Attenuated Interannual Variability of Austral Winter Antarctic Sea Ice Over Recent Decades

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Abstract Changes in Antarctic sea ice modify surface circulation, deep-water formation, and overturning circulation, affecting the ecosystem and the atmosphere-ocean-ice interaction. Recent studies focused on long-term trends of Antarctic sea ice, but whether its variability has changed is less clear. By examining reanalysis data sets, we show an interdecadal attenuation in variability of austral winter Antarctic sea ice since the late 1990s. This mainly arises from declined surface pressure variations in response to a combined effect of El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). Compared to the pre-1999 period, ENSO and the SAM have reduced variability in the post-1999 period, and the linkage between them and Antarctic climate has weakened. The decreased level of variability over the 1999–2017 period may facilitate a more sensitive response of Antarctic sea ice to an external forcing, by enhancing the signal-to-noise ratio.

1. Introduction

In the recent decade, Antarctic sea ice has received much attention because of its slightly increasing trend, in sharp contrast with the rapidly decreasing Arctic sea ice in the context of global warming (Meelh et al., 2016; Zhang et al., 2019). However, recent research has signified a converse that the warming reaches the South Pole, showing a temperature increase with more than three times of the global average rate over the last three decades (Clem et al., 2020). For the Antarctic sea ice, an abrupt decline was reported since austral spring 2016 (Meelh et al., 2019; Purich & England, 2019; Stuecker et al., 2017; G. Wang et al., 2019; Z. Wang et al., 2019). The Antarctic climate seems not immune from the impacts from global warming as well. In the context of global warming, interannual variability, which can be viewed as the “noise” superimposed on the long-term trends, may also play a role in its own vulnerability. Thus, interannual variability of the Antarctic sea ice is investigated in our study, with a focus on the interdecadal change and relationship with large-scale climate modes.

On the interannual time scale, an “Antarctic Dipole” is the leading oscillation mode, reflected in both Antarctic sea ice and surface air temperature fields (Holland et al., 2005; Yuan & Martinson, 2000, 2001). This phenomenon is mainly contributed by tropical Pacific variability (Song et al., 2011; Turner, 2004; Yuan, 2004; Yuan et al., 2018). The prevailing mechanism for the teleconnection between tropical and polar regions is attributed to the El Niño-Southern Oscillation (ENSO)-excited Rossby wave trains. During El Niño
conditions, increased convection in the central and eastern tropical Pacific leads to upper level vorticity anomalies, generating southward propagating Rossby waves. This results in an anomalous high surface pressure over the Amundsen Sea region, representing a weakening Amundsen Sea Low (ASL) (see the location shown in Figure S1).

Recent advances clarify the diverse response to the eastern Pacific (EP) and central Pacific (CP) El Niño based on reanalysis data and modeling studies (Ciasto et al., 2015; Wilson et al., 2014, 2016). Compared with EP El Niño, CP El Niño generates a weaker and westward-shifting Pacific-South America teleconnection, resulting in a less remarkable positive pressure over the Amundsen-Bellingshausen Seas (Sun et al., 2013). Another explanation for the tropical-polar teleconnection involves the zonal wind and the meridional atmospheric circulation changes. During El Niño conditions, contrasting sea surface temperature (SST) signals between the tropical Pacific and the Atlantic result in the strengthened (weakened) Hadley cell and Ferrel cell in the South Pacific (Atlantic), which can be conducive to enhanced (weakened) poleward heat transport within the South Pacific (Atlantic) troposphere, generating dipole signals over the Antarctic region (Yuan et al., 2018).

The Southern Annular Mode (SAM), which reflects meridional movement of westerly jet in the Southern Hemisphere, exerts an impact on the surface pressure around the Antarctic and the relevant sea ice distribution (Gillett et al., 2006; Marshall, 2003). In its positive phase, the SAM is manifested as positive pressure anomalies over the midlatitude and negative pressure anomalies over the high latitudes (Thompson & Wallace, 2000). This favors expansion of sea ice due to enhanced Ekman drift in the ocean that favors northward advection of sea ice (Stammerjohn et al., 2008). On the other hand, increased westerlies can also bring up the subsurface water through Ekman pumping, which affects the sea ice melt or formation (Purich et al., 2016). In addition, a non-annual component exists in the SAM, giving rise to regional enhanced anomalies over the Amundsen-Bellingshausen Seas (Lefebvre et al., 2004).

As stated above, ENSO and the SAM share the common anomaly center near the Amundsen-Bellingshausen Seas, which is a key region to monitor the ENSO-SAM relationship and the associated impacts on Antarctic climate. ENSO and the SAM are not independent, but their relationship is non-stationary (Wang & Cai, 2013), which rely on the different phase and the intensity of their variability (Yu et al., 2015). For example, ENSO variability has experienced an interdecadal shift since the late 1990s, featuring a weaker amplitude and increased occurrences of CP El Niño instead of EP Niño (Guan & McPhaden, 2016; Hu et al., 2013, 2017). This may alter the ENSO-excited teleconnection and hence the Antarctic climate. In addition, the in-phase or out-of-phase relationship of ENSO and the SAM may also influence the variability intensity in the Antarctic region. Thus, it is of interest to investigate the changes in Antarctic sea ice interannual variability based on the latest observational data, as well as changes in the relationship between ENSO and the SAM.

2. Data Sets and Methods

We use the sea ice concentration (SIC) and sea level pressure (SLP) data from the fifth generation ECMWF reanalysis for the global climate and weather (ERA5), calculated for 1980–2017 (Hersbach et al., 2020). SST is derived from the Ocean ReAnalysis System 5 (ORAS5, Zuo et al., 2019). SST anomalies over the region of 5°N to 5°S, 170–120°W, with a 5-month running mean employed (Rayner et al., 2003), downloaded online (https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34). The Niño3.4 index is derived as the area-averaged SST anomalies among the region of 5°N to 5°S, 170–120°W, with a 5-month running mean employed (Rayner et al., 2003), and the data are also downloaded online (https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino4). The SAM index is described as the station-based index from Marshall (2003) (https://legacy.bas.ac.uk/met/gjma/sam.html). The ASL index is monitored using the regional mean SLP within the ASL sector (170–298°E, 80–60°S) (Hosking et al., 2013).

Several statistical methods are used, including the empirical orthogonal function (EOF), partial correlation and regression analysis, and wavelet power spectrum analysis. We apply the EOF analysis to obtain the most
prominent mode of Antarctic sea ice oscillating on interannual scale. Correlations and regression analysis are used to examine the relationship between large-scale climate modes and Antarctic climate. The wavelet power spectrum is a useful tool to assess on what frequency band the leading mode time series is most energetic during the entire period.

3. Results

3.1. Characteristics of Antarctic Sea Ice Interannual Variations

We begin our analysis by investigating the spatial and temporal characteristics of the Antarctic SIC interannual variability during austral winter. A dipole structure stands out as the oscillation leading mode, with notable opposite signs over Amundsen-Bellingshausen Seas and Antarctic Peninsula (Figure 1a), consistent with previous studies (Yuan, 2004; Yuan & Martinson, 2001). The time series of EOF PC1 displays a weakened oscillation since the late 1990s, with the standard deviation decreased by 38.0% in the second half period (1999–2017) (upper panel of Figure 1b, solid line). Further, we extract one time series of detrend SIC anomalies over the high oscillation region (66°S, 135°W; white cross in Figure 1a), which clearly shows reduced post-1999 variability to 67.6% of the pre-1999 level (upper panel of Figure 1b, dashed line). To directly demonstrate the interdecadal evolution of sea ice interannual variability, we present moving standard deviation values of the leading principal component, at the center year of a 19-year sliding window (lower panel of Figure 1b). A significant decline is seen to commence in 1999. Thus, the 1998/1999 period is chosen as a breaking point to detect the related mechanisms over the pre-1999 and post-1999 periods. Also, this breaking point is the median of this period.

To underline the interdecadal variability attenuation, standard deviation maps of detrended SIC anomalies are demonstrated separately for the pre-1999 and post-1999 periods (Figures S2a and S2b). Consistent with Figure 1, the most prominent variations occur at the periphery of Ross Sea and Amundsen-Bellingshausen Seas. This is due to the feature that sea ice around the Antarctic continental margin is more consolidated and less affected by surface wind changes. By contrast, winter sea ice reaches its annual maximum near the ice edge region, where strong variability exists and is more vulnerable to changes of surface winds and ocean currents. Compared to the pre-1999 period, magnitude of variability significantly declined in the South Pacific sector. Considering the SIC linkages with the overlying atmosphere circulation, standard deviations of detrended SLP anomalies are examined (Figures S2c and S2d). Similarly, the surface pressure variations attenuated in the South Pacific sector.

To better illustrate the changes, differences in the standard deviation of SIC (Figure 1c) and SLP (Figure 1d) between post-1999 and pre-1999 periods are presented. Regions of the Amundsen Sea and Antarctic Peninsula exhibit a pronounced SIC variability reduction, in line with difference in the SLP due to the surface winds. To verify the close linkage between SIC and SLP, we separately regress the SLP anomalies onto the SIC EOF leading principal component over the pre-1999 and post-1999 periods (Figures 1e and 1f). A pronounced contraction of positive anomalies occurs in the ASL region, which demonstrates the critical roles of surface pressure and associated winds in determining the changes in SIC variability.

A wavelet power spectrum analysis is used to examine on what frequency band the leading mode time series is most energetic during the entire period. As shown in Figure S3, SIC PC1 exhibits prominent interannual variations, with a successive high energy band around 5–6 years. In accordance with Figure 1b, the wavelet spectrum displays higher energy in the pre-1999 period, with the post-1999 period being less significant. To further focus on interannual scale variability, we calculate the integral of 2–8 years scale spectrum. The resulting time series peaks at around the year of 1990, further confirming the strong variations over the pre-1999 period.

3.2. Changes in Variability of ASL/SAM/ENSO and Their Relationship

The above results illustrate the robust reduction of SIC variability, as well as the critical roles of surface pressure in determining the attenuation of SIC variability. To elucidate the associated mechanism, we examine the variability changes of ENSO and the SAM, along with their interaction with high-latitude atmospheric circulation.

Both ENSO and the SAM can modulate the Antarctic climate by altering the position and intensity of surface pressure over the Amundsen Sea region, which is commonly measured by an ASL index, defined as the...
Figure 1. Attenuated interannual variability of austral winter (June-July-August [JJA]) Antarctic SIC during the period of 1980–2017. (a) Spatial pattern of the leading EOF mode of detrended SIC (unit: %). (b) Upper panel shows the normalized time series of the leading EOF mode of detrended SIC (solid line), with the red solid line indicating the first half period 1980–1998 and the blue solid line indicating the second half period 1999–2017. Dashed line represents the SIC time series at the grid point (66°S, 135°W) marked as “white cross” in (a). Lower panel presents the moving standard deviation of the leading principal component at the center year of a 19-year sliding window. (c) Map of differences in standard deviation of SIC between the periods of 1999–2017 and 1980–1998 (unit: %). (d) Same as (c), but for the sea level pressure (unit: Pa). (e) SLP regression pattern onto the SIC EOF PC1 for the period 1980–1998 (unit: Pa s.d.⁻¹). Significance above the 95% confidence level are marked with dots. (f) Same as (e), but for the period 1999–2017 (unit: Pa s.d.⁻¹). Amplitudes in (e) and (f) are scaled by one standard deviation of the corresponding time series in (e) and (f).
regional mean SLP within the ASL sector (170°–298°E, 80°–60°S). Thus, we first assess the change rate of the standard deviation in the ASL, the SAM, and Niño3.4 index (Figure 2). Despite the superimposed interannual fluctuations, these indices all exhibit decreased variability in the post-1999 period, at a rate of 31%, 15%, and 14%, which are in accordance with the SIC results.

A significant correlation, at 0.62, is found between the SIC EOF PC1 and the ASL index, further confirming the connection between SIC and SLP (Figure 2a). However, the correlations between SIC and the ENSO/SAM are less strong (Figures 2b and 2c). This is due to the combined influences from ENSO and the SAM, which obscure the direct connection between them. As such, we employ partial correlation analysis to detect the linkage between any two modes, which is an effective tool to remove the impact from the third one (Figure 2d). Take the partial correlation between ENSO and the ASL as an example; the coefficient of the pre-1999 period is up to 0.7067. It indicates that an El Niño event leads to a weakening ASL (anomalous high pressure). However, it reduces to 0.4038 during the post-1999 period, implying a weakened linkage between the tropics and high latitudes. By applying a Fisher r-to-z transformation, we calculate the value of z to assess the significance of the difference between these two correlation coefficients. Results show that correlations between ENSO and the ASL (or SAM) over the two periods are statistically different from each other above the 90% confidence level (p < 0.1). This indicates weaker effects from the tropical Pacific on the Antarctic climate in the post-1999 period.

After removing the ENSO’s impact, the SAM index shares high coherence with the ASL during the pre-1999 period (–0.84). This relationship decreases slightly in the post-1999 period (–0.77). But the correlation coefficients between the two periods are not statistically different. This is because the ASL is in part a manifestation of the SAM signal in the high latitudes. Thus, the impact of reduced variability of the SAM on in the Antarctic sea ice is reflected in the reduced influence from the ASL.

Additionally, a reduced association of ENSO with the SAM is also presented. The in-phase (out-of-phase) relationship between ENSO and the SAM indicates a negative (positive) correlation between them, which...
influences the Antarctic climate by the superimposing (offsetting) effects. For example, the positive phase of ENSO (El Niño), together with the negative phase of the SAM, could induce an intensified anomalous high pressure over the Amundsen Sea region (Stammerjohn et al., 2008). Hence, we separately select the years in which Niño3.4 and SAM index exceed the ±0.5 standard deviation, which are considered as the occurrence of ENSO or SAM events. Next, we count the ENSO/SAM in-phase and out-of-phase numbers over the two periods. The results show that both periods show five out-of-phase situations. But three in-phase situations exist in the pre-1999 period and two in the post-1999. Thus, the in-phase or out-of-phase situations may contribute little to the variability reduction. It is the magnitude of the ENSO's and the SAM's variability that dominate the reduction phenomenon.

The above results imply that attenuated variability of the ASL, the SAM, and ENSO may reduce the fluctuations of Antarctic surface pressure, diminishing variability of the anomalous sea ice. Moreover, any two modes reveal a weakening connection, further limiting the Antarctic SIC variations from the forcing of the tropics and the Southern Hemisphere atmospheric circulation. In the following, we elucidate the spatial relationships between SIC and the SAM/ENSO over the two periods, respectively.

### 3.3. ENSO’s Impact on Antarctic Sea Ice Variability

During austral winter, both SST perturbations in the tropical EP and the CP generate a teleconnection structure, featuring a stationary Rossby wave train. Thus, the tropics can be a “pacemaker” of the Antarctic climate, as found by several prior studies (Schneider et al., 2012; Simpkins et al., 2012; Stammerjohn et al., 2008; Yuan, 2004). To directly demonstrate the key regions in which significant linkages between the tropical Pacific and the Antarctic Dipole operate during austral winter, we first regress the SST anomalies onto the leading principal component of SIC (Figure 3a). Significant positive SST anomalies occurring in the CP SST are linked to the Antarctic Dipole. To further detect the effects from the tropical Pacific independent of the SAM, we perform a partial correlation analysis of SLP and SIC anomalies with the Niño3.4 index to examine the ENSO’s role in determining the Antarctic climate fluctuations.

For the pre-1999 period, response of SLP to El Niño event displays a notable meridional dipole structure in the South Pacific sector, with low (high) anomalies in the middle (high) latitudes, resembling the negative phase of SAM in the Pacific sector of the Antarctic (Figure 3b). The associated winds bring cold air into the Peninsula region and promote a northward sea ice drift, both contributing to the positive SIC anomalies there (Figure 3d). Conversely, the negative SIC signals in the periphery of the Ross-Amundsen Seas are related to the poleward advection of warm air and sea ice, leading to the decreasing sea ice (Figure 3d). By contrast, the above SLP dipole structure tends to be weaker in the post-1999 period, hence the reduced connection with sea ice (Figures 3c and 3e). Our results are not sensitive to the choice of Niño3.4 or Niño4 indices, especially considering that we are comparing the relative difference between the pre-1999 and post-1999 period (Figure S4).

The weakening in ENSO variability since the late 1990s has been documented (Hu et al., 2013; Lübbecke & McPhaden, 2014; McPhaden, 2012). It shifted toward weaker amplitude, higher frequency, along with an increased frequency of CP El Niño. The associated mechanisms are related to a shift to the La Niña-like background state after the late 1990s, exhibiting stronger trade winds and a steeper thermocline than normal (Hu et al., 2013; Xiang et al., 2013). Since the imbalance between zonal winds and the zonal mean thermocline depth is a trigger mechanism of the ENSO periodicity, the above features constrain the eastward migration of warm water in the western tropical Pacific and the development of EP El Niño, contributing to reduced ENSO-related variability (Hu et al., 2013; Lübbecke & McPhaden, 2014). After the late 1990s, the more frequent occurrences of CP El Niño can not only give rise to a westward shift and weakened wave train teleconnection but also induce a weaker ascending branch of Ferrel cell within the Southern Hemisphere high latitudes (Sun et al., 2013). Therefore, the combined effects contribute to decreased variability of SLP and SIC in the West Antarctica. Our results suggest that the change in variability in the tropics can also transmit its influences on the Antarctic sea ice fluctuations via the teleconnection, affecting the Antarctic climate.

### 3.4. SAM’s Impact on the Antarctic Sea Ice Variability

As the dominant mode of atmospheric variability in the Southern Hemisphere, the SAM alters the strength and position of westerlies, acting on the ocean Ekman transport and pumping (Purich et al., 2016; Stammerjohn et al., 2008). As stated above, the intensity of SAM’s variability has decreased by 15% in the
post-1999 period, which is a contributing factor to the attenuation of SIC variability (Figure 2b). Next, whether changes exist in the SAM’s spatial structure is a focus of this section. Here, we perform a partial correlation analysis of SLP and SIC fields associated with the SAM index. Compared to the post-1999 period, SLP anomalies in the pre-1999 period display more equatorward

**Figure 3.** ENSO's impact on the Antarctic climate. (a) SST (from ORAS5) regression pattern onto the normalized SIC EOF PC1 for the period 1980–2017 (unit: °C s.d.⁻¹). Maps of partial correlation coefficients of SLP with Niño3.4 index for the periods of (b) 1980–1998 and (c) 1999–2017. Maps of partial correlation coefficients of SIC with Niño3.4 index for the periods of (d) 1980–1998 and (e) 1999–2017. Significance above the 95% confidence level are marked with dots.
westerlies in the South Pacific, corresponding to a deeper ASL and a stronger non-annular component of the SAM (Figures 4a and 4b). For the pre-1999 period, the SLP trough in the Amundsen-Bellingshausen Seas corresponds to anticyclonic surface winds, favoring intrusion of poleward warm air near the Antarctic Peninsula and Weddell Sea and the equatorward cold air in the Amundsen Sea. Thus, the SIC anomalies show a dipole-like pattern in these regions, which shows strong consistency with the surface winds. In addition, the SLP anomalies in the Ross Sea and the Indian Ocean sector display a positive phase of the SAM, resulting in a northward ocean Ekman transport, favoring an expansion and increase of sea ice in these regions (Figure 4c). In short, the SIC spatial distributions are in good agreement with the surface pressure in the pre-1999 period.

In comparison, the above close coherence is not so significant in the post-1999 period (Figures 4b and 4d). In other words, sea ice variability is not sensitive to the overlying atmospheric circulation. A less significant non-annular component of SAM in the South Pacific sector results in a weaker SIC dipole structure. Hence, a reduced magnitude in variability of the SAM, combined with a less significant non-annular component in the spatial structure, contribute to the SIC attenuation in the post-1999 period.

4. Conclusions

We find an interdecadal attenuation in the austral winter Antarctic sea ice interannual variability from 1980–1998 to 1999–2017. We first employ the EOF analysis to obtain the leading oscillation mode of detrend austral winter SIC anomalies. A dipole-like structure located in the West Antarctic explains 25.52% variance, with a notable weakened amplitude since the late 1990s. This phenomenon is confirmed by the standard
deviation differences between the pre-1999 and post-1999 periods, with the periphery of Ross-Amundsen Seas and Antarctic Peninsula showing the most prominent decline.

The robust reduction of sea ice variations is largely attributable to the suppressed surface pressure, which affects the sea ice distribution via intrusions of warm or cool air and sea ice advection. By examining the regression pattern of SLP anomalies onto the leading principal component of SIC over the two periods, we show a significant contraction of positive anomalies in the ASL region. It confirms the critical role of surface winds on the SIC Antarctic Dipole pattern. Hence, we detect the contributing factors to the variability changes of SLP. Both ENSO and the SAM could modulate the intensity and position of ASL, leading to the sea ice changes by surface winds. Compared with the pre-1999 period, standard deviation of the ASL, the SAM, and ENSO reduced by 31%, 15%, and 14%, respectively, for the post-1999 period; also, the associations between any two of them are weakened, contributing to reduced sea ice fluctuations.

The post-1999 weakening of ENSO variability, manifested as decreased amplitude and a higher frequency of CP ENSO, had been attributed to a shift to a La Niña-like background state, favoring stronger trade winds and steeper thermocline, limiting the eastward migration of warm water from the western tropical Pacific (Hu et al., 2013; Lübbecke & McPhaden, 2014; McPhaden, 2012). Tropical Pacific variability reduction further exerts a constrained influence on the stationary Rossby waves, limiting the magnitude of SIC anomalies in the West Antarctica. For the SAM, a reduced magnitude in its variability and a less significant non-annular component in the spatial structure contribute to the SIC attenuation in the post-1999 period.

Sea ice variability is a measure of departures from the mean state, which is considered as the noise superimposed on the low frequency or trends. An implication of this work is that the attenuation of Antarctic sea ice variability over the recent two decades may make it more sensitive to external forcing, like the abrupt decline that occurred in 2016/2017.

Conflict of Interest

The authors declare no competing financial and non-financial interests.

Data Availability Statement

Data used in this study can be downloaded online (ERAS5: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5; ORAS5: https://www.ecmwf.int/en/research/climate-reanalysis/ocean-reanalysis; Niño3.4 index: https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34; Niño4 index: https://www.psl.noaa.gov/gcos_wgsp/Timeseries/Nino4; and SAM index: https://legacy.bas.ac.uk/met/jgma/sam.html).

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Acknowledgments

We thank professor Xiaojun Yuan and another reviewer for their helpful comments. This work is supported by the National Key Research and Development Program of China (nos. 2018YFA0605700 and 2019YFC150 9100). W. C. is supported by CSIRO, a joint research Center for Southern Hemisphere Oceans Research between QNLM and CSIRO.
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