RESEARCH ARTICLE

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.

Keywords

Sea-surface temperature; the Atlantic Multidecadal Oscillation; Southern Annular Mode; zonal wavenumber three

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Abbreviations

CAM5: Community Atmosphere Model, version 5
EOF: empirical orthogonal function
ERA5: European Centre for Medium Range Weather Forecasts Reanalysis, fifth generation
JAS: July, August and September
MSLP: mean sea level pressure
NASA: National Aeronautics and Space Administration, USA
NOAA: National Oceanic and Atmospheric Administration, USA
PC: principal component
SAM: Southern Annular Mode
SST: sea-surface temperature

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-Wriggleworth 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

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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 climatology. Here, we show the results as the difference between the idealized experiment and the control experiment averaged over 50 years.

Results

There was a significantly increasing trend in Antarctic sea-ice extent in austral winter (JAS) from 1979 to 2014 (18 527 km^2 yr^{-1}; $p < 0.01$) and an abrupt decrease from 2014 to 2020 (-191 360 km^2 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 km^2 yr^{-1} ($p < 0.01$) and –133 378 km^2 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.

EOF mode	Pacific	Atlantic	Indian
Mode 1	0.16	0.94*	0.76*
Mode 2	–0.43*	–0.20	–0.56*
Mode 3	0.84*	0.03	–0.23

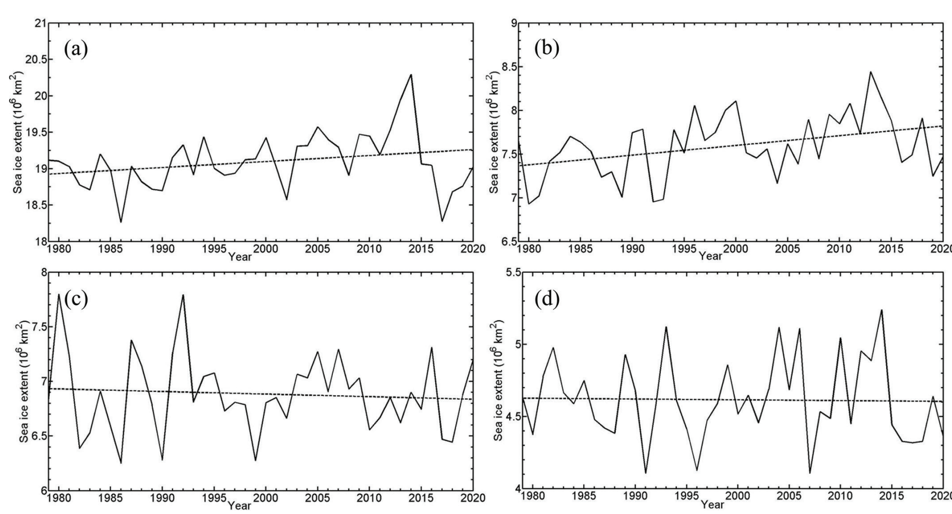

Fig. 1 The time series of Antarctic sea-ice extent in (a) the total Southern Ocean, (b) the Pacific, (c) Atlantic and (d) Indian sectors of the Southern Ocean for austral winter (JAS). The dashed lines denote the trends in the time series.

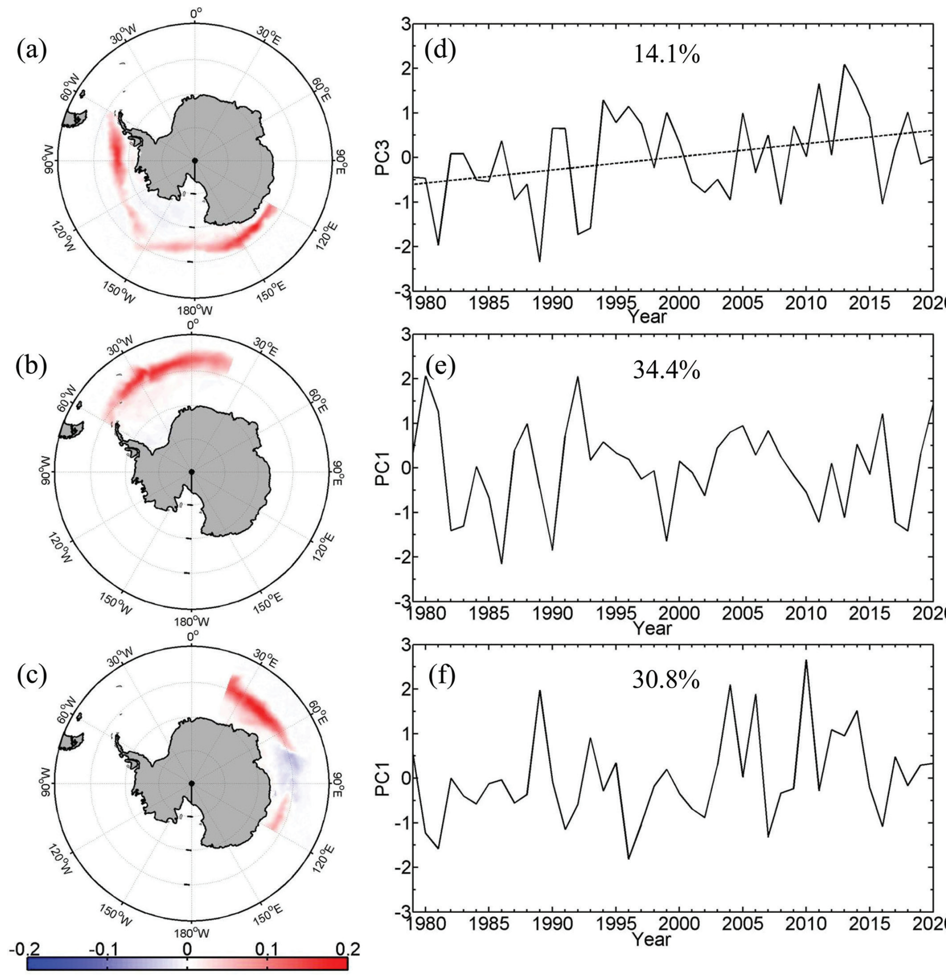

Fig. 2 The (a–c) spatial pattern and (d–f) time series of the third mode shown through EOF analysis of winter sea-ice concentration in the Pacific sector of the (a, d) Southern Ocean, (b, e) the first mode in the Atlantic sector of the Southern Ocean and (c, f) the first mode in the Indian sector of the Southern Ocean. The percentages in (d–f) denote the fraction of the total variance explained by the three modes. The dashed line in (d) indicates the trend in the time coefficient of the third mode.

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-eastern 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-westerly 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

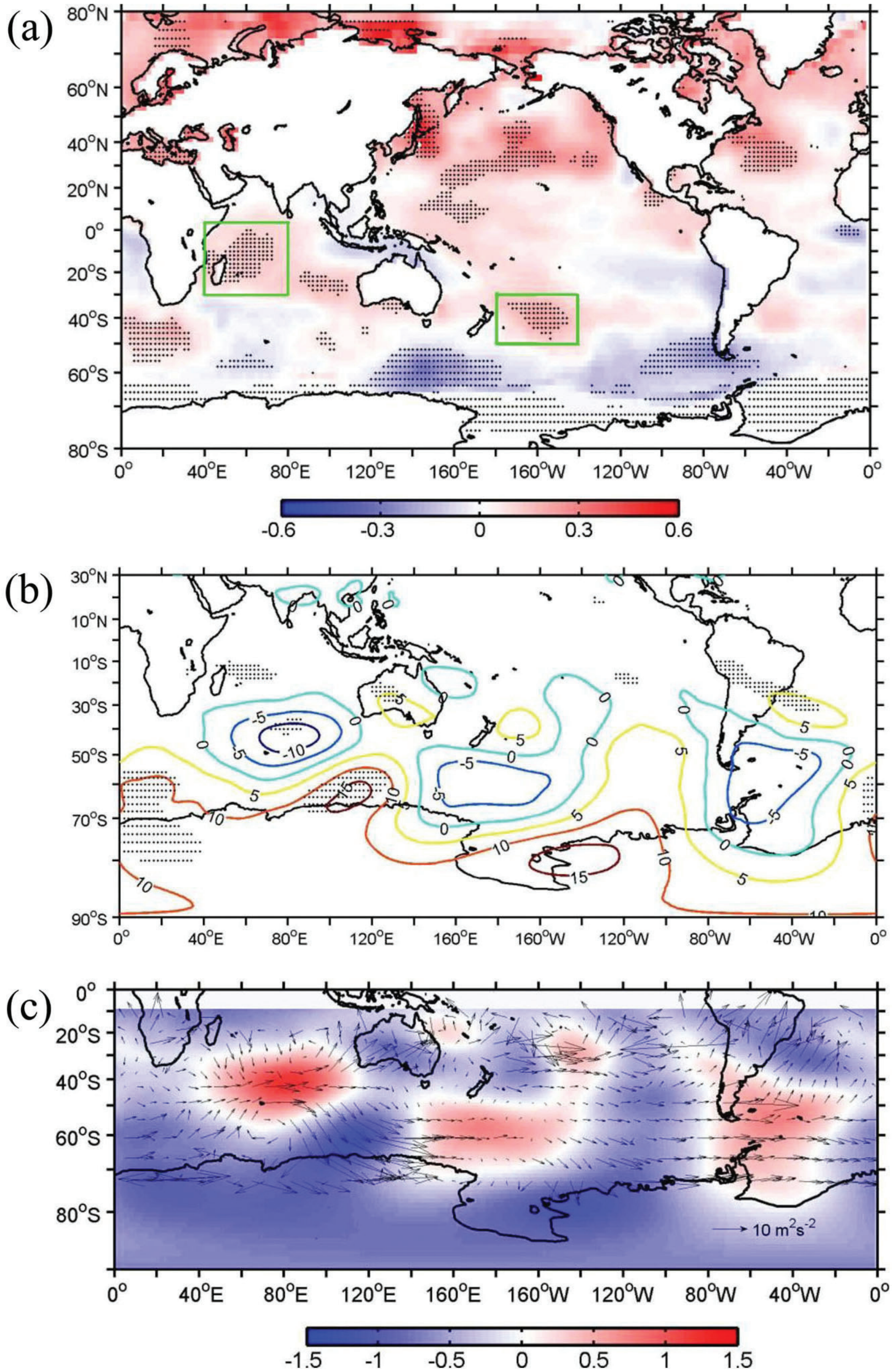

Fig. 3 Regression maps of (a) SST (°C), (b) 500-hPa geopotential height (gpm) and (c) streamfunction ($m^2 s^{-1} 10^7$) and wave activity flux (vectors; Takaya & Nakamura 2001) into the PC3 for the Pacific sea-ice concentration in austral winter (JAS). Dotted regions indicate that the anomaly is statistically 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

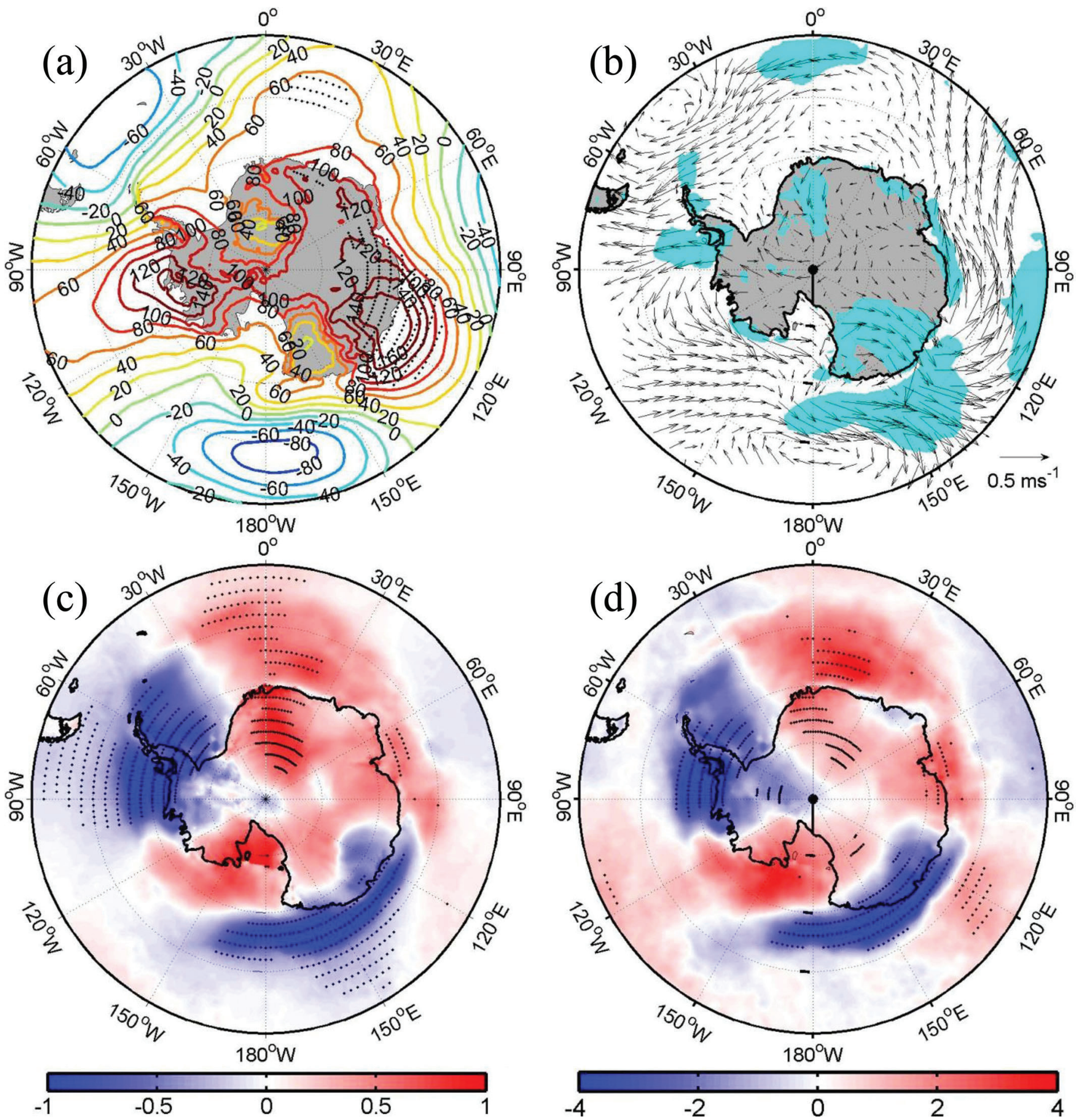

Fig. 4 Regression maps of (a) MSLP (Pascal), (b) 10-m wind field, (c) 2-m air temperature (°C) and (d) downward longwave radiation (10^5 W m^{-2}) onto the PC3 for the Pacific sea-ice concentration in austral winter (JAS). Dots in (a), (c) and (d) and shading regions in (b) indicate that the anomaly is statistically significant at the 95% confidence level.

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

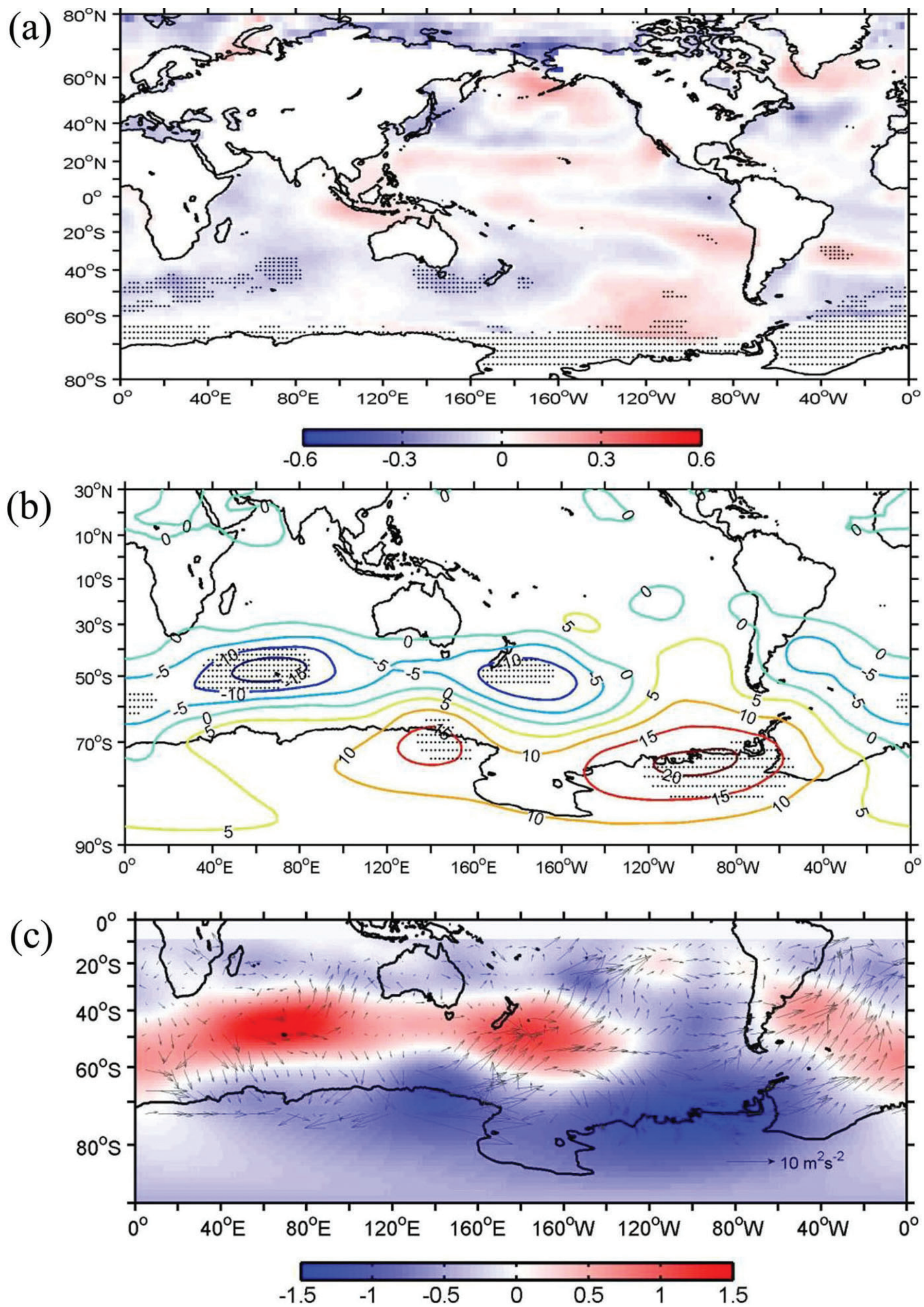

Fig. 5 Regression maps of anomalous (a) SST (°C), (b) 500-hPa geopotential height (gpm) and (c) streamfunction (m^2 s^{-1}10^7) and wave activity flux (vectors) into the PC1 for the Atlantic sector of the Southern Ocean in austral summer (JAS). Dotted regions indicate that the anomaly is statistically significant at the 95% confidence level.

(Fig. 5c). 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).

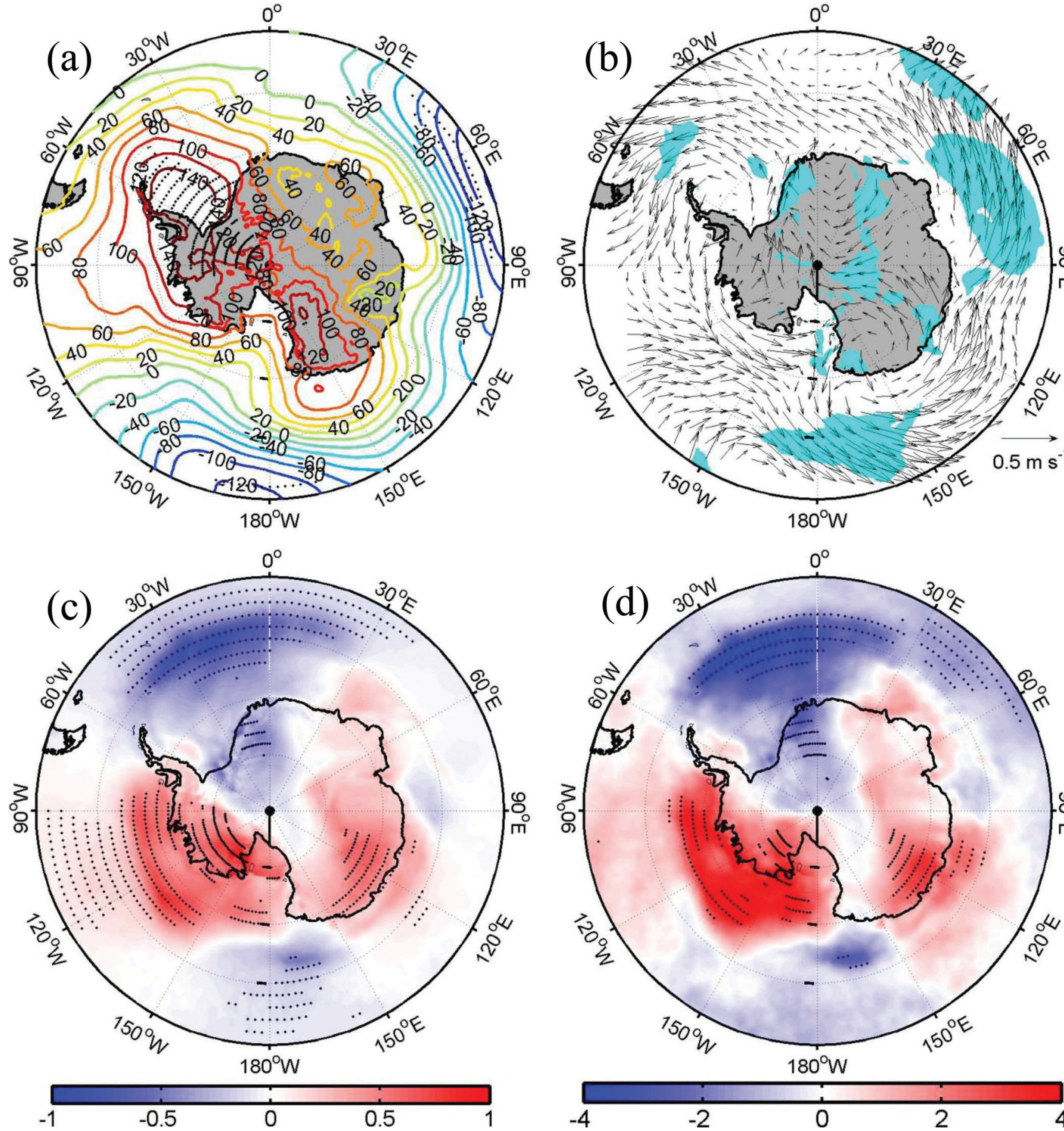

Fig. 6 Regression maps of (a) MSLP (Pascal), (b) 10-m wind field, (c) 2-m air temperature (°C) and (d) downward longwave radiation (10^5 W s^{-1}) into the PC1 of sea-ice concentration for the Atlantic sector of the Southern Ocean. Dots in (a), (c) and (d) and shading regions in (b) indicate that the 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),

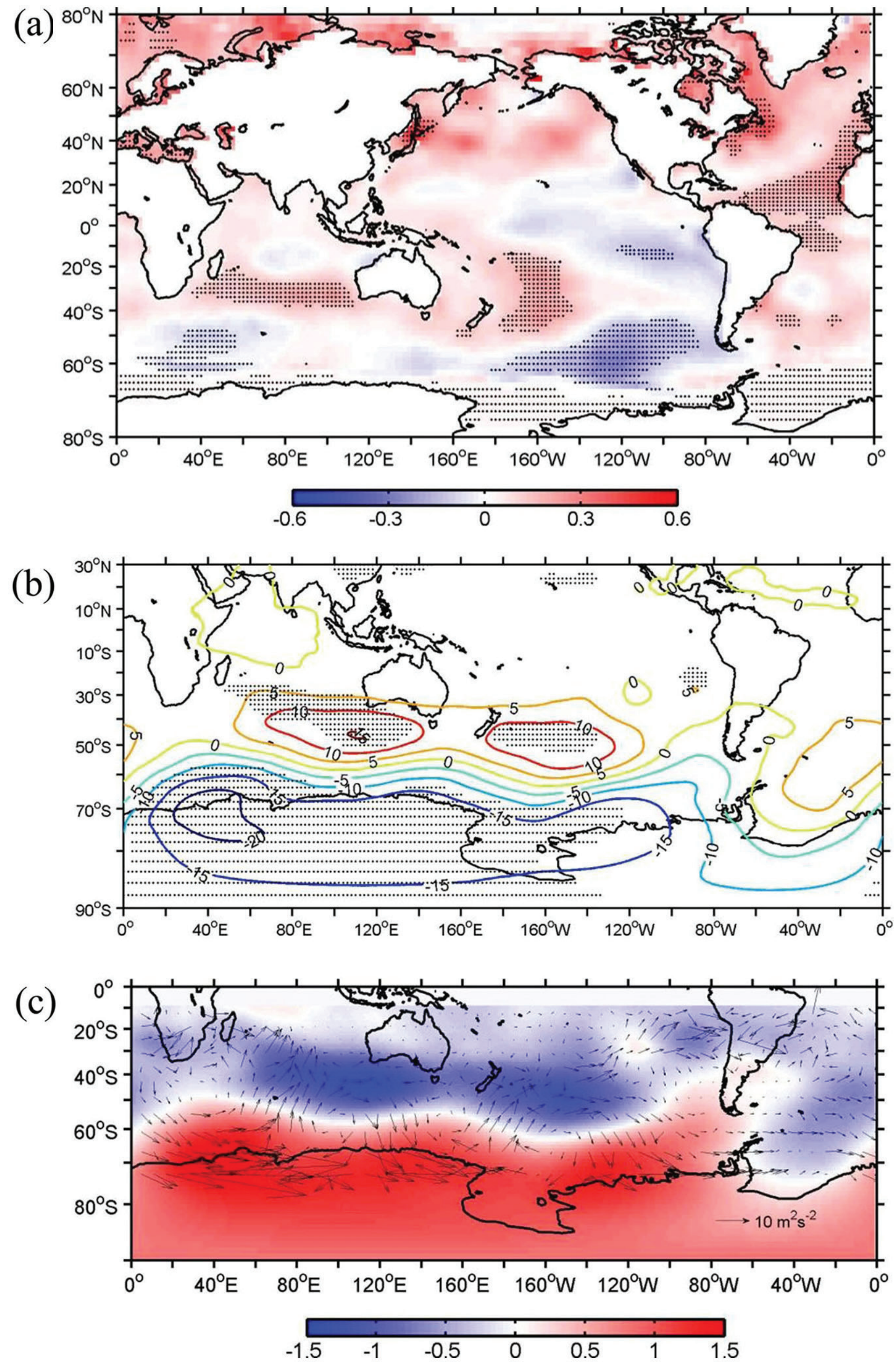

Fig. 7 Regression maps of (a) 500-hPa geopotential height (gpm), (b) SST (°C) and (c) streamfunction (m^2 s^{-1}) and wave activity flux (vectors) into the PC1 for the Indian sector of the Southern Ocean in austral summer (JAS). Dotted regions indicate that the anomaly is statistically significant at the 95% confidence level.

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).

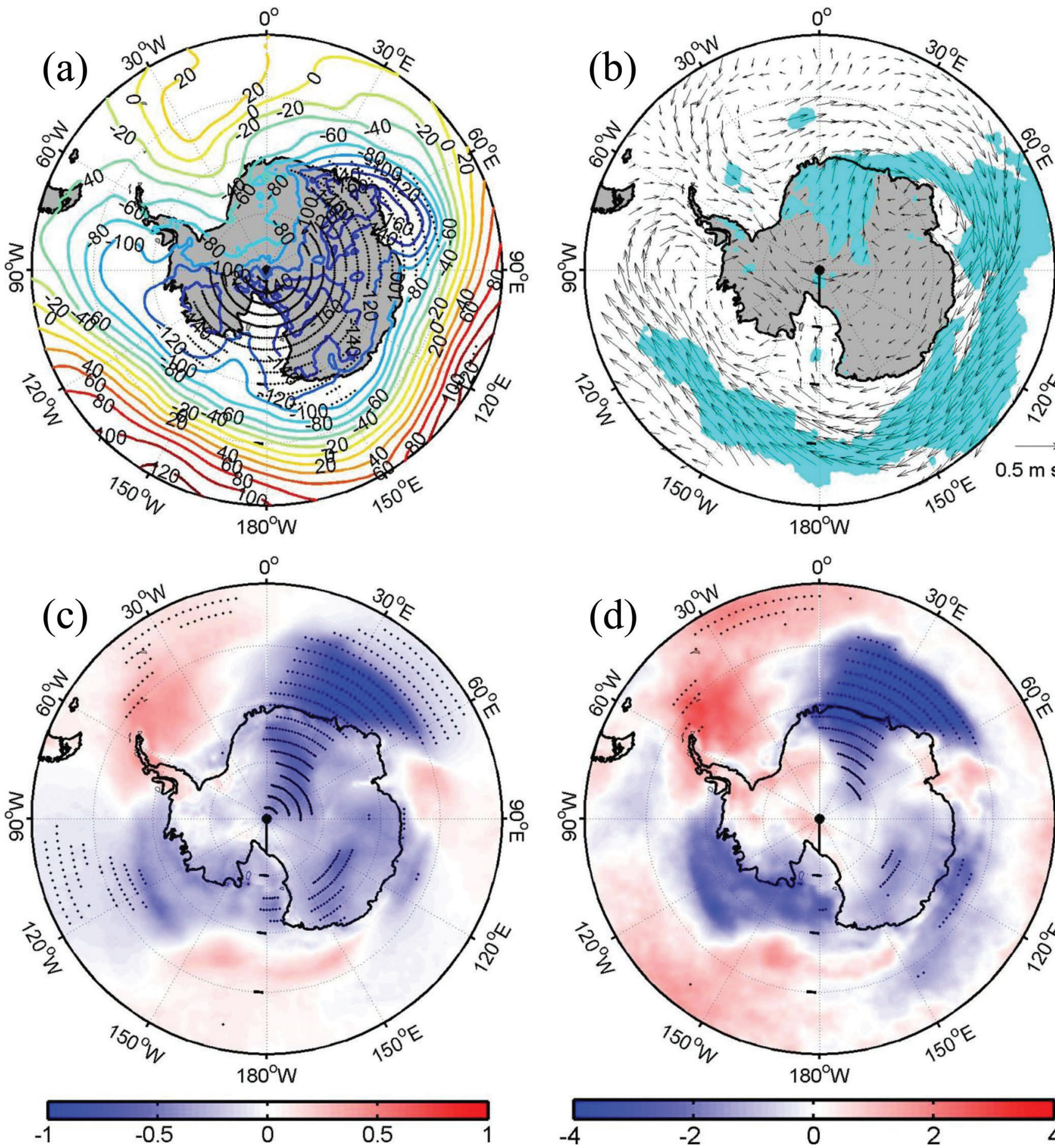

Fig. 8 Regression maps of (a) MSLP (Pascal), (b) 10-m wind field, (c) 2-m air temperature (°C) and (d) downward longwave radiation (10^5 W s^{-1}) into the PC1 of sea-ice concentration for the Indian sector of the Southern Ocean. Dotted in panels (a), (c) and (d) and shaded regions in (b) indicate that the anomaly is statistically significant at the 95% confidence level.

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.

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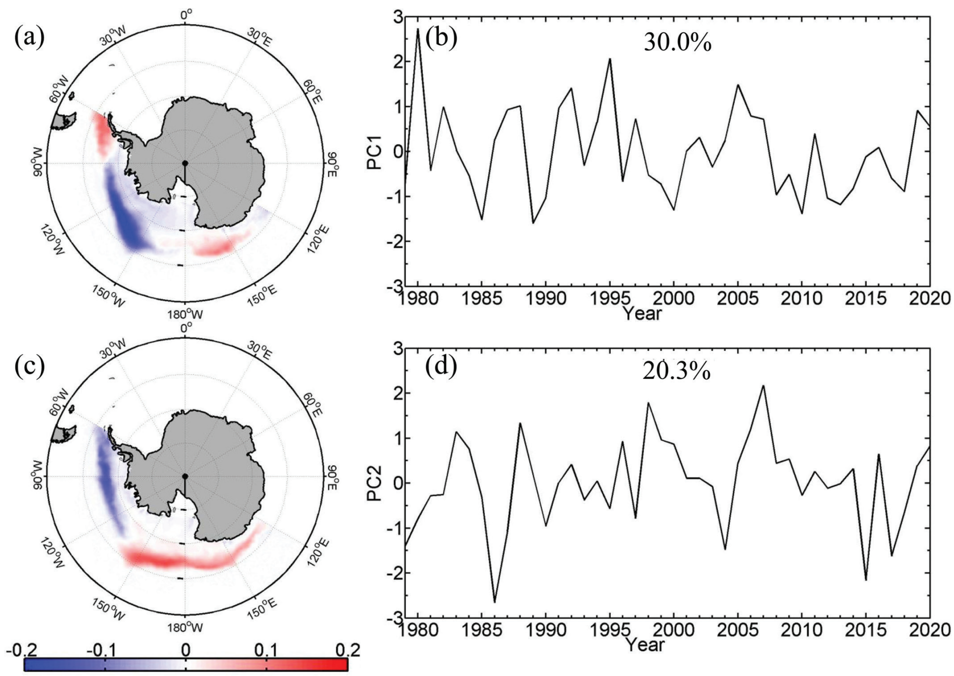

Fig. 9 The (a), (c) spatial pattern and (b), (d) time series of the (a), (b) first and (c), (d) second modes of the EOF analysis of winter sea-ice concentration in the Pacific sector of the Southern Ocean. The percentages in (b) and (d) denote the fraction of the total variance explained by the two modes.

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

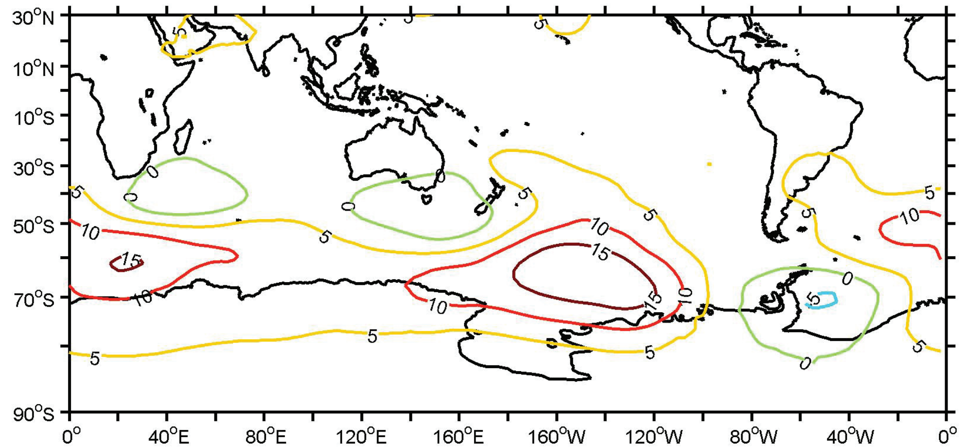

Fig. 10 Anomalous 500-hPa geopotential heights of the idealized minus control experiments.

first mode showed a tripole structure, whilst the second displays a dipole structure. Their time coefficients exhibited interannual variability and insignificant trends (Fig. 10b, d). The two modes do not make much of a contribution 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 subsurface temperature.

Our study is the first to consider together the increasing 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 trend 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 predictions 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 variability of sea-ice extent in the Southern Ocean. The interannual 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 understanding 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 (https://www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production). The monthly SST data are derived from the NOAA extended reconstructed SST data version 5 (https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html).

Disclosure statement

The authors declare no conflict of interest.

References

Anderson S., Tonboe R., Kern S. & Schyberg H. 2006. Improved retrieval of sea ice total concentration from spaceborne passive microwave observations using numerical weather prediction model fields: an intercomparison of nine algorithms. *Remote Sensing of Environment 104*, 374–392, doi: 10.1016/j.rse.2006.05.013.

Bintanja R., van Oldenborgh G.J., Drijfhout S.S., Wouters B. & Katsman C.A. 2013. Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience 6*, 376–379, doi: 10.1038/NGEO1767.

Bintanja R., van Oldenborgh G.J. & Katsman C.A. 2015. The effect of increased fresh water from Antarctic ice shelves on future trends in Antarctic sea ice. *Annual of Glaciology 56*, 120–126, doi: 10.3189/2015AoG69A001.

Blanchard-Wrigglesworth E., Roach L.A., Donohoe A. & Ding Q. 2021. Impact of winds and Southern Ocean SSTs on Antarctic sea ice trends and variability. *Journal of Climate 34*, 949–965, doi: 10.1175/JCLI-D-20-0386.1.

Cavalieri D.J., Parkinson C.L. Gloersen P. & Zwally H.J. 1996. *Updated yearly. Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, version 1. NSIDC- 0051*. Boulder, CO: NASA National Snow and Ice Data Center Distributed Active Archive Center. Accessed on the internet at https://nsidc.org/data/nsidc-0051/versions/1 on 17 March 2021.

Chung E.S., Kim S.J., Timmermann A., Ha K.J., Lee S.K., Stuecker M.F., Rodgers K.B., Lee S.S. & Huang, L. 2022. Antarctic sea-ice expansion and Southern Ocean cooling linked to tropical variability. *Nature Climate Change 12*, 461–468, doi: 10.1038/s41558-022-01339-z.

Ciasto L.M. & England M.H. 2011. Observed ENSO teleconnections to Southern Ocean SST anomalies diagnosed from a surface mixed layer heat budget. *Geophysical Research Letters 38*, L09701, doi: 10.1029/2011GL046895.

Ciasto L.M., Simpkins G.R. & England M.H. 2015. Teleconnections between tropical Pacific SST anomalies and extratropical Southern Hemisphere climate. *Journal of Climate 28*, 56–65, doi: 10.1175/JCLI-D-14-00438.1.

Ding Q., Steig E.J., Battisti D.S. & Küttel M. 2011. Winter warming in West Antarctica caused by central tropical Pacific warming. *Nature Geoscience 4*, 398–403, doi: 10.1038/NGEO1129.

Dong X., Wang Y., Hou S., Ding M., Yin, B. & Zhang, Y. 2020. Robustness of the recent global atmospheric reanalyses for Antarctic near-surface wind speed climatology. *Journal of Climate 33*, 4027–4043, doi: 10.1175/JCLI-D-19-0648.1.

Eayrs C., Li X., Raphael M.N. & Holland D.M. 2021. Rapid decline in Antarctic sea ice in recent years hints at future change. *Nature Geoscience 14*, 460–464, doi: 10.1038/s41561-021-00768-3.

Ferreira D., Marshall J., Bitz C.M., Solomon S. & Plumb, A. 2015. Antarctic ocean and sea ice response to ozone depletion: a two-time scale problem. *Journal of Climate* 28, 1206–1226, doi: 10.1175/JCLI-D-14-00313.1.

Fogt R.L. & Bromwich D.H. 2006. Decadal variability of the ENSO teleconnection to the high-latitude South Pacific governed by coupling with the Southern Annular Mode. *Journal of Climate 19*, 979–997, doi: 10.1175/JCLI3671.1.

Fogt R.L., Bromwich D.H. & Hines, K.M. 2011. Understanding the SAM influence on the south Pacific ENSO teleconnection. *Climate Dynamics 36*, 1555–1576, doi: 10.1007/s00382-010-0905-0.

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

Gossart A., Helsen S., Lenaerts J.T.M., Broucke S.V., van Lipzig N.P.M. & Souverijns N. 2019. An evaluation of surface climatology in state-of-the-art reanalyses over the Antarctic ice sheet. *Journal of Climate 32*, 6899–6915, doi: 10.1175/JCLI-D-19-0030.1.

Harangozo S.A. 2004. The relationship of Pacific deep tropical convection to the winter and springtime extratropical atmospheric circulation of the South Pacific in El Niño events. *Geophysical Research Letters 31*, L05206, doi: 10.1029/2003GL018667.

Hersbach H., Bell B., Berrisford P., Hirahara S., Horányi A., Muñoz-Sabater J., Nicolas J., Peubey C., Radu R., Schepers D., Simmons A., Soci C., Abdalla S., Abellan X., Balsamo G., Bechtold P., Biavati G., Bidlot J., Bonavita M., De Chiara G., Dahlgren P., Dee D., Diamantakis M., Dragani R., Flemming J., Forbes R., Fuentes M., Geer A., Haimberger L., Healy S., Hogan R.J., Hólm E., Janisková M., Keeley S., Laloyaux P., Lopez P., Lupu C., Radnoti G., de Rosnay P., Rozum I., Vamborg F., Villaume S. & Thépaut J.-N. 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society 146*, 1999–2049, doi: 10.1002/qj.3803.

Hobbs W.R., Bindoff N.L. & Raphael M.N. 2015. New perspectives on observed and simulated Antarctic sea ice extent trends using optimal fingerprinting techniques. *Journal of Climate 28*, 1543–1560, doi: 10.1175/JCLI-D-14-00367.1.

Hobbs W.R., Massom R., Stammerjohn S., Reid P., Williams G. & Meier W. 2016. A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change 143*, 228–250, doi: 10.1016/j.gloplacha.2016.06.008.

Holland P.R., Bracegridle T., Dutrieux P., Jenkins A. & Steig E.J. 2019. West Antarctic ice loss influenced by internal climate variability and anthropogenic forcing. *Nature Geoscience 12*, 718–724, doi: 10.1038/s41561-019-0420-9.

Huang B., Thorne P.W., Banzon V., Boyer T., Chepurin G., Lawrimore J.H., Menne M.J., Smith T.M., Vose R.S. &

Zhang H.-M. 2017. Extended reconstructed sea surface temperature version 5 (ERSSTv5): upgrades, validations, and intercomparisons. *Journal of Climate 30*, 8179–8820, doi: 10.1175/JCLI-D-16-0836.1.

Kidston J., Renwick J. & McGregor J. 2009. Hemispheric-scale seasonality of the Southern Annular Mode and impacts on the climate of New Zealand. *Journal of Climate 22*, 4759–4770, doi: 10.1175/2009JCLI2640.1.

Kohyama T. & Hartmann D.L. 2016. Antarctic sea ice response to weather and climate modes of variability. *Journal of Climate 29*, 721–741, doi: 10.1175/JCLI-D-15-0301.1.

Li X., Cai W., Meehl G., Chen D., Yuan X., Holland R.D., Ding Q., Fogt R., Markle B.R., Wang G., Bromwich D., Turner J., Xie S., Steig E., Gille S., Xiao C., Wu B., Lazzara M., Chen X., Stammerjohn S., Holland P., Holland M., Cheng X., Price s., Wang Z., Bitz C., Shi J., Gerber E., Liang X., Goosse H., Yoo C., Ding M., Geng L., Xin M., Li C., Dou T., Liu C., Sun W., Wang X. & Song C. 2021. Tropical teleconnection impacts on Antarctic climate changes. *Nature Reviews Earth & Environment 2*, 680–698, doi: 10.1038/s43017-021-00204-5.

Li X., Gerber E.P., Holland D.M. & Yoo C. 2015. A Rossby wave bridge from the tropical Atlantic to West Antarctica. *Journal of Climate 28*, 2256–2273, doi: 10.1175/JCLI-D-14-00450.1.

Li X., Holland D.M., Gerber E.P. & Yoo C. 2014. Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. *Nature 505*, 538–542, doi: 10.1038/nature12945.

Meehl G.A., Arblaster J.M., Bitz C.M., Chung C.T.Y. & Teng H. 2016. Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nature Geoscience 9*, 590–595, doi: 10.1038/NGEO2751.

Meehl G.A., Arblaster J.M., Chung C.T.Y., Holland M.M., DuVivier A., Thompson L., Yang D. & Bitz C.M. 2019. Sustained ocean changes contributed to sudden Antarctic sea ice retreat in the late 2016. *Nature Communication 10*, article no. 14, doi: 10.1038/s41467-018-07865-9.

Neale R.B., Chen C.-C., Gettelman A., Lauritzen P.H., Park S., Williamson D.L., Conley A.J., Garcia R., Kinnison D., Lamarque J.-F., Marsh D., Mills M., Smith A.K., Tilmes S., Vitt F., Morrison H., Cameron-Smith P., Collins W.D., Iacono M.J., Easter R.C., Ghan S.J., Liu X., Rash P.J. & Taylor M.A. 2012. *Description of the NCAR Community Atmosphere Model (CAM5). NCAR Technical Note TN-486+STR.* Boulder, CO: National Center for Atmospheric Research.

North G.R., Bell T.L., Cahalan R.F. & Moeng F.J. 1982. Sampling errors in the estimation of empirical orthogonal functions. *Monthly Weather Review 110*, 699–706, doi: 10.1175/1520-0493(1982)110<0699:SEITEO>2.0.CO;2.

Nuncio M. & Yuan X. 2015. The influence of the Indian Ocean Dipole on Antarctic sea ice. *Journal of Climate 28*, 2682–2690, doi: 10.1175/JCLI-D-14-00390.1.

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. *Proceedings of the National Academy of Sciences of the United States of America 116*, 14414–14423, doi: 10.1073/pnas.1906556116.

Parkinson C.L. & DiGirolamo N.E. 2021. Sea ice extents continue to set new records: Arctic, Antarctic, and global results. *Remote Sensing of Environment 267*, article no. 112753, doi: 10.1016/j.rse.2021.112753.

Pauling A.G., Bitz C.M., Smith I.J. & Langhorne P.J. 2016. The response of the Southern Ocean and Antarctic sea ice to fresh water from ice shelves in an Earth System model. *Journal of Climate 29*, 1655–1672, doi: 10.1175/JCLI-D-15-0501.1.

Polvani L.M., Banerjee A., Chemke R., Doddridge E.W., Ferreira D., Gnanadesikan A., Holland M.A., Kostov Y., Marshall J., Seviour W.J.M., Solomon S. & Waugh D.W. 2021. Interannual SAM modulation of Antarctic sea ice extent does not account for its long-term trends, pointing to a limited role for ozone depletion. *Geophysical Research Letters 48*, e2021GL094871, doi: 10.1029/2021GL094871.

Purich A. & Doddridge E. W. 2023. Record low Antarctic sea ice coverage indicates a new sea ice state. *Communications Earth & Environment 4*, article no. 314, doi: 10.1038/s43247-023-00961-9.

Purich A. & England M.H. 2019. Tropical teleconnections to Antarctic sea ice during austral spring 2016 in coupled pacemaker experiments. *Geophysical Research Letters 46*, 6848–6858, doi: 10.1029/2019GL082671.

Purich A., England M.H., Cai W. & Chikamoto Y. 2016. Tropical Pacific SST drivers of recent Antarctic sea ice trends. *Journal of Climate 29*, 8931–8948, doi: 10.1175/JCLI-D-16-0440.1.

Ramon J., Lledó L., Torralba V., Soret A. & Doblas-Reyes F.J. 2019. What global reanalysis best represents near-surface winds? *Quarterly Journal of the Royal Meteorological Society 145*, 3236–3251, doi: 10.1002/qj.3616.

Raphael M.N. 2007. The influence of atmospheric zonal wave three on Antarctic sea ice variability. *Journal of Geophysical Research—Atmospheres 112*, D12112, doi: 10.1029/2006JD007852.

Raphael M.N., Marshall G.J., Turner J., Fogt R.L., Schneider D., Dixon D.A., Hosking J.S., Jones J.M. & Hobbs W.R. 2017. The Amundsen Sea low: variability, change, and impact on Antarctic climate. *Bulletin of the American Meteorological Society 97*, 111–121, doi: 10.1175/BAMS-D-14-00018.1.

Rayner N.A., Parker D.E., Horton E.B., Folland C.K., Alexander L.V., Rowell D.P., Kent E.C. & Kaplan A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research—Atmospheres 108*, article no. 4407, doi: 10.1029/2002JD002670.

Schlosser E., Haumann F.A. & Raphael M.N. 2018. Atmospheric influences on the anomalous 2016 Antarctic sea ice decay. *The Cryosphere 12*, 1103–1119, doi: 10.5194/tc-12-1103-2018.

Schneider D.P. & Deser C. 2018. Tropically driven and externally forced patterns of Antarctic sea ice change: reconciling observed and modeled trends. *Climate Dynamics 50*, 4599–4618, doi: 10.1007/s00382-017-3893-5.

Shu Q., Song Z. & Qiao F. 2015. Assessment of sea ice simulations in the CMIP5 models. *The Cryosphere* 9, 399–409, doi: 10.5194/tc-9-399-2015.

Simpkins G.R., Ciasto L.M., Thompson D.W.J. & England M.H. 2012. Seasonal relationships between large-scale climate variability and Antarctic sea ice concentration. *Journal of Climate 25*, 5451–5469, doi: 10.1175/JCLI-D-11-00367.1.

Simpkins G.R., McGregor S., Taschetto A.S., Ciasto L.M. & England M.H. 2014. Tropical connections to climatic change in the extratropical Southern Hemisphere: the role of Atlantic SST trends. *Journal of Climate 27*, 4923–4936, doi: 10.1175/JCLI-D-13-00615.1.

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. *Geophysical Research Letters 44*, 9008–9019, doi: 10.1002/2017GL074691.

Sun S. & Eisenman I. 2021. Observed Antarctic sea ice expansion reproduced in a climate model after correcting biases in sea ice drift velocity. *Nature Communications 12*, article no. 1060, doi: 10.1038/s41467-021-21412-z.

Swart N.C. & Fyfe J.C. 2013. The influence of recent Antarctic ice-sheet retreat on simulated sea-ice trends. *Geophysical Research Letters 40*, 4328–4332, doi: 10.1002/grl.50820.

Takaya K. & Nakamura H. 2001. A formulation of a phase-independent wave-activity flux for stationary and migratory quasigeostrophic eddies on a zonally varying basic flow. *Journal of the Atmospheric Sciences 58*, 608–627, doi: 10.1175/1520-0469(2001)058<0608:AFOAPI>2.0.CO;2.

Turner J. 2004. The El Niño–Southern Oscillation and Antarctica. *International Journal of Climatology 24*, 1–31, doi: 10.1002/joc.965.

Turner J., Phillips T., Marshall G.J., Hosking J.S., Pope J.O., Bracegirdle T.J. & Deb P. 2017. Unprecedented springtime retreat of Antarctic sea ice in 2016. *Geophysical Research Letters 44*, 6868–6875, doi: 10.1002/2017GL073656.

Uotila P., Holland P.R.R., Vihma T., Marsland S.J.J. & Kimura N. 2014. Is realistic Antarctic sea-ice extent in climate models the result of excessive ice drift? *Ocean Modelling 79*, 33–42, doi: 10.1016/j.ocemod.2014.04.004.

Wang G., Hendon H.H., Arblaster J.M., Lim E.-P., Abhik S. & van Rensch P. 2019. Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. *Nature Communication 10*, article no. 13, doi: 10.1038/s41467-018-07689-7.

Wilks D.S. 2006. *Statistical methods in the atmospheric sciences.* San Diego: Academic Press.

Yu L., Zhong S., Sui C. & Sun B. 2024. Sea surface temperature anomalies related to the Antarctic sea ice extent variability in the past four decades. *Theoretical and Applied Climatology 155*, 2415–2426, doi: 10.1007/s00704-023-04820-7.

Yu L., Zhong S. & Sun B. 2022. Synchronous variation patterns of monthly sea ice anomalies at the Arctic and Antarctic. *Journal of Climate 35*, 2823–2847, doi: 10.1175/JCLI-D-21-0756.1.

Yu L., Zhong S., Vihma T., Sui C. & Sun B. 2021. Sea ice changes in the Pacific sector of the Southern Ocean in austral autumn closely associated with the negative polarity of the South Pacific Oscillation. *Geophysical Research Letters 48*, e2021GL092409, doi: 10.1029/2021GL092409.

Yu L., Zhong S., Vihma T., Sui C. & Sun B. 2022. Linking the Antarctic sea ice extent changes during 1979–2020 to seasonal modes of Antarctic sea ice variability. *Environmental Research Letters 17*, article no. 114026, doi: 10.1088/1748-9326/ac9c73.

Yu L., Zhong S., Winkler J.A., Zhou M., Lenschow D.H., Li B., Wang X. & Yang Q. 2017. Possible connection of the opposite trends in Arctic and Antarctic sea ice cover. *Scientific Reports 7*, article no. 45804, doi: 10.1038/srep45804.

Zhang J.L. 2007. Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. *Journal of Climate 20*, 2515–2529, doi: 10.1175/JCLI4136.1.

Zhang X., Deser C. & Sun L. 2021. Is there a tropical response to recent observed Southern Ocean cooling? *Geophysical Research Letters 48*, e2020GL091235, doi: 10.1029/2020GL091235.