The relationship between Antarctic sea-ice extent change and the main modes of sea-ice variability in austral winter

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Abstract

Accompanying global warming, Antarctic sea-ice extent shows a somewhat increasing trend from 1979 to 2014, followed by an abrupt decrease after 2016. Our previous study examined the change of Antarctic sea-ice extent in austral summer, autumn and spring. In this study, we turn our attention to the austral winter, relating the main modes of sea-ice variability to sea-ice extent in the Pacific, Atlantic and Indian sectors of the Southern Ocean. We find that the modes with the strongest correlation with the sea-ice extent are the third, first and first modes in the Pacific, Atlantic and Indian sectors, respectively. Atmospheric circulation anomalies of zonal wavenumber three over the Southern Ocean, related to planetary wave trains induced by the SST anomalies over the south-western Pacific and the southern Indian oceans, can explain sea-ice concentration anomalies of the third mode in the Pacific sector through thermodynamic and dynamic processes. Sea-ice anomalies of the first modes in the Atlantic and Indian sectors result from atmospheric circulation anomalies of a positive and negative phases of the Southern Annular Mode, respectively. The anomalous Southern Annular Mode is also associated with wave trains over the Southern Ocean excited by SST anomalies over the southern Indian Ocean and the south-western Pacific Ocean. The relationship between SST anomalies and Antarctic sea-ice anomalies can provide a reference for the prediction of Antarctic sea-ice anomalies in austral winter on interannual and decadal timescales.

Introduction

In the context of global warming induced by increased greenhouse gas emissions, the change in Arctic and Antarctic sea-ice extent experiences completely different trajectories. In contrast to the abrupt decrease in Arctic, Antarctic sea-ice extent increased from 1979 to 2014, and it decreased abruptly after 2014 (Parkinson 2019). Previous studies highlighted either the increasing trend in Antarctic sea-ice extent in the former period or the decreasing trend in the latter period. Fewer studies have focused on the shift of the trend in wintertime Antarctic sea-ice extent.

The increasing trend in Antarctic sea-ice extent has been examined by a number of studies (Ding et al. 2011; Hobbs et al. 2016; Blanchard-Wrigglesworth et al. 2021; Li et al. 2021). The influencing factors include the SAM (Ferreira et al. 2015), the Amundsen Sea Low (Raphael et al. 2017), zonal-wavenumber-three pattern (Raphael 2007), the Pacific Decadal Oscillation, the Interdecadal Pacific Oscillation and the Atlantic Multidecadal Oscillation (Hobbs et al. 2015; Yu et al. 2017; Yu, Zhong & Sun 2022), and the South Pacific Oscillation (Yu et al. 2021), ocean-ice feedback (Zhang 2007; Goosse & Zunz 2014) and melting ice shelves (Bintanja et al. 2013; Bintanja et al. 2015). Several other studies have found that ice-shelf melt does not explain Antarctic sea-ice increase (e.g., Swart & Fyfe 2013; Pauling et al. 2016). In addition, SSTs and sea-ice drift are crucial for Antarctic sea-ice change (Blanchard-Wrigglesworth et al. 2021; Sun & Eisenman 2021; Zhang et al. 2021). Recent studies have suggested that external forcings (ozone depletion and increased greenhouse gas emission) do not make a significant contribution to the increasing trend (Schneider & Deser 2017; Parkinson & DiGirolamo 2021; Polvani et al. 2021).

The decreasing trend after 2014 also results from several factors (Eayrs et al. 2021), including anomalous
Antarctic sea-ice extent and variability  L. Yu et al.

subsurface sea temperature (Meehl et al. 2019; Purich & Doddridge 2023), Southern Ocean SSTs and winds (Blanchard-Wrigglesworth et al. 2021), tropical SST (Stuecker et al. 2017; Wang et al. 2019; Yu et al. 2024), and atmospheric circulation anomalies in the troposphere (Turner et al. 2017; Schlosser et al. 2018) and in the stratosphere (Wang et al. 2019). Although several studies have analysed the increasing trend from 1979 to 2014 in austral winter, studies investigating the more recent negative trend have largely focused only on austral spring and summer. Moreover, fewer studies consider together the increasing and decreasing trend in Antarctic sea-ice extent in austral winter. Much of the previous work has focused on assessing climate models and providing evidence of winter trends in Antarctic sea ice; an explanation of the driving mechanisms is still lacking (Uotila et al. 2014; Shu et al. 2015).

Previous studies have suggested that tropical SST anomalies influence Antarctic sea ice through teleconnections (Harangozo 2004; Turner 2004; Fogt et al. 2006; Fogt et al. 2011; Ciasto & England 2011; Simpkins et al. 2012; Li et al. 2014; Simpkins et al. 2014; Ciasto et al. 2015; Li et al. 2015; Nuncio & Yuan 2015; Kohyama & Hartmann 2016; Meehl et al. 2016; Holland et al. 2019; Purich et al. 2016; Purich & England 2019; Chung et al. 2022). Li et al. (2021) reviewed tropical-extratropical teleconnections. Anomalous SSTs in the tropical and subtropical Indian, Pacific and Atlantic oceans induce an anomalous vortex in the upper troposphere which can then excite a wave train. The wave train propagates towards higher latitudes and, if the anomalies reach the Southern Ocean, can lead to anomalous geopotential height, surface atmospheric circulation and Antarctic sea ice. Building on our previous study highlighting the change in Antarctic sea-ice extent for non-winter seasons (Yu, Zhong, Vihma et al. 2022), this study examines the change in sea-ice extent in austral winter. The large regional variability of Antarctic sea ice prevents us from correlating the change in total wintertime Antarctic sea-ice extent with any of the first four modes of Antarctic sea-ice concentration variability over the Southern Ocean. In this study, we divide the Southern Ocean into three sectors: the Pacific sector (120°E–60°W), the Atlantic sector (60°W–20°E) and the Indian sector (20°E–120°E). Similar to our previous study, we examine the relationship between Antarctic sea-ice extent and the first three modes of Antarctic sea-ice variability in each sector.

**Data sets and methods**

The National Snow and Ice Data Center provides monthly Antarctic sea-ice concentration data, which has a polar stereographic grid of 25-km resolution for the period of October 1978 to the present (Cavalieri et al. 1996). The sea-ice concentration data are produced by the NASA Team algorithm. For large-scale Antarctic sea-ice variability, which is the focus of this analysis, the results are similar using either the NASA Team or the Bootstrap algorithms (Anderson et al. 2006). Sea-ice extent is defined as the total area of grid cells with sea-ice concentration greater than 15%. The austral winter refers to the months JAS.

Atmospheric variables used in this study are derived from the ERA5 (Hersbach et al. 2020). Previous studies suggested that the atmospheric variables from ERA5 are consistent with observed products (Gossart et al. 2019; Ramon et al. 2019; Dong et al. 2020). NOAA Extended Reconstructed SST version 5 provides SST data (Huang et al. 2017).

EOF analysis is an effective method to extract the main modes of three-dimensional variability (Wilks 2006). We employed the EOF method to obtain separately the main modes of sea-ice concentration variability in the Pacific (120°E–60°W), Atlantic (60°W–20°E) and Indian (20°E–120°E) sectors of the Southern Ocean. Each mode is composed of spatial patterns (EOFs) and corresponding time coefficients (PCs). Each of the first three modes is distinguishable from its neighbouring modes following North et al. (1982). To interpret the spatial pattern of each EOF mode, we regressed atmospheric and oceanic variables onto the PCs. We evaluated the statistical significance of relationships with a Student's *t*-test.

To demonstrate that anomalous SSTs are the driver for the observed atmospheric response, we carried out simulations with prescribed SSTs and sea ice using CAM5, which is the atmospheric component of the Community Earth System Model. CAM5 has a vertical resolution of 30 levels and a horizontal resolution of 1.9° latitude × 2.5° longitude. For more details about the CAM5 model, we refer the reader to Neale et al. (2012). We carried out one control and one idealized experiment. The control run was a 50-year long simulation in which CAM5 was forced by the climatological annual cycle of SST and sea-ice concentration from the Hadley Centre Sea Ice and Sea Surface Temperature data set (Rayner et al. 2003). The last 20 years were retained as reference years to restart the idealized experiment. For the idealized experiment, 2°C SST anomaly was applied in two regions—0–30°S, 40–80°E and 30–50°S, 180–140°W—where the SST anomalies regressed onto the PC3 for the Pacific sea-ice concentration in austral winter were significant (Fig. 3a). The warm SST anomalies were added from 1 July to 30 September each year, whilst the SST and sea-ice conditions during the rest of a year were the same as the
L. YU et al. The relationship between Antarctic sea-ice extent change and the main modes

Results

There was a significantly increasing trend in Antarctic sea-ice extent in austral winter (JAS) from 1979 to 2014 (18 527 km² yr⁻¹; \( p < 0.01 \)) and an abrupt decrease from 2014 to 2020 (-191 360 km² yr⁻¹; \( p < 0.06; \) Fig. 1a). The decreasing trend was more than 10 times that of the increasing trend. A similar change is also observed in the time series of sea-ice extent in the Pacific sector of the Southern Ocean (Fig. 1b). The trends in sea-ice extent in the Pacific sector were 17 629 km² yr⁻¹ (\( p < 0.01 \)) and -133 378 km² yr⁻¹ (\( p < 0.05 \)) for the 1979–2014 and 2014–2020 periods, respectively. In the Atlantic sector, there was no significant increasing or decreasing trend in sea-ice extent for either of the two periods (Fig. 1c). The increasing and decreasing trends in sea-ice extent in the Indian sector for the two periods are not significant (\( p > 0.1; \) Fig. 1d).

EOF analyses of sea-ice concentration in the Pacific, Atlantic and Indian sectors of the Southern Ocean resulted in correlations between the PCs of the first three modes and Antarctic sea-ice extent in each of the three sectors (Table 1). The strongest correlations are the third mode in the Pacific sector (0.84), the first mode in the Atlantic sector (0.94) and the first mode in the Indian sector (0.76). The three modes can represent well the change of the sea-ice extent in the three sectors. The three modes explain 14.4%, 34.4% and 30.8% of the total variance, respectively (Fig. 2). The EOF of the third mode of sea-ice variability in the Pacific sector showed positive anomalies at the ice marginal zone and negative values in the inner zone (Fig. 2a). The PC of the third mode also exhibited an increasing trend from 1979 to 2014 and a decreasing trend from 2014 to 2020, which is consistent with the change of the sea-ice extent in the Pacific sector (Fig. 2d). The EOF of the first mode in the Atlantic sector also showed positive sea-ice anomalies over most of the region with the exception of southern Weddell Sea (Fig. 2b). The EOF of the first mode of sea-ice variability in the Indian sector displayed a tripole structure of negative anomalies at 90°E flanked by positive anomalies (Fig. 2c). The PCs of the two first modes displayed no significant trends (Fig. 2e, f).

We examined the influencing factors of the above-mentioned modes in the three sectors through regression analysis of atmospheric and oceanic variables onto the PCs of the three modes. The regression maps for the Pacific sector are shown in Figs. 3 and 4. There were positive SST anomalies over most of the Pacific Ocean and the North Atlantic Ocean, resembling a positive phase of the Atlantic Multidecadal Oscillation (Fig. 3a). Positive SST anomalies also occurred over the

Table 1. Correlation coefficients between the time series of sea-ice extent and PCs of the first three modes in the Pacific, Atlantic and Indian sectors of the Southern Ocean for austral winter. The asterisk indicates that the anomaly is statistically significant at the 99% confidence level.

<table>
<thead>
<tr>
<th>EOF mode</th>
<th>Pacific</th>
<th>Atlantic</th>
<th>Indian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>0.16</td>
<td>0.94*</td>
<td>0.76*</td>
</tr>
<tr>
<td>Mode 2</td>
<td>-0.43*</td>
<td>-0.20</td>
<td>-0.56*</td>
</tr>
<tr>
<td>Mode 3</td>
<td>0.84*</td>
<td>0.03</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

Fig. 1 The time series of Antarctic sea-ice extent in (a) the total Southern Ocean, (b) the Pacific, (c) Atlantic and (d) Indian sectors of the Southern Ocean for austral winter (JAS). The dashed lines denote the trends in the time series.
southern Indian Ocean and the south-eastern Atlantic Ocean. Corresponding 500-hPa height anomalies displayed positive values over the Antarctic continent (Fig. 3b). There was a zonal-wavenumber-three structure tilted in a north-west–south-east orientation over the Southern Ocean. As shown in Fig. 3c, anomalous stream function and wave activity flux indicate that the positive SST anomalies east of New Zealand and over the tropical western Indian Ocean induced two wave trains. Based on the Gill-mode pattern, there were positive height anomalies in response to the positive SST anomalies. One wave train propagated south-eastwards, first towards the southern Pacific Ocean and then entered the southern Atlantic Ocean. The other propagated from the southern Indian Ocean to the south-eastern Pacific Ocean and the southern Atlantic Ocean. The two wave trains together affected the height anomalies over the Southern Ocean.

Anomalous MSLP also showed a zonal-wavenumber-three structure (Fig. 4a). Anomalous 10-m easterly winds dominated over most of the Southern Ocean (Fig. 4b). The anomalous southerly winds induced by positive MSLP anomalies over the Bellingshausen Sea pushed the sea ice off the coast, expanding the sea-ice cover over the south-western Pacific Ocean. Similarly, the anomalous southerly winds over the western Ross Sea and Wilkes Land also favoured the positive sea-ice concentration over the south-western Pacific Ocean. The north-westery winds over the Amundsen and eastern Ross seas pushed sea ice onto the coast, decreasing the sea-ice cover there. Besides the dynamic effects, anomalous winds were also related to anomalous surface air
L. YU et al. The relationship between Antarctic sea-ice extent change and the main modes

Fig. 3 Regression maps of (a) SST [°C], (b) 500-hPa geopotential height [gpm] and (c) streamfunction [m²·s⁻¹] and wave activity flux (vectors; Takaya & Nakamura 2001) into the PC3 for the Pacific sea-ice concentration in austral winter (JAS). Dotted regions indicate that the anomaly is statistically significant at the 95% confidence level. The green box indicates anomalous SST in the idealized experiment.

Temperature through thermal advection processes (Fig. 4c). The positive (negative) surface air temperature occurred over the Amundsen and the eastern Ross Seas (the rest of the Pacific sector), which facilitated the decreasing (increasing) sea-ice cover there. The downward longwave radiation anomalies played an important
role in surface air temperature anomalies (Fig. 4d). The spatial pattern of anomalous downward longwave radiation was similar to that of surface air temperature, but opposite to that of the sea-ice anomalies.

For the first mode of sea-ice variability in the Atlantic sector, anomalous 500-hPa geopotential height presented a negative phase of the SAM (Fig. 5b). The correlation between the PC1 and the SAM index in austral winter was –0.31 ($p < 0.05$). There was a dipole structure of negative (positive) values over the southern Atlantic Ocean (Weddell Sea). The spatial pattern of height anomalies was related to the SST anomalies over the south of Australia and the southern Indian Ocean (Fig. 5a), which excited a planetary wave train over the Southern Ocean.
Negative SST anomalies controlled the Weddell Sea (Fig. 5a), which was consistent with negative surface air temperature anomalies (Fig. 6c). Positive MSLP anomalies over the Antarctic Peninsula (Fig. 6a) induced anomalous anticyclonic circulation, which were associated with anomalous south-westerly and southerly winds over the Weddell Sea (Fig. 6b), increasing sea-ice cover there. The dry and cold air from the continent of West Antarctica also decreased surface air temperature over the Weddell Sea, facilitating the growth of sea ice there. Decreased downward longwave radiation also helped the expansion of sea ice over the Weddell (Fig. 6d).

Fig. 5 Regression maps of anomalous (a) SST (°C), (b) 500-hPa geopotential height (gpm) and (c) streamfunction (m² s⁻¹) and wave activity flux (vectors) into the PC1 for the Atlantic sector of the Southern Ocean in austral summer (JAS). Dotted regions indicate that the anomaly is statistically significant at the 95% confidence level.
The anomalous 500-hPa geopotential height for the first mode in the Indian sector manifested a positive phase of the SAM (Fig. 7b), and the correlation of the SAM and the PC1 was 0.42 ($p < 0.05$). The positive height anomalies over the mid-latitude southern Indian Ocean corresponded to positive SST anomalies (Fig. 7a), which excited a planetary wave train over the Southern Ocean (Fig. 5c), contributing to the anomalous heights over the Southern Ocean. The tripole structure of SST anomalies was consistent with surface air temperature (Fig. 8c). The anomalously negative MSLP over Dronning Maud Land (Fig. 8a) was related to anomalous southerly winds (Fig. 8b).
expanding sea-ice covers the Cosmonauts Sea. Anomalous northerly winds were linked to decreased sea-ice cover. Meanwhile, the anomalous positive (negative) downward longwave radiation also influenced positive (negative) surface air temperature, limiting (favouring) the growth of sea ice in the Indian sector (Fig. 8c, d).

Fig. 7 Regression maps of (a) 500-hPa geopotential height (gpm), (b) SST (°C) and (c) streamfunction (m² s⁻¹) and wave activity flux (vectors) into the PC1 for the Indian sector of the Southern Ocean in austral summer (JAS). Dotted regions indicate that the anomaly is statistically significant at the 95% confidence level.
These regression results do not definitively demonstrate that SST anomalies forced the wintertime Antarctic sea-ice change. The trend in PCs may also have influenced the causal link between the two different variables. To confirm the role of SST anomalies in wintertime Antarctic sea-ice change in the Pacific sector, we carried out an idealized experiment using the CAM5 atmospheric model. In this experiment, we increased 2°C in the two regions—0–30°S, 40–80°E and 30–50°S, 180–140°W—above their climatological values, where SST anomalies regressed onto the PC3 for the Pacific sea-ice concentration in austral winter were significant (Fig. 3a; Li et al.).

Fig. 8 Regression maps of (a) MSLP (Pascal), (b) 10-m wind field, (c) 2-m air temperature (°C) and (d) downward longwave radiation ($10^5$ W m$^{-2}$) into the PC1 of sea-ice concentration for the Indian sector of the Southern Ocean. Dotted in panels (a), (c) and (d) and shaded regions in (b) indicate that the anomaly is statistically significant at the 95% confidence level.
L. YU et al. The relationship between Antarctic sea-ice extent change and the main modes

2021). Figure 9 shows the anomalous 500-hPa geopotential height of the idealized minus control experiments, which is similar to the regression map (Fig. 3b), though the positive height anomalies over the Ross Sea were stronger and more northerly and the negative values weaker. The simulated height anomalies prove that positive SST anomalies in the Indian and Pacific oceans in the two regions can have triggered the aforementioned wave train, influencing Antarctic sea-ice extent. The positive SST anomalies in the south-eastern Indian Ocean were less significant; they may have played a role in the formation of the wave train, though they are not involved in the idealized experiment. The positive SST anomalies in the south-eastern Indian Ocean may produce the difference between simulated and observed heights.

Conclusion and discussion

In this study, we found that, as in other seasons, the sea-ice extent over the Southern Ocean in austral winter (JAS) also exhibited a positive trend from 1979 to 2014 and a negative trend from 2014 to 2020, as suggested by Parkinson (2019). The change in the sea-ice extent in the Pacific sector of the Southern Ocean is consistent with that of the Southern Ocean as a whole. The Atlantic and Indian sectors did not show this change in trend but experienced substantial interannual variability. For each sector, we investigated the reason for the change in sea-ice extent. The change in sea-ice extent in the Pacific sector was related to the third mode of sea-ice concentration variability. The positive SST anomalies over the southern Indian Ocean triggered two wave trains, which induced atmospheric circulation anomalies of zonal wavenumber three over the Southern Ocean, suggesting the wintertime asymmetry in SAM (Kidston et al. 2009). Through dynamic and thermodynamic processes, the anomalous atmospheric circulations were linked with anomalous sea-ice concentration, contributing to the change in sea-ice extent in the Pacific sector.

The sea-ice extent change in the Atlantic sector, corresponding to the first mode of sea-ice variability, was related to a negative phase of the SAM. Anomalous MSLPs over the Antarctic Peninsula induced an anomalous anticyclonic circulation, which was associated with anomalous southerly winds, expanding the sea-ice cover over most of the Atlantic sector. In contrast, the sea-ice extent change corresponding to the first mode in the Indian sector was associated with a positive phase of the SAM. The tripole structure of sea-ice variability of the first mode results from anomalously negative MSLP over Dronning Maud Land, which induced a cyclonic circulation there, influencing dynamic and thermodynamic sea-ice processes in the Indian sector.

The spatial patterns of the first and second modes of wintertime sea-ice variability in the Pacific sector (Fig. 10a, c) differ from that of the third mode (Fig. 2a). The
first mode showed a tripole structure, whilst the second
displays a dipole structure. Their time coefficients exhib-
tied interannual variability and insignificant trends (Fig.
10b, d). The two modes do not make much of a contribu-
tion to the trend in wintertime sea ice in the Southern
Ocean.

A recent paper suggested that there may be different
mechanisms at play for two periods—prior to 2016 and
after 2016—on the account of different Southern Ocean
subsurface temperatures (Purich & Doddridge 2023).
There are also different persistence characteristics for the
two different periods. This study highlights mainly the
effect of subsurface sea temperature in the Southern
Ocean on Antarctic sea-ice extent. Our results assess the
impact of atmospheric forcing induced by the planetary
wave trains excited by the lower-latitude SST anomalies,
but we cannot rule out the influence of the changing sub-
surface temperature.

Our study is the first to consider together the increas-
ing trend in Antarctic sea ice for austral winter from 1979
to 2014 and the decreasing trend from 2014 to 2020, and
it unifies the mechanism for the two trends. The shift of
the sea-ice extent trend only occurs in the Pacific sector.
We note that SST anomalies over the southern Indian
Ocean play a critical role in the shift of sea-ice extent
in the Pacific sector of the Southern Ocean. On interdecadal timescales, the impact of SST over the Indian
Ocean on Antarctic sea ice should be probed further,
though previous studies have examined their impact on
other timescales (Nuncio & Yuan 2015; Yu et al. 2021).
The significant relationship between wintertime sea-ice
concentration variability in the Southern Ocean and SST
anomalies in the Indian and Pacific sectors presents a
potential mechanism by which to improve our predic-
tions of change and variability of wintertime Antarctic
sea-ice extent. Although sea-ice extents in the Indian and
Atlantic sectors of the Southern Ocean do not show a
shift of their trends, they contribute to interannual vari-
ability of sea-ice extent in the Southern Ocean. The inter-
annual variability of sea-ice extent in two sectors is also
related to the SST anomalies in Southern Hemisphere,
especially in south-western Pacific and southern Indian
Oceans, where wave trains are excited. These interannual
results highlight the need for improving our understand-
ing of the teleconnection mechanism relating sea-ice
extent in Indian and Atlantic sectors and SST anomalies
in south-western Pacific and southern Indian Oceans. A
better understanding of the role of these teleconnections
is necessary to improve the predictability of sea ice in
these regions on interannual timescales.

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Data availability

The monthly Antarctic sea-ice concentration data set
is available from the US National Snow and Ice
Data Center (http://nsidc.org/data/NSIDC-0051). Monthly
mean atmospheric variables are provided by the ERA5.

**Disclosure statement**

The authors declare no conflict of interest.

**References**


The relationship between Antarctic sea-ice extent change and the main modes

L. YU et al.


