climate system due to its radiation effects on atmospheric circulation, cloud formation and precipitation patterns (Lemke et al., 1980; Bracegirdle et al., 2015). Antarctic sea ice covers about half of the world's total sea ice area and is generally distributed around the edge of the Antarctic continent. The variability of Antarctic sea ice significantly contributes to the variation of total global sea ice and exert important influences on the global climate, and thus research on this topic is of particular significance.

In order to intuitively represent the long-term trend of sea ice, it is necessary to analyze the related parameters characterizing sea ice. At present, most studies about sea ice focus on the temporal and spatial characteristics of sea ice concentration (SIC) and sea ice extent (SIE). There are also some studies about the variation of sea ice thickness (SIT)

* Corresponding author, ORCID: 0000-0001-8335-7272, E-mail: hailong.liu@sjtu.edu.cn

and sea ice volume (SIV). SIC is the ratio of the area covered by sea ice to the total area in a specific region, and SIE is the sum of the areas with SIC greater than 15% in the region of research (Wang et al., 2020).

In the past four decades, the trends of Antarctic sea ice and Arctic sea ice are opposite (Comiso et al., 2017; Parkinson, 2019). In general, the Antarctic SIE is on the rise, and the annual average SIE reaches $12.8\times10^6$ km$^2$ in 2014, which is the highest value since 1979. However, the trend of Arctic SIE starts going down from 1979 (Parkinson, 2019). Previous study used reconstructions and have found that Antarctic sea ice trends changed sign around 1960 and total Antarctic sea ice significantly increases in all four seasons during the recorded period since 1979 in the twentieth century (Fogt et al., 2022). During 1978–2015, Arctic SIE decreases by about 4.36% per decade on average, while Antarctic SIE increases by about 1.7% per decade on average (Comiso et al., 2017). Possible explanations for the increasing trend of Antarctic SIE have been proposed, such as atmospheric teleconnection modes in different tropical regions and their resulting high latitude thermal advection in the southern hemisphere (Li et al., 2014; Simpkins et al., 2014), intensification of cyclone activity over the region caused by the deepening of Amundsen Low (Turner et al., 2009; Meehl et al., 2016), enhanced wind activities around the South Pole due to the positive phase of Southern Hemisphere Annular Mode (SAM) (Turner et al., 2015; Stuecker et al., 2017) , internal variability over long time scales in the Southern Ocean with rising atmospheric $CO_2$ (Singh et al., 2019) and so on. Nevertheless, there is still no consensus on the mechanism of long-term increase of Antarctic sea ice.

Surprisingly, Antarctic SIE decreases rapidly after 2014 (Wang et al., 2019). The average annual SIE decreases by $1.2\times10^6$ km$^2$ between 2015 and 2016, which is the largest decrease since 1979. The dramatic decline of Antarctic SIE happens from September to December 2016, and the negative monthly SIE anomaly decreases to the lowest record since 1979 in December 2016 (Parkinson 2019; Li et al., 2021). From 2014 to 2017, the decline rate of Antarctic SIE is much higher than that of Arctic SIE (Parkinson, 2019). In addition, SIC in most areas of the Southern Ocean also shows a downward trend from 2014 to 2019, especially in the Weddell Sea and Ross Sea (Hao et al., 2021).

The rapid decline of Antarctic SIC and SIE in 2015–2016 has attracted the attention and discussion, and the related studies on the characteristics and the dominant factors of this decline have been enriched in recent years. Eayrs et al. (2021) and Li et al. (2021) reviewed the atmospheric and oceanic causes for the rapid decline of Antarctic sea ice in 2016. However, they only regarded the decline of sea ice in 2016 as a single event and described which environmental factors controlled this process. They did not link this event with the background of climate variability. At this present review we summarize the spatial and temporal characteristics of Antarctic sea ice variation at different time scales, and comb the causes of the decline of Antarctic sea ice in 2015–2016 from the perspective of atmosphere and ocean direct processes and the modulated effects of climate variability, respectively. Finally, the key issues that need to be solved about Antarctic sea ice are put forward in four aspects: the time range of satellite observation data, the variation of SIT, the natural and anthropogenic attribution of long-term change of SIE, and the latest observation that Antarctic SIE rapidly declines again in 2021–2022.

# 2 Characteristics of Antarctic sea ice variation

The characteristics of Antarctic sea ice variation depend on regions, such as Ross Sea, Amundsen-Bellingshausen Sea and Weddell Sea are affected by Amundsen Low and the variation of sea ice in those regions is always influenced by the changes of Amundsen Low (Li et al., 2021). According to most studies (Simpkins et al., 2012; Parkinson, 2019; Hao et al., 2021), the Southern Ocean is divided into five regions: Ross Sea (RS, 160°E–130°W), Amundsen-Bellingshausen Sea (ABS, 130°W–60°W), Weddell Sea (WS, 60°W–20°E), Indian Ocean (IO, 20°E–90°E), western Pacific Ocean (PO, 90°E–160°E). Antarctic sea ice variation shows annual cycle, significant inter-annual characteristics and long-term trends. The variations of the Antarctic sea ice on different time scales are described and summarized as follows.

## 2.1 Annual cycle

The atmospheric temperature and ocean temperature in the southern hemisphere vary with the seasonal cycle, which leads to the significant seasonal variation of Antarctic sea ice. That is, SIE reaches the minimum in summer and the highest value in winter. Parkinson (2019) researched the annual cycle of Antarctic SIE during January 1979 and December 2018 in the Southern Ocean and the five regions and found that the quite prominent annual cycle has minimum monthly SIE always occurring in February, which is lower than $5\times10^6$ km$^2$ and maximum SIE occurring in September, which is more than $17\times10^6$ km$^2$. The annual cycle of SIE in the Weddell Sea and Amundsen-Bellingshausen Sea is similar to that in the Southern Ocean. Although the peaks of SIE in the western Pacific Ocean and Ross Sea occur in September, the SIEs in August and October are not much different from those in September. While, the maximum SIE in the Indian Ocean occurs in October rather than September, making this region unique with the most asymmetric annual cycle. We extend the time to December 2021 and calculate the annual cycle (shown as Figure 1), and the results are consistent with those of Parkinson (2019).

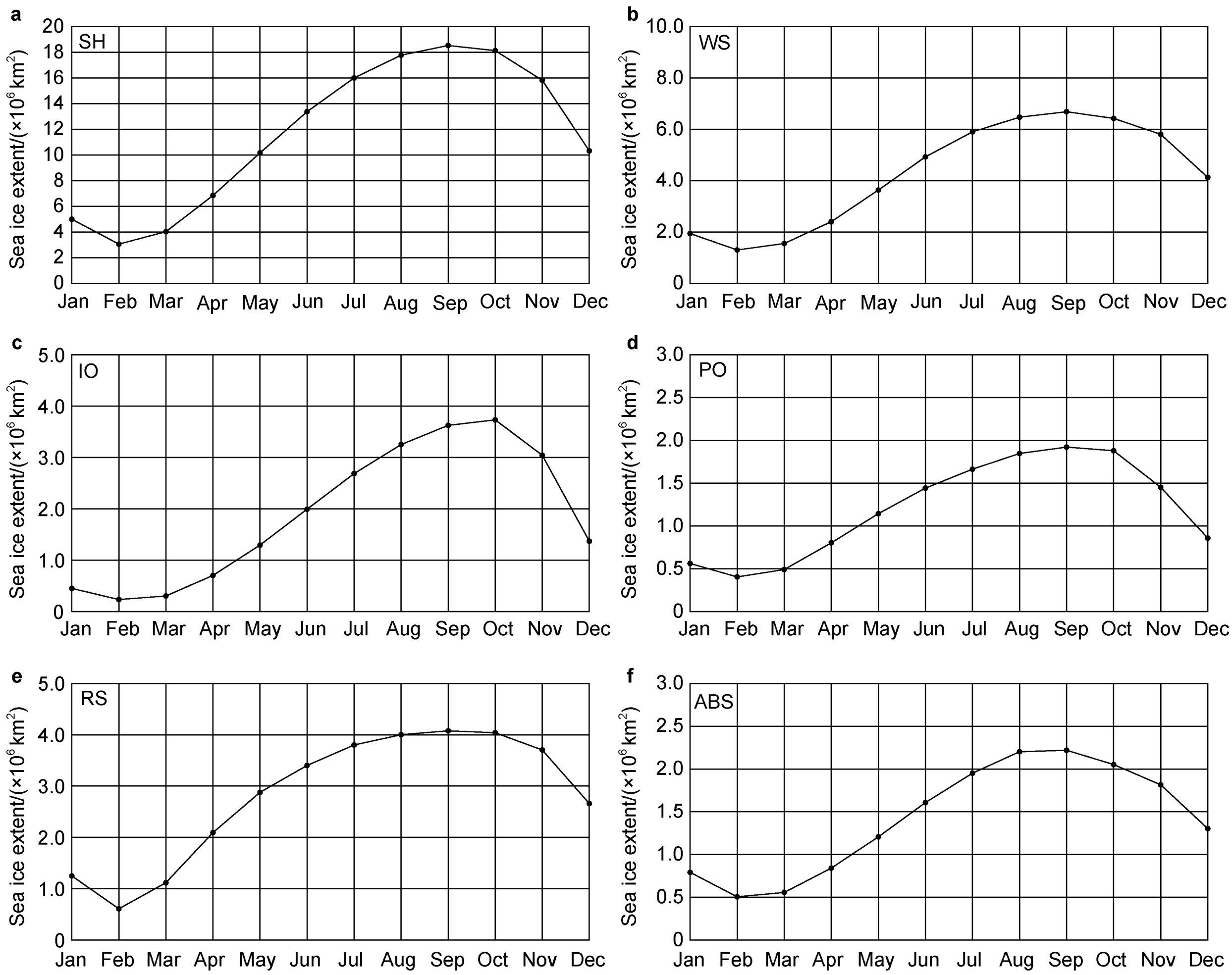


**Figure 1** SIE climatology from January 1979 to December 2021. **a**, Southern Ocean (SH); **b**, Weddell Sea (WS); **c**, Indian Ocean (IO); **d**, western Pacific Ocean (PO); **e**, Ross Sea (RS); **f**, Amundsen-Bellingshausen Sea (ABS). Subgraphs are reproduced based on reference (Parkinson, 2019). The data is from the National Snow and Ice Data Center (Fetterer et al., 2017), which is updated until December 2021.

Kurtz and Markus (2012) analyzed the seasonal variation of Antarctic SIT and SIV from 2003 to 2008 using the ICE-SAT satellite data from NASA, they found that the thickest sea ice is found off the coast of the Antarctic continent in the western Weddell Sea, Amundsen-Bellingshausen Sea, and the western Ross Sea and the thinnest sea ice is generally located in the eastern Weddell Sea, Ross Sea and parts of the Indian Ocean and western Pacific Ocean. Most areas of thin ice in the eastern Weddell Sea are observed to expand northward in autumn, while thick ice in the Weddell Sea expand northward in spring. The new thin ice increases in autumn, and the thick ice probably persists after sea ice melts in summer (Worby et al., 2008). Antarctic SIT decreases most during summer from January to March because a large amount of annual thin ice melts and increases gradually in autumn and winter and reaches the peak in August, then SIT decreases gradually from September to December due to melting, according to the study of Chen et al. (2019).

## 2.2 Interannual variability

The variations of yearly average SIE in the Southern Ocean and the five regions from 1979 to 2021 are shown in Figure 2. The time series is extended based on Parkinson (2019). Antarctic yearly average SIE varies over a period of four to six years, and amplitudes of variation are generally not more than $1.0\times10^6$ km$^2$ before 2011. However, the amplitude of SIE from 2012 to 2017 gets significantly larger. In 2014, yearly average SIE is about $12.8\times10^6$ km$^2$, the maximum value since 1979. Then it begins to significantly decline and yearly average SIE decreases by about $1.2\times10^6$ km$^2$ from 2015 to 2016 (Figure 2a). Among the five regions, the annual fluctuation of SIE in Weddell Sea is the most significant and the one in western Pacific Ocean is least noticeable and the decline from 2015 to 2017 is not quite remarkable (Figure 2b). The annual fluctuation of SIE in Indian Ocean is not obvious compared with that in Weddell Sea, but yearly average SIE declines from 2014 to 2016 (Figure 2c). Yearly average SIE in the western Pacific

Ocean reaches the peak in 2013, and then decreases for three consecutive years (Figure 2d). The annual fluctuation of SIE in Ross Sea is also noticeable and it decreases significantly from 2013 to 2017 (Figure 2e). The annual fluctuation of SIE in Amundsen-Bellingshausen Sea is not obvious and the decline of SIE from 2015 to 2016 is not significant compared with the declines before (Figure 2f). The results above are consistent with those of Parkinson (2019).

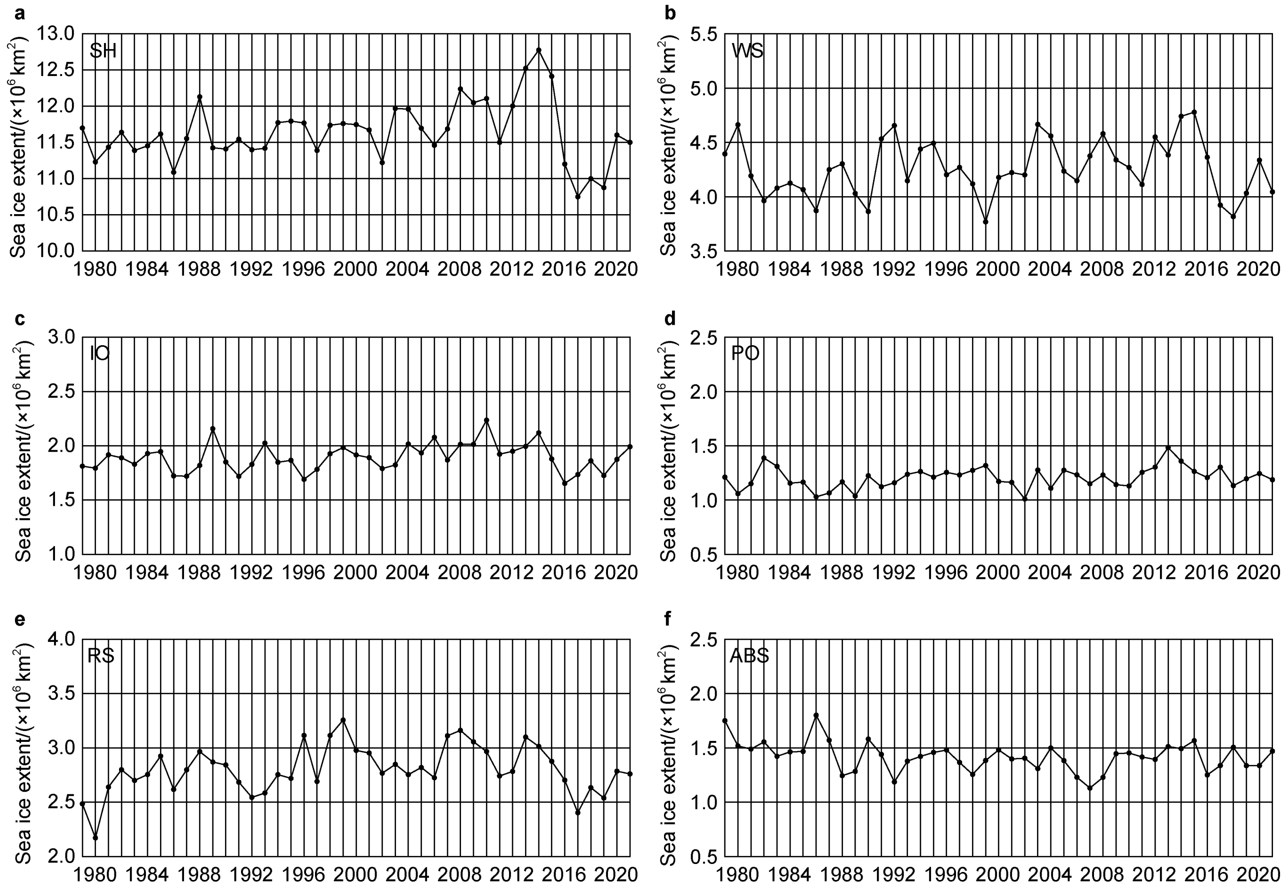


**Figure 2** Yearly averages SIE for 1979–2021. **a**, Southern Ocean (SH); **b**, Weddell Sea (WS); **c**, Indian Ocean (IO); **d**, western Pacific Ocean (PO); **e**, Ross Sea (RS); **f**, Amundsen-Bellingshausen Sea (ABS). Subgraphs are reproduced based on Parkinson (2019). The data is from the National Snow and Ice Data Center (Fetterer et al., 2017), which is updated until December 2021.

For the characters of yearly average SIT variation from 2013 to 2018, Chen et al. (2019) found that yearly average SIT increases from 2013 to 2014 and reaches the peak, and then decreases rapidly from 2015 to 2017 based on CryoSat-2 data. Whereafter, yearly average SIT in 2018 increases slightly compared with 2017.

Previous studies have found that SAM, El Niño-Southern Oscillation (ENSO), tropical Atlantic meridional dipole of sea surface temperature anomalies and Indian Ocean dipole (IOD) can influence the variation of Antarctic sea ice in interannual time scale. SAM is the dominant climate variability in the southern hemisphere (Thompson et al., 2000), which has opposite effects on Antarctic sea ice at different time scales (Ferreira et al., 2015; Hobbs et al., 2016; Eayrs et al., 2021). At the interannual time scale, west wind in some regions of the Southern Ocean is strengthened when SAM is positive, and pushes ice northward through Ekman effect, leading to the increase of Antarctic SIE (Simpkins et al., 2012). On long-time scales of more than a decade, the northward transport of water caused by Ekman effect would encourage deeper and warmer water to be pumped to the surface, contributing to sea ice melting (Schlosser et al., 2018). Holland et al. (2017) found that an initial expansion of the sea ice was due to the positive SAM anomalies during austral summer using simulations of global climate models.

ENSO can also affect high latitudes through atmospheric Rossby wave propagation (Karoly, 1989). Anomalously deep convection would be induced by positive sea surface temperature (SST) anomalies in the tropical Pacific region and excitation of an atmospheric Rossby wave train called the Pacific-South America (PSA) model (Mo and Higgins, 1998; Kidson, 1999; Zhang et al., 2016). It first affects the intensity of the Amundsen Low and then changes SIC through thermal and dynamic processes. The response is most obvious in the eastern Ross Sea and Amundsen-Bellingshausen Sea, especially in autumn and winter (Turner, 2014). In addition, ENSO can also change the large-scale meridional circulation intensity in the South Atlantic and South Pacific, causing the abnormal heat transport to the pole, resulting in the increase or decrease of Antarctic sea ice (Liu et al., 2002). SAM and ENSO exhibit regional and seasonal differences in their impacts on Antarctic sea ice anomalies (Simpkins et al., 2012). For example, when the SAM is in positive phase, the sea ice is less in the Weddell Sea and more in the Ross Sea and Amundsen Sea (Lefebvre et al., 2004). The trends in the winter ice edge over the Ross Sea and Amundsen-Bellingshausen Sea regions are highly correlated to trends in atmospheric anomalies associated with ENSO (Kwok et al., 2016). Moreover, Crosta et al. (2021) revealed combined effects of ENSO and the SAM to modulate SST and sea ice in the Indian Ocean at the decadal-to-centennial timescales.

The meridional SST-dipole in the tropical Atlantic generates anomalous Rossby waves through the anomalous deep convection over the equatorial Atlantic which drives the anomalous local Hadley cell, and the Atlantic–Pacific interaction causing perturbations to the Walker cell (Li et al., 2014, 2015a, 2015b; Ren et al., 2022). The interannual teleconnection between the tropical Atlantic meridional dipole mode and Antarctic SIC anomalies occurs in the austral autumn season and leads to the tri-polar SIC anomalies in the Ross Sea, Antarctic Peninsula, and east of the Weddell Sea (Ren et al., 2022).

Yuan and Martinson (2000) calculated the relationship between Antarctic sea ice and global sea surface temperature, and determined that SST changes in the equatorial Indian Ocean have more impact on Antarctic sea ice than those in the equatorial Pacific Ocean. There is a persistent and positive correlation between Antarctic sea ice and southeast Indian Ocean SST (Rai et al., 2008). The spring Indian Ocean dipole sign is highly correlated with summer Antarctic sea ice, causing SIC in Ross Sea, east of the Ross Sea and in South Atlantic Ocean positive and sea ice loss in the South Pacific and Weddell Sea (Feng et al. 2019). And when IOD occurs, the atmospheric circulation anomaly causes the north (south) wind anomaly, which is accompanied by the north (south) heat flux anomaly, leading to the increase (or decrease) of sea ice (Feng et al. 2019).

## 2.3 Decadal and long-term change

On decadal time scale, the Pacific Decadal Oscillation (PDO) and the Atlantic Decadal Oscillation (AMO) also have impacts on Antarctic sea ice change. The PDO and AMO affect the atmospheric circulation in the Antarctic through the Rossby wave (Meehl et al., 2016; Purich et al., 2016). Studies have found that when PDO is in a negative phase from the late 1990s to 2015, and the central Pacific SST anomaly is negative, triggering a Rossby wave train propagating southward from the tropical Pacific, with a low pressure center over the Amundsen Sea and Bellingshausen Sea, and the anomalous Rossby wave train is robust in all seasons except summer in Southern Hemisphere (Hall and Visbeck, 2002; Clem and Fogt, 2015; Lee et al., 2017). Similarly, in all seasons except summer, positive SST anomalies associated with the AMO in the North Atlantic and tropical Atlantic would generate a stationary Rossby wave train that propagates around the Southern Ocean and promotes negative pressure anomalies around the Amundsen Low (Li et al., 2015a, 2015b).

Both the positive phase of AMO and the negative phase of PDO promote the Rossby wave train and the deepening of the Amundsen Low (ASL), and the positive AMO can also influence the negative PDO through the inter-basin interaction (Li et al., 2021). As a result, the deepened Amundsen Low leads to the cold atmospheric advection and near-shore sea ice drift, causing the sea ice increase in the eastern Ross Sea, and the nearshore winds in the northern Antarctic Peninsula melting and compressing sea ice along the coasts of Amundsen and Bellingshausen (Holland and Kwok, 2012; Hosking et al., 2013; Purich et al., 2016; Kwok et al., 2017; Wang et al., 2019; Hao et al., 2021). Due to the location of ASL and the seasonality of sea ice cover, the impact of ASL on sea ice varies greatly with season (Li et al., 2021).

Previous studies and satellite data showed that Antarctic SIE in September 2014 is $19.76\times10^6$ km$^2$, the maximum since 1979, and then it declines rapidly from 2015 to 2016 and decreases to $2.29\times10^6$ km$^2$ in February 2017, a record minimum (Schlosser et al., 2018; Parkinson, 2019). Schlosser et al. (2018) analyzed the long-term change of SIE anomalies in the Southern Ocean from January 1979 to December 2017 and found that the long-term trend of Antarctic SIE anomalies is positive before 2015, and SIE anomaly reaches the maximum in January 2015. From January 2015 to December 2016, the Antarctic SIE anomalies show an obvious downward trend, and decreases to the minimum in December 2016. Stuecker et al. (2017) and Eayrs et al. (2021) also made the same conclusion.

Hao et al. (2021) studied the monthly trends of SIE during January 1979 to December 2019 in the Southern Ocean and five regions, and calculated the long-term trend from January 1979 to December 2013 and January 2014 to December 2019. They found that the trend of Antarctic SIE anomaly from 1979 to 2013 is positive, but SIE anomaly decreases significantly after 2014. Furthermore, all the regions show negative trends with decreasing SIE in recent years since 2014, and the trends in those regions from 1979 to 2013 are most positive except in Amundsen-Bellingshausen Sea (Figure 3f). We extend the time series to December 2021 and calculate the long-term trends from 1979 to 2021, 1979 to 2013 and 2014 to 2021 (shown as Figure 3), finding that the results about trends from 1979 to 2013 are the same, but the downward trends from 2014 to 2021 are smaller compared with those from 2014 to 2019. In addition, among the five regions, the largest positive trend of SIE anomalies is in Ross Sea (Figure 3e) from

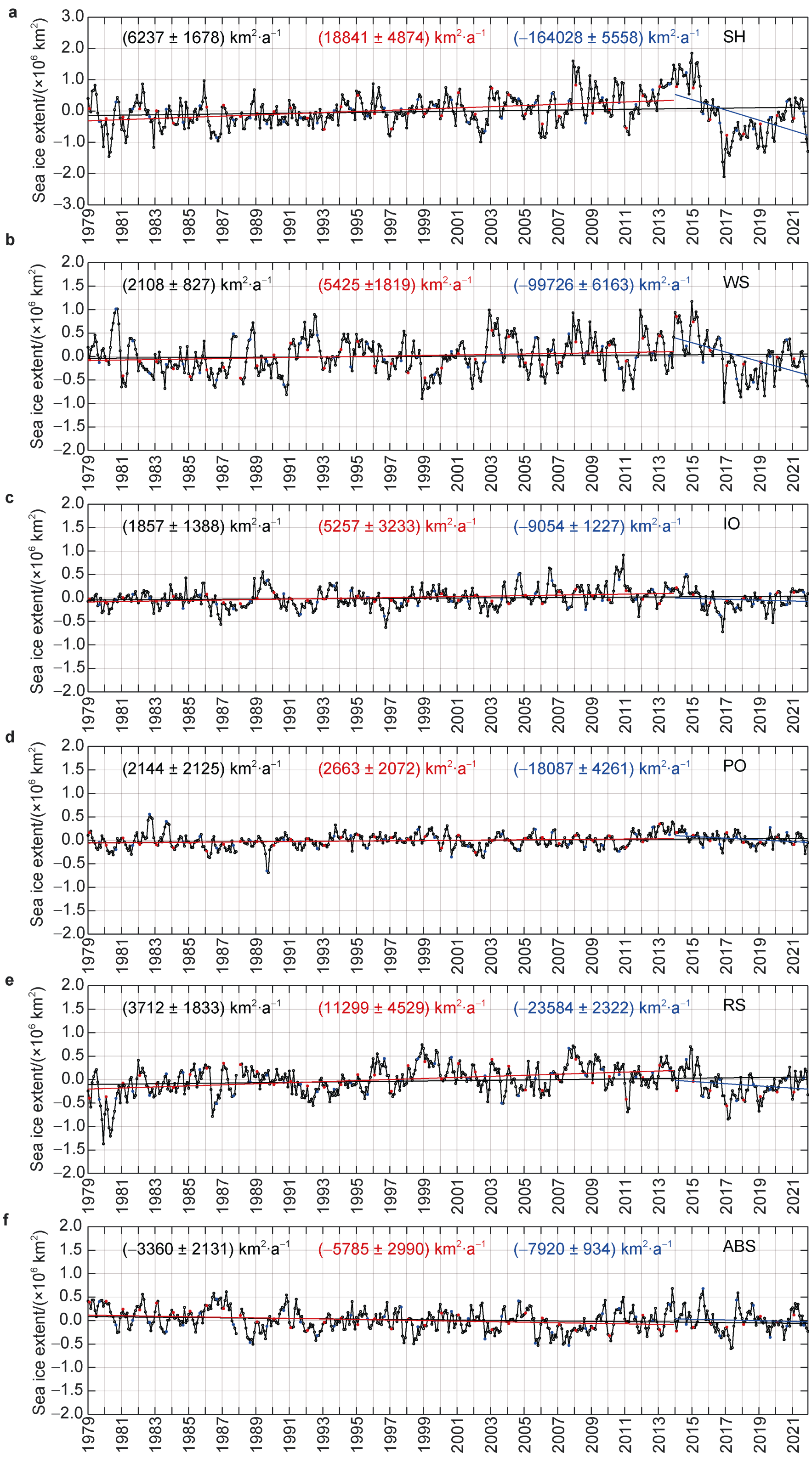


**Figure 3** Long-time trends of monthly SIE anomalies during January 1979 to December 2021 (black line), January 1979 to December 2013 (red line) and January 2014 to December 2021 (blue line) (Red dots represent February and blue dots represent September), the numbers indicate the slope and standard deviations. **a**, Southern Ocean (SH); **b**, Weddell Sea (WS); **c**, Indian Ocean (IO); **d**, western Pacific Ocean (PO); **e**, Ross Sea (RS); **f**, Amundsen-Bellingshausen Sea (ABS). Subgraphs are reproduced based on Hao et al. (2021). The data is from the National Snow and Ice Data Center (Fetterer et al., 2017), which is updated until December 2021.

1979 to 2013, and the negative trend after 2014 in Weddell Sea decreases the fastest.

# 3 Causes of the 2015–2016 rapid decline of Antarctic sea ice

The dramatic change of Antarctic sea ice after 2014 is a hot topic in the community. There have been many discussions on the causes for the rapid decline of Antarctic SIE from 2015 to 2016. The abnormal conditions of atmosphere, ocean and thermal radiation, as well as climate variabilities such as the SAM and ENSO may affect the variation of sea ice. Currently, there is no consistent explanation for the specific mechanism underlying the dramatic decline in Antarctic SIE during 2015–2016. This paper summarizes the possible explanations for the dramatic decline.

## 3.1 Direct thermal and dynamic processes of the atmosphere and ocean

The influence of atmosphere and ocean on Antarctic sea ice is complex and can affect sea ice both individually and by their interaction (Meehl et al., 2016; Stuecker et al., 2017; Wang et al., 2019). The sea surface atmosphere plays a thermodynamic role through cold and warm air advection, and this effect acts fast, affecting the melting of sea ice (Haumann et al., 2014; Kwok et al., 2017). Ocean influences mainly play a role on long-time scales (Gordon and Huber, 1990). The upper ocean plays a role through heat transfer between the sea surface atmosphere and the deep ocean (Zhang, 2007; Goosse and Zunz, 2014). The freezing and melting of sea ice can be accelerated or slowed down through strong heat feedback (Stammerjohn et al., 2012). Large-scale atmospheric circulation controls the speed and direction of sea surface wind, regulating these thermodynamic and dynamic processes (Turner et al., 2015; Meehl et al., 2016; Stuecker et al., 2017).

### 3.1.1 Overview of influential factors

The rapid decline of SIE in 2016 is caused by the superposition of different factors such as thermal and dynamic effects of SST and wind anomalies in different regions of the Southern Ocean (Schlosser et al., 2018). The sudden decline of sea ice after 2015 is largely attributed to changes in near-sea surface winds. Numerical experiments of Wang et al. (2020) show that wind-driven changes in sea ice captures most of the observed sea ice loss from 2014 to 2016. According to the study of Wang et al. (2020), since the beginning of 2016, the large-scale meridional current and cyclone in the Southern Ocean are strong and continuous, resulting in strong Ekman suction, forming a warm SST state from April to October 2016. The warm water conditions hinder the growth of sea ice and make monthly SIE in October 2016 hit a record low. Extreme atmospheric circulation also generates strong sea surface winds, which generates strong sea ice drift. When cold air flows over sea ice from the southwest, the sea ice drifts farther north than the wind anomaly, allowing more sea ice to be transported from areas affected by cold advection to warmer northern areas. This effect counteracts the atmospheric thermal effect and even makes SIE in this region decrease. Drift of sea ice is the main reason for the rapid decline of Antarctic SIE in spring 2016, while warm SST conditions play a minor role.

### 3.1.2 Cloud and radiation

Hao et al. (2021) believed that the decrease of Antarctic sea ice is mainly due to the increase of energy absorbed by the atmosphere and the increase of energy transported southward. Cloud cover and thermal radiation affect the energy absorbed by the sea surface atmosphere in the Southern Ocean (Wang et al., 2019). Increased cloud cover helps the atmosphere absorb more long-wave radiation, warming the sea surface and contributing to the loss of sea ice. On the one hand, reduced cloud cover reduces downward long-wave radiation, resulting in a negative sea surface radiation budget and promoting the growth of sea ice. On the other hand, solar radiation may increase due to reduced cloud cover, leading to local warming of sea water and melting of sea ice (Hao et al., 2021).

The influence of cloud cover and thermal radiation on sea ice shows regional characteristics. Hao et al. (2021) found that during 2014–2019, in Weddell Sea, eastern Pacific Ocean and western Ross Sea, sea ice is significantly affected by cloud cover and thermal radiation. In the Weddell Sea region, cloud cover shows negative anomalies in summer and autumn from 2014 to 2019. The decrease of cloud cover leads to a decrease of downward net long-wave radiation and an increase of solar radiation. The sea surface atmosphere absorbs more solar radiation in summer, which causes local sea water warming and promotes sea ice melting. Further, this process delays ice freezing in autumn, resulting in a decrease in winter sea ice. Then the loss of sea ice allows the atmosphere and ocean to absorb more solar radiation in the spring, further leading to earlier spring ice melt. This positive feedback plays a dominant role in the decline of sea ice in Weddell Sea after 2014. In the eastern Pacific Ocean and the western Ross Sea, increased cloud cover in winter and spring from 2014 to 2019 makes local sea water absorb more downward long-wave radiation and become warmer, preventing sea ice growth. Meanwhile, the more open sea water makes sea ice more vulnerable to dynamic processes that have impacts on sea ice decline.

### 3.1.3 Cyclone activities

Cyclonic activities can also influence changes in the Antarctic SIE (Simmonds et al., 2003; Gorodetskaya et al., 2014). The cyclones in the southern hemisphere are clockwise. There is north wind in the east of the cyclones, leading to the extrusion of sea ice, the advection of warm air, and the melting of the sea ice edge. There is south wind to the west of the cyclone, which drifts the sea ice northward. And cold air advection also promotes the formation of new sea ice at the sea ice edge. The strong west wind in the north of the cyclone causes the sea ice to drift northward through Ekman transport (Schlosser et al., 2018). Turner et al. (2020) found that on 9 September 2016, low pressure system is generated in the region of 70°S–80°S and 60°W–0°, while high pressure is generated in the north of the region. The combined effects of the two result in strong west wind anomalies in Weddell Sea, and the sea ice is drifted to the northeast by the Ekman effect, causing the decrease of sea ice in the northwestern Weddell Sea. In addition, from 11 to 15 December 2016, a deep low pressure appears in Weddell Sea, resulting in intense cyclone activities. The north wind in the east of the cyclone transports warm air to Weddell Sea, reducing the sea ice in this area.

### 3.2 Modulation of climate variability

#### 3.2.1 Southern Hemisphere Annular Mode

The SAM phase changes from positive to negative in 2016, which influences the rapid decline of Antarctic sea ice in spring 2016 through the interaction between atmosphere and ocean (Holland et al., 2017; Turner et al., 2017). SAM index is highly negative in November 2016 and this low SAM index would suggest a rather meridional flow, resulting in a comparatively large meridional exchange of heat (Schlosser et al., 2018). However, Schlosser thought the SAM explains only part of the variability of the circulation. The Indian Ocean region controls the total Antarctic SIE during November and the SIE in this region depends on the phase of the SAM (Turner et al., 2017). The SIE decreases more in the Indian Ocean when the SAM is negative, which is consistent with larger poleward heat flux (Marshall and Thompson, 2016). What's more, negative SAM can cause the transport of warm water from the lower layer of the Southern Ocean to the upper layer by affecting the Ekman suction, which is conducive to the warming of the upper ocean, and then leads to the reduction of sea ice (Meehl et al., 2019). Wang et al. (2019) thought the low SAM in Nov–Dec 2016 is tightly tied to warming events in the polar stratosphere which may become more likely in the future as a result of the mending of the Antarctic ozone hole.

#### 3.2.2 Zonal wave number 3

Zonal wave number 3 (ZW3) describes the general zonal asymmetry of temperate circulation in the southern hemisphere, which is characterized by significant alternating patterns of cold (northward) and warm (southward) meridional flows, affecting sensible heat exchange between the ocean and atmosphere (Raphael, 2007; Stuecker et al., 2017; Turner et al., 2017). The influence of ZW3 on Antarctic sea ice in the winter of 2016 is clear. Schlosser et al. (2018) found that in Indian Ocean, Ross Sea and Amundsen-Bellingshausen Sea, there is a very strong ZW3 structure with obvious meridional heat flux mode from August to October 2016. The persistent ZW3 mode is caused in part by teleconnection forcing of negative the Indian Ocean Dipole, and the positive ZW3 index is predominant from mid-April until mid-October in 2016 (Schlosser et al., 2018; Purich et al., 2019). It is shown that strong meridional heat transport is generated in these regions, which is conducive to sea ice decreasing (Kusahara et al., 2018). In addition, due to atmospheric and oceanic processes such as the decrease of albedo and the increase of turbulent heat flow in the ocean after sea ice melting, SIE continues to decrease in the later period. Therefore, the Antarctic SIE is significantly reduced even though ZW3 does not show obvious positive anomaly in November and December. ZW3 creates prerequisites for sea ice melting at the end of 2016 (Schlosser et al., 2018; Li et al., 2021).

#### 3.2.3 Teleconnection

While we know that anomalous wind leads to most of the observed sea ice loss from 2014 to 2016 shown as Section 3.1.1 above, the key is that atmospheric teleconnection contributes to these changes in near-sea surface winds (Schlosser et al., 2018; Purich et al., 2019), such as combination of the PDO shift in 2014–2016 and the negative SAM in 2016 weakened the surface westerlies in the Southern Ocean (Meehl et al., 2019; Wang et al., 2019). With the anomalous surface northerly winds that due to teleconnections with the tropical ocean and the resulting advection of warm air toward Antarctica (Schlosser et al., 2018), temperatures of sea water above 400 m in the Southern Ocean have increased since 2016, conducive to sea ice loss (Meehl et al., 2019). The strong El Niño in 2015/2016 induces extreme SST anomalies in Amundsen-Bellingshausen Sea and the eastern Ross Sea, and the subsequent weak La Niña makes the SST anomalies stable and continues until the spring of 2016, resulting in the reduction of SIE (Stuecker et al. 2017). The strong negative SAM at the end of 2016 is contrary to the normal situation corresponding to La Niña (Stuecker et al., 2017; Crosta et al., 2021; Li et al, 2021). Stuecker et al. (2017) thought that the negative SAM is caused by the internal variability of the atmosphere, and the phenomenon might further increase SST and reduce sea ice in the eastern Ross Sea and Amundsen Sea. Using fully coupled climate models and observed tropical SST data, Purich and England (2019) found that teleconnection in tropical Indian Ocean contributes to sea ice decline in spring 2016, while the influence from tropical Pacific Ocean is minor. Therefore, more simulation experiments are needed to verify whether the 2015/2016 ENSO event has a particular impact on the rapid decline of Antarctic SIE in 2016.

## 4 Summary and outlook

Arctic SIE continuously decreases over the past four decades, while Antarctic SIE shows an increasing trend until 2014, and then rapidly declines (Comiso et al., 2017; Parkinson, 2019). We summarize the variation characteristics of Antarctic sea ice at different time scales. The minimum SIE is always in February and the maximum SIE is always in September for annual cycle (Parkinson, 2019). Antarctic yearly average SIE varies over a period of four to six years, and amplitudes of yearly SIE from 2012 to 2017 gets significantly larger, compared with those before 2011. The trend of Antarctic monthly SIE anomalies is positive before 2015, and monthly SIE anomaly reaches the maximum in January 2015. Then it shows an obvious downward trend from January 2015 to December 2016, and monthly SIE anomaly decreases to the minimum in December 2016 (Stuecker et al., 2017; Schlosser et al., 2018; Eayrs et al., 2021).

The rapid decline of Antarctic SIE from 2015 to 2016 is caused by the direct thermal and dynamic effects of atmosphere and ocean, as well as by the effects of climate variabilities (Meehl et al., 2016; Stuecker et al., 2017). The strong and persistent large-scale meridional currents and cyclones in the Southern Ocean form the warm ocean surface state from April to October 2016 and lead to the enhancement of sea ice drift, causing the rapid decline of Antarctic SIE in spring 2016 (Wang et al., 2020). What's more, the reductions of sea ice in Weddell Sea, the eastern Pacific Ocean and western Ross Sea during 2014–2019 are significantly affected by cloud cover and thermal radiation (Hao et al., 2021), and the decrease of sea ice in Weddell Sea is also due to the strong cyclone activities in September and December 2016 (Turner et al., 2020). For modulation of climate variabilities, ZW3 structure in Indian Ocean, Ross Sea and Amundsen-Bellingshausen Sea from August to October 2016 generates strong meridional heat transport and favors sea ice loss (Kusahara et al., 2018). Negative PDO during 2014 and 2016 strengthens westerlies, causing warmer subsurface water in the Southern Ocean upward through Ekman suction. And then the negative SAM in late 2016 contributes to anomalously warm SSTs and surface wind, producing the rapid decrease of Antarctic SIE (Meehl et al., 2019; Eayrs et al., 2021). The strong El Niño in 2015/2016 induces extreme SST anomalies in Amundsen-Bellingshausen Sea and the eastern Ross Sea and continues until the spring of 2016, resulting in the reduction of SIE (Stuecker et al., 2017).

Previous researchers have studied the variation of Antarctic SIE and the factors affecting the variation from different perspectives. The challenges of Antarctic sea ice research for the future are also listed. For example, Li et al. (2021) believed that the importance of atmospheric dynamic and thermal effects on the decline of sea ice is still controversial and needs to be verified by more model simulations. Wang et al. (2021) proposed that it is necessary to clarify the joint effect of multiple climate variabilities on the variation of Antarctic SIE, and to comprehensively understand the coupling effect of the interaction between atmosphere and ocean on the slow and abrupt changes of the Antarctic sea ice. After reviewing the previous achievements and challenges, we summarize four key issues that urgently need to be solved in the field of Antarctic sea ice.

First of all, the current satellite observation data of Antarctic sea ice are quite limited and the length of time series is short. Particularly there is rarely satellite observation data of SIT, which not only hinders the prediction of future sea ice change, but also limits our understanding of the relationship between sea ice change and climate variability on the long-time scale. How to accurately estimate the Antarctic SIC and SIT before 1979 using numerical simulation is the first key problem to study Antarctic sea ice. There are also numerical simulations and reconstruction to study changes in Antarctic sea ice (Roach et al., 2020; Fogt et al., 2022). Through numerical simulation, scholars can discover the internal rules of sea ice changes and predict how it would change in the future. In addition, the existing satellite observation data of SIT are retrieved from satellite altimetry, and then there are some errors due to the influence of snow cover. Therefore, it is necessary to further improve the algorithm to improve the accuracy of SIT data.

Secondly, due to the limitation of the satellite data of Antarctic SIT, most of the previous studies about sea ice focus on the two indexes of SIE and SIC. However, it is also crucial to combine SIT and SIV to analyze the variation of Antarctic sea ice and its relationship with the climate. Then the second question that needs to be solved about the Antarctic sea ice is whether the variation of SIC and SIT are spatially consistent. SIC and SIE only reflect the change of the horizontal area of sea ice, while the change of sea ice is not only the increase and decrease of the horizontal area, but also the increase and decrease of the vertical thickness. Considering the changes of SIT and SIV, we can analyze the characteristics of Antarctic sea ice variation more accurately and systematically.

After solving the first two problems, it will necessary to discuss whether to attribute the long-term trend of Antarctic sea ice to anthropogenic forcing or natural climate change (Crosta et al., 2021). No uniform conclusion has been made in previous studies. Hobbs et al. (2016) concluded that the natural variability of Antarctic sea ice may be much greater than the observed in the past few decades through paleoclimatic records and numerical simulation studies. Handcock et al. (2020) believed that linear method may not be the most appropriate method to determine the change trend of Antarctic sea ice variation, and the essential feature of the variation is the variability less than a decade. The study of Wang et al. (2019) showed that the rapid decline of SIE after 2014 is largely the result of accidental and natural changes, but the large amount of greenhouse gases emitted by human activities still affect the variation of Antarctic sea ice. Holland et al. (2019) believed that the increase of greenhouse gases leads to the reversal of climate, making the wind above the continental shelf fracture in the Amundsen Sea change. And then the east wind in the 1920s switches to the zonal wind close to 0°, affecting the surrounding SST and sea ice drift. Therefore, the mechanism leading to long-time scale variation of sea ice is a key issue for future research on the Antarctic sea ice.

The latest satellite data of Antarctic sea ice showed that Antarctic monthly SIE decreases to a record low in February 2022 (Raphael and Handcock, 2022; Turner et al., 2022; Wang et al., 2022), which ushers in new problems and challenges in the research of Antarctic sea ice. Scholars begin to pay attention to the causes for this recent event. Raphael and Handcock (2022) suggested that the record low SIE in summer of 2022 could be caused by the early retreat of sea ice in August 2021. The sea ice loss in 2021–2022 mainly occurs in the Ross Sea and Weddell Sea (Turner et al., 2022; Wang et al., 2022). The Amundsen Low reaches a record low in October/November 2021 and is accompanied with strong southerly winds in the western of Ross Sea, moving sea ice away from the coast, exposing the ocean and warming the ocean with solar heating, further melting the sea ice (Turner et al., 2022). However, the positive surface heat fluxes in spring contribute the most to sea ice melt in the Weddell Sea (Wang et al., 2022), and the record strong westerly wind causes sea ice to drift eastward in the northern Weddell Sea (Turner et al., 2022). As for the rapid decline of Antarctic SIE in spring 2016, Wang et al. (2020) attributed the cause mainly to the dynamic effect of wind caused by low pressure system. By comparing the SAM and PDO of the two Antarctic SIE declines in 2015–2016 and 2021–2022, we found that the SAM phase is negative and PDO phase is positive at the end of 2016, while the SAM is in positive phase and the PDO is in negative phase at the end of 2021. Although the phases of SAM and PDO are opposite, respectively, in the above two periods, Antarctic SIE decreases rapidly through the interaction between the atmosphere and the ocean. For these two extreme events of the Antarctic SIE, we raise the final key question: Whether the mechanisms leading to these two declines are related and subject to the combined effects of climate variability. A following research article on this question will be presented.

**Acknowledgments** This work is supported by Sino-German Mobility Program (Grant no. M0333), Deep Blue Program of Shanghai Jiao Tong University (Grant no. SL2021ZD204) and Grant of Shanghai Frontiers Science Center of Polar Science (SCOPS). We appreciate Dr. Tingfeng Dou and Dr. Tingting Liu as reviewers, and Associate Editor Dr. Ruibo Lei for their constructive comments that have further improved the manuscript.

## References

Aagaard K, Carmack E C. 1989. The role of sea ice and other fresh water in the Arctic circulation. J Geophys Res Oceans, 94(C10): 14485, doi:10.1029/jc094ic10p14485.

Bracegirdle T J, Stephenson D B, Turner J, et al. 2015. The importance of sea ice area biases in 21st century multimodel projections of Antarctic temperature and precipitation. Geophys Res Lett, 42(24): 10832-10839, doi:10.1002/2015gl067055.

Chen Y Z, Ji Q, Pang X P. 2019. Spatio-temporal variation of Antarctic sea ice thickness using CryoSat-2 satellite altimeter data. J Glaciol Geocryol, 41(5): 1214-1220 (in Chinese with English abstract).

Clem K R, Fogt R L. 2015. South Pacific circulation changes and their connection to the tropics and regional Antarctic warming in austral spring, 1979–2012. J Geophys Res Atmos, 120(7): 2773-2792, doi:10.1002/2014jd022940.

Comiso J C, Meier W N, Gersten R. 2017. Variability and trends in the Arctic sea ice cover: results from different techniques. J Geophys Res Oceans, 122(8): 6883-6900, doi:10.1002/2017jc012768.

Crosta X, Etourneau J, Orme L C, et al. 2021. Multi-decadal trends in Antarctic sea-ice extent driven by ENSO–SAM over the last 2,000 years. Nat Geosci, 14(3): 156-160, doi:10.1038/s41561-021-00697-1.

Eayrs C, Li X C, Raphael M N, et al. 2021. Rapid decline in Antarctic sea ice in recent years hints at future change. Nat Geosci, 14(7): 460-464, doi:10.1038/s41561-021-00768-3.

Feng J J, Zhang Y Z, Cheng Q M, et al. 2019. Analysis of summer Antarctic sea ice anomalies associated with the spring Indian Ocean dipole. Glob Planet Change, 181: 102982, doi:10.1016/j.gloplacha.2019.102982.

Ferreira D, Marshall J, Bitz C M, et al. 2015. Antarctic Ocean and sea ice response to ozone depletion: a two-time-scale problem. J Clim, 28(3): 1206-1226, doi:10.1175/jcli-d-14-00313.1.

Fetterer F, Knowles K, Meier W N, et al. 2017. Sea Ice Index, Version 3. Boulder, Colorado, USA: National Snow and Ice Data Center, doi:10.7265/N5K072F8.

Fogt R L, Sleinkofer A M, Raphael M N, et al. 2022. A regime shift in seasonal total Antarctic sea ice extent in the twentieth century. Nat Clim Change, 12(1): 54-62, doi:10.1038/s41558-021-01254-9.

Goosse H, Zunz V. 2014. Decadal trends in the Antarctic sea ice extent ultimately controlled by ice-ocean feedback. Cryosphere, 8(2): 453-470, doi:10.5194/tc-8-453-2014.

Gordon A L, Huber B A. 1990. Southern Ocean winter mixed layer. J Geophys Res Oceans, 95(C7): 11655, doi:10.1029/jc095ic07p11655.

Gorodetskaya I V, Tsukernik M, Claes K, et al. 2014. The role of atmospheric rivers in anomalous snow accumulation in East Antarctica. Geophys Res Lett, 41(17): 6199-6206, doi:10.1002/2014gl060881.

Hao G H, Shen H, Sun Y M, et al. 2021. Rapid decrease in Antarctic sea ice in recent years. Acta Oceanol Sin, 40(7): 119-128, doi:10.1007/s13131-021-1762-x.

Hall A, Visbeck M. 2002. Synchronous variability in the southern hemisphere atmosphere, sea ice, and ocean resulting from the annular mode. J Climate, 15(21): 3043-3057, doi:10.1175/1520-0442(2002)015<3043: svitsh>2.0.co;2.

Handcock M S, Raphael M N. 2020. Modeling the annual cycle of daily Antarctic sea ice extent. Cryosphere, 14(7): 2159-2172, doi:10.5194/tc-14-2159-2020.

Haumann F A, Notz D, Schmidt H. 2014. Anthropogenic influence on recent circulation-driven Antarctic sea ice changes. Geophys Res Lett, 41(23): 8429-8437, doi:10.1002/2014gl061659.

Hobbs W R, Massom R, Stammerjohn S, et al. 2016. A review of recent changes in Southern Ocean sea ice, their drivers and forcings. Glob

Planet Change, 143: 228-250, doi:10.1016/j.gloplacha.2016.06.008.

Holland M M, Landrum L, Kostov Y, et al. 2017. Sensitivity of Antarctic sea ice to the Southern Annular Mode in coupled climate models. Clim Dyn, 49(5): 1813-1831, doi:10.1007/s00382-016-3424-9.

Holland P R, Bracegirdle T J, Dutrieux P, et al. 2019. West Antarctic ice loss influenced by internal climate variability and anthropogenic forcing. Nat Geosci, 12(9): 718-724, doi:10.1038/s41561-019-0420-9.

Holland P R, Kwok R. 2012. Wind-driven trends in Antarctic sea-ice drift. Nat Geosci, 5(12): 872-875, doi:10.1038/ngeo1627.

Hosking J S, Orr A, Marshall G J, et al. 2013. The influence of the Amundsen-Bellingshausen Seas Low on the climate of West Antarctica and its representation in coupled climate model simulations. J Clim, 26(17): 6633-6648, doi:10.1175/jcli-d-12-00813.1.

Karoly D J. 1989. Southern Hemisphere circulation features associated with El Niño-Southern Oscillation events. J Climate, 2(11): 1239-1252, doi:10.1175/1520-0442(1989)002<1239: shcfaw>2.0.co;2.

Kidson J W. 1999. Principal modes of southern hemisphere low-frequency variability obtained from NCEP-NCAR reanalyses. J Climate, 12(9): 2808-2830, doi:10.1175/1520-0442(1999)012<2808: pmoshl>2.0.co; 2.

Kirkman C H Ⅳ, Bitz C M. 2011. The effect of the sea ice freshwater flux on Southern Ocean temperatures in CCSM3: deep-ocean warming and delayed surface warming. J Clim, 24(9): 2224-2237, doi:10.1175/2010jcli3625.1.

Kurtz N T, Markus T. 2012. Satellite observations of Antarctic sea ice thickness and volume. J Geophys Res, 117(C8): C08025, doi:10.1029/2012jc008141.

Kusahara K, Reid P, Williams G D, et al. 2018. An ocean-sea ice model study of the unprecedented Antarctic sea ice minimum in 2016. Environ Res Lett, 13(8): 084020, doi:10.1088/1748-9326/aad624.

Kwok R, Comiso J C, Lee T, et al. 2016. Linked trends in the South Pacific sea ice edge and Southern Oscillation Index. Geophys Res Lett, 43(19): 10295-10302, doi:10.1002/2016gl070655.

Kwok R, Pang S S, Kacimi S. 2017. Sea ice drift in the Southern Ocean: regional patterns, variability, and trends. Elem Sci Anthropocene, 5:32, doi:10.1525/elementa.226.

Lee S K, Volkov D L, Lopez H, et al. 2017. Wind-driven ocean dynamics impact on the contrasting sea-ice trends around West Antarctica. J Geophys Res Oceans, 122(5): 4413-4430, doi:10.1002/2016jc012416.

Lefebvre W, Goosse H, Timmermann R, et al. 2004. Influence of the Southern Annular Mode on the sea ice-ocean system. J Geophys Res, 109(C9): C09005, doi:10.1029/2004jc002403.

Lemke P, Trinkl E W, Hasselmann K. 1980. Stochastic dynamic analysis of polar sea ice variability. J Phys Oceanogr, 10(12): 2100-2120, doi:10.1175/1520-0485(1980)010<2100: sdaops>2.0.co;2.

Li S, Han Z, Liu N, et al. 2021. A review of the researches on the record low Antarctic sea ice in 2016 and its formation mechanisms. Haiyang Xuebao, 43(7):1-10, doi:10.12284/hyxb2021119 (in Chinese with English abstract).

Li X C, Holland D M, Gerber E P, et al. 2014. Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. Nature, 505(7484): 538-542, doi:10.1038/nature12945.

Li X C, Holland D M, Gerber E P, et al. 2015a. Rossby waves mediate impacts of tropical oceans on West Antarctic atmospheric circulation in austral winter. J Clim, 28(20): 8151-8164, doi:10.1175/JCLI-D-15-0113.1.

Li X C, Gerber E P, Holland D M, et al. 2015b. A rossby wave bridge from the tropical Atlantic to West Antarctica. J Clim, 28(6): 2256-2273, doi:10.1175/JCLI-D-14-00450.1.

Li X C, Cai W J, Meehl G A, et al. 2021. Tropical teleconnection impacts on Antarctic climate changes. Nat Rev Earth Environ, 2(10): 680-698, doi:10.1038/s43017-021-00204-5.

Liu J P, Yuan X, Rind D, et al. 2002. Mechanism study of the ENSO and southern high latitude climate teleconnections. Geophys Res Lett, 29(14): 1679, doi:10.1029/2002gl015143,

Marshall G J, Thompson D W J. 2016. The signatures of large-scale patterns of atmospheric variability in Antarctic surface temperatures. J Geophys Res Atmos, 121(7): 3276-3289, doi:10.1002/2015jd024665.

Massom R A, Stammerjohn S E. 2010. Antarctic sea ice change and variability–Physical and ecological implications. Polar Sci, 4(2): 149-186, doi:10.1016/j.polar.2010.05.001.

Meehl G A, Arblaster J M, Bitz C M, et al. 2016. Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. Nat Geosci, 9(8): 590-595, doi:10.1038/ngeo2751.

Meehl G A, Arblaster J M, Chung C T Y, et al. 2019. Sustained Ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. Nat Commun, 10: 14, doi:10.1038/s41467-018-07865-9.

Mo K C, Higgins R W. 1998. The Pacific–South American modes and tropical convection during the Southern Hemisphere winter. Mon Weather Rev, 126(6): 1581-1596, doi: 10.1175/1520-0493(1998)126<1581:tpsama>2.0.co;2.

Parkinson C L. 2019. A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. Proc Natl Acad Sci USA, 116(29): 14414-14423, doi:10.1073/pnas.1906556116.

Purich A, England M H, Cai W J, et al. 2016. Tropical Pacific SST drivers of recent Antarctic sea ice trends. J Clim, 29(24): 8931-8948, doi:10.1175/jcli-d-16-0440.1.

Purich A, England M H. 2019. Tropical teleconnections to Antarctic sea ice during austral spring 2016 in coupled pacemaker experiments. Geophys Res Lett, 46(12): 6848-6858, doi: /10.1029/2019gl082671.

Rai S, Khare N, Pandey A C. 2008. Antarctica sea ice variability and southeast Indian Ocean SST: possible relationship. Indian J Mar Sci, 37(1): 35-39.

Raphael M N. 2003. Impact of observed sea-ice concentration on the Southern Hemisphere extratropical atmospheric circulation in summer. J Geophys Res Atmos, 108(D22): 4687, doi:10.1029/2002jd003308.

Raphael M N. 2007. The influence of atmospheric zonal wave three on Antarctic sea ice variability. J Geophys Res Atmos, 112(D12): D12112, doi: 10.1029/2006JD007852.

Raphael M N, Handcock M S. 2022. A new record minimum for Antarctic sea ice. Nat Rev Earth Environ, 3(4): 215-216, doi:10.1038/s43017-022-00281-0.

Ren X Y, Zhang L, Cai W J, et al. 2022. Influence of tropical Atlantic meridional dipole of sea surface temperature anomalies on Antarctic autumn sea ice. Environ Res Lett, 17(9): 094046, doi:10.1088/1748-9326/ac8f5b.

Roach L A, Dörr J, Holmes C R, et al. 2020. Antarctic sea ice area in CMIP6. Geophys Res Lett, 47(9): e2019GL086729, doi:10.1029/2019gl086729.

Schlosser E, Haumann F A, Raphael M N. 2018. Atmospheric influences on the anomalous 2016 Antarctic sea ice decay. Cryosphere, 12(3):

1103-1119, doi:10.5194/tc-12-1103-2018.

Simmonds I, Keay K, Lim E P. 2003. Synoptic activity in the seas around Antarctica. Mon Weather Rev, 131(2): 272-288, doi:10.1175/1520-0493(2003)131<0272: saitsa>2.0.co;2.

Simpkins G R, Ciasto L M, Thompson D W J, et al. 2012. Seasonal relationships between large-scale climate variability and Antarctic sea ice concentration. J Clim, 25(16): 5451-5469, doi:10.1175/jcli-d-11-00367.1.

Simpkins G R, McGregor S, Taschetto A S, et al. 2014. Tropical connections to climatic change in the extratropical southern hemisphere: the role of Atlantic SST trends. J Climate, 27(13): 4923-4936, doi:10.1175/jcli-d-13-00615.1.

Singh H A, Polvani L M, Rasch P J. 2019. Antarctic sea ice expansion, driven by internal variability, in the presence of increasing atmospheric $CO_2$. Geophys Res Lett, 46(24): 14762-14771, doi:10.1029/2019gl083758.

Stammerjohn S, Massom R, Rind D, et al. 2012. Regions of rapid sea ice change: an inter-hemispheric seasonal comparison. Geophys Res Lett, 39(6): L06501, doi:10.1029/2012gl050874.

Stuecker M F, Bitz C M, Armour K C. 2017. Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season. Geophys Res Lett, 44(17): 9008-9019, doi:10.1002/2017gl074691.

Thompson D W J, Wallace J M, Hegerl G C. 2000. Annular modes in the extratropical circulation. Part II: trends. J Climate, 13(5): 1018-1036, doi:10.1175/1520-0442(2000)013<1018: amitec>2.0.co;2.

Turner J. 2004. The El Niño-southern oscillation and Antarctica. Int J Climatol, 24(1): 1-31, doi:10.1002/joc.965.

Turner J, Comiso J C, Marshall G J, et al. 2009. Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophys Res Lett, 36(8): L08502, doi:10.1029/2009gl037524.

Turner J, Guarino M V, Arnatt J, et al. 2020. Recent decrease of summer sea ice in the Weddell Sea, Antarctica. Geophys Res Lett, 47(11): e2020GL087127, doi:10.1029/2020gl087127.

Turner J, Holmes C, Caton Harrison T, et al. 2022. Record low Antarctic sea ice cover in February 2022. Geophys Res Lett, 49(12): e2022GL098904, doi:10.1029/2022gl098904.

Turner J, Hosking J S, Bracegirdle T J, et al. 2015. Recent changes in Antarctic sea ice. Phil Trans R Soc A, 373(2045): 20140163, doi:10.1098/rsta.2014.0163.

Turner J, Phillips T, Marshall G J, et al. 2017. Unprecedented springtime retreat of Antarctic sea ice in 2016. Geophys Res Lett, 44(13): 6868-6875, doi:10.1002/2017gl073656.

Wang G M, Hendon H H, Arblaster J M, et al. 2019. Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. Nat Commun, 10: 13, doi:10.1038/s41467-018-07689-7.

Wang J F, Luo H, Yang Q H, et al. 2022. An unprecedented record low Antarctic sea-ice extent during austral summer 2022. Adv Atmos Sci, 39(10): 1591-1597, doi:10.1007/s00376-022-2087-1.

Wang J F, Yang Q H, Yu L J, et al. 2021. A review on Antarctic sea ice change and its climate effects. Haiyang Xuebao, 43(7): 11-22, doi:10.12284/hyxb2021151 (in Chinese with English abstract).

Wang Z L, Li Z, Zeng J Y, et al. 2020. Spatial and temporal variations of Arctic sea ice from 2002 to 2017. Earth Space Sci, 7(9): e2020EA001278, doi:10.1029/2020ea001278.

Wang Z M, Turner J, Wu Y, et al. 2019. Rapid decline of total Antarctic sea ice extent during 2014–16 controlled by wind-driven sea ice drift. J Clim, 32(17):5381-5395, doi: 10.1175/JCLI-D-18-0635.1.

Worby A P, Geiger C A, Paget M J, et al. 2008. Thickness distribution of Antarctic sea ice. J Geophys Res Oceans, 113(C5): C05S92, doi:10.1029/2007jc004254.

Yuan X, Martinson D. 2000. Antarctic sea ice extent variability and its global connectivity. J Clim, 13: 1697-1717, doi:10.1175/1520-0442(2000)0131697: asieva>2.0.co;2.

Zhang J L. 2007. Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. J Clim, 20: 2515-2529, doi:10.1175/jcli41 36.1.

Zhang L, Ma H, Wu L X. 2016. Dynamics and mechanisms of decadal variability of the Pacific-South America mode over the 20th century. Clim Dyn, 46(11): 3657-3667, doi:10.1007/s00382-015-2794-8.