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LETTER

Linking the Antarctic sea ice extent changes during 1979–2020 to seasonal modes of Antarctic sea ice variability

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Abstract

The Antarctic sea ice extent slowly expanded through the four-decade-long satellite era until 2014 when the expansion came to a halt, followed by a rapid contraction in the next couple of years. This sudden unexpected trend reversal has sparked considerable research interest and several mechanisms have been proposed to explain it; however, much remains to be explored. In this study, we show that the long-term increasing trend in the Antarctic sea ice extent and its recent reversal can be largely explained by the first, second and fourth empirical orthogonal function mode of sea ice variability in austral summer, autumn and spring, respectively. We illustrate that the sea ice variability represented by the three modes is mostly consistent with what is expected from the anomalous atmospheric circulations associated with planetary wavetrains that are triggered by anomalous sea surface temperature (SST) and convective activities over the Southern Indian and Pacific Oceans. More specifically, the results suggest a teleconnection between the increasing periods in the Antarctic sea ice extent in the past four decades and the positive SST anomalies over the southeastern Indian Ocean and the western tropical Pacific Ocean. The opposite occurs over the decreasing period. Accordingly, the same mechanisms, in different phases, have been associated with the periods of increasing and decreasing Antarctic sea ice extent.

1. Introduction

The impact of the Antarctic sea ice extends from the stability of local ice shelves (Massom *et al* 2018) to regional weather (Uotila *et al* 2011) and marine ecosystems (Norkko *et al* 2007), and to global ocean circulation (Heuzé 2021) and radiation balance (Riihelä *et al* 2021). In the past four decades, the overall Antarctic sea ice extent slowly expanded from 1979 to 2014, followed by a rapid contraction to a minimum in 2016 (Parkinson 2019). This abrupt shift in the trend of the Antarctic sea ice extent has attracted much attention from academics and practitioners, but the underlying causes are yet to be fully understood.

A myriad of mechanisms have been proposed to explain the increasing trend in the total Antarctic sea ice extent prior to 2014 (Hobbs *et al* 2016). A primary mechanism is believed to be changes in wind fields, including the strengthening circumpolar westerly winds and changes in local/regional winds (Holland and Kwok 2012, O'Kane *et al* 2013, Blanchard-Wrigglesworth *et al* 2021). These changes in wind fields have been linked to the increases in atmospheric greenhouse gases and decreases in stratospheric ozone concentrations (Thompson *et al* 2011, Marshall *et al* 2015), and also to large-scale climate modes, represented mainly by the Southern Annular Mode (SAM) (Ferreira *et al* 2015), the Amundsen Sea Low (ASL) (Raphael *et al* 2017), the zonal wave three (ZW3) (Raphael 2007), the Pacific decadal oscillation (PDO) (Yu *et al* 2017, 2022), the Atlantic Multidecadal Oscillation (AMO) (Li *et al* 2014, Yu *et al* 2017), the South Pacific

Oscillation (Yu *et al* 2021) and the El Niño–Southern Oscillation (Stammerjohn *et al* 2008). Other plausible explanations include the feedbacks related to ocean–ice interaction (Zhang 2007, Goosse and Zunz 2014), local sea surface temperature (SST) (Blanchard-Wrigglesworth *et al* 2021), ice drift (Sun and Eisenman 2021), and melting ice shelves with an increase in freshwater amount in the Southern Ocean (Bintanja *et al* 2013, 2015).

Compared to the increasing trend in the Antarctic sea ice extent prior to 2014, fewer explanations have been given to the recent sea ice decline (Eayrs *et al* 2021), which include warming subsurface Southern Ocean (Meehl *et al* 2019), anomalous SST in the tropical oceans (Stuecker *et al* 2017, Wang *et al* 2019), anomalous high-latitude climate modes (Turner *et al* 2017, Schlosser *et al* 2018), and anomalous Antarctic stratospheric polar vortex (Wang *et al* 2019). These factors are strongly interactive. For example, the rapid sea ice decline in 2016 has been attributed to the extreme atmosphere-ocean anomalies over both the eastern tropical Indian Ocean and the far-western Pacific Ocean, which triggered atmospheric planetary wavetrains that propagated to the Antarctic, generated wind anomalies, changed the sea ice patterns and reversed the hemispheric sea-ice-extent trend (Schlosser *et al* 2018).

Most previous studies have investigated the evolution of the Antarctic sea ice extent separately for the periods before and after the trend reversal around 2014. However, is it possible that both the increase of the Antarctic sea ice extent prior to 2014 and the decrease thereafter are actually linked to the same mechanisms but different phases? Our study here is aimed at addressing this question through analyses of monthly sea ice and SST data as well as atmospheric data in the past four decades using statistical method such as empirical orthogonal function (EOF) and linear regression.

2. Datasets and methods

Monthly Antarctic sea ice concentration data, which is produced using the U.S. National Aeronautics and Space Administration Team algorithm on a polar stereographic grid of 25 km grid spacing (Cavalieri *et al* 1996), was obtained from the U.S. National Snow & Ice Data Center for the period of October 1978 through December 2020. For this study, the Antarctic sea ice extent for each season is defined as the sum of the areas of the pixel with seasonal sea ice concentration of at least 0.15. In addition, the four austral seasons here refer to spring: October, November, and December (OND); summer: January, February and March (JFM); autumn: April, May, and June (AMJ); winter: July, August and September (JAS). Because the leading EOF modes fail to capture a large portion of the sea ice trend in austral winter, winter season is excluded from the rest of the analyses.

The source of atmospheric variables used for our analysis is the European Centre for Medium Range Weather Forecasts fifth-generation reanalysis (ERA5) (Hersbach *et al* 2020). The atmospheric variables, which include 200 hPa geopotential height, mean sea level pressure, 2 m air temperature, 10 m wind field, and surface downward longwave radiation, are used to explore the connections between sea ice variability and the atmospheric circulation anomalies. As the next-generation reanalysis, the ERA5 is superior to other global reanalysis products in capturing atmospheric variables over the Antarctic continent and the Southern Ocean (Gossart *et al* 2019, Ramon *et al* 2019, Tetzner *et al* 2019, Dong *et al* 2020). In addition, SST data from U.S. National Oceanic and Atmospheric Administration Extended Reconstructed SST V5 (Huang *et al* 2017) also is utilized to assess the relationship between the changes of the Antarctic sea ice concentration and the global SST anomalies.

EOF analysis (Wilks 2006) is utilized to extract the main modes of the variability of the seasonal sea ice concentration anomalies over the Southern Ocean. The seasonal sea ice concentration anomalies are calculated by the subtraction of the climatological seasonal sea ice concentration from the seasonal concentration for each year from 1979 to 2020. The EOF modes reveal possible spatial patterns (EOFs) of sea ice variability and how they change with time (corresponding time coefficients or principal component, PC), and the EOFs and PCs are orthogonal to each other. The first four modes are distinguishable from the neighboring modes following North *et al* (1982). Regression analysis is employed to explain the spatial pattern of each EOF mode. Correlation analysis is also used to relate the Antarctic sea ice extent to the PCs. The significance level of the regression analysis was assessed by the student's t-test. To determine the propagation and source of planetary waves, we utilize wave activity flux (WAF) defined by Takaya and Nakamura (2001) and Rossby wave source (RWS) suggested by Sardeshmukh and Hoskins (1988).

3. Results

We begin with showing how the total Antarctic sea ice extent for austral summer, autumn and spring changed from 1979 through 2020. The time series show an increasing trend from 1979 to 2014 and a sharp decrease in spring 2015 and 2016 and in summer and autumn 2016 and 2017, followed by an increase in all three seasons (figure 1). The rates of reduction of the sea ice extent from 2014 to 2020 (-3.3, -3.5, and -1.4×10^5 km^2 yr^{-1} for austral summer, autumn, and spring, respectively) are an order of magnitude larger than the rates of expansion

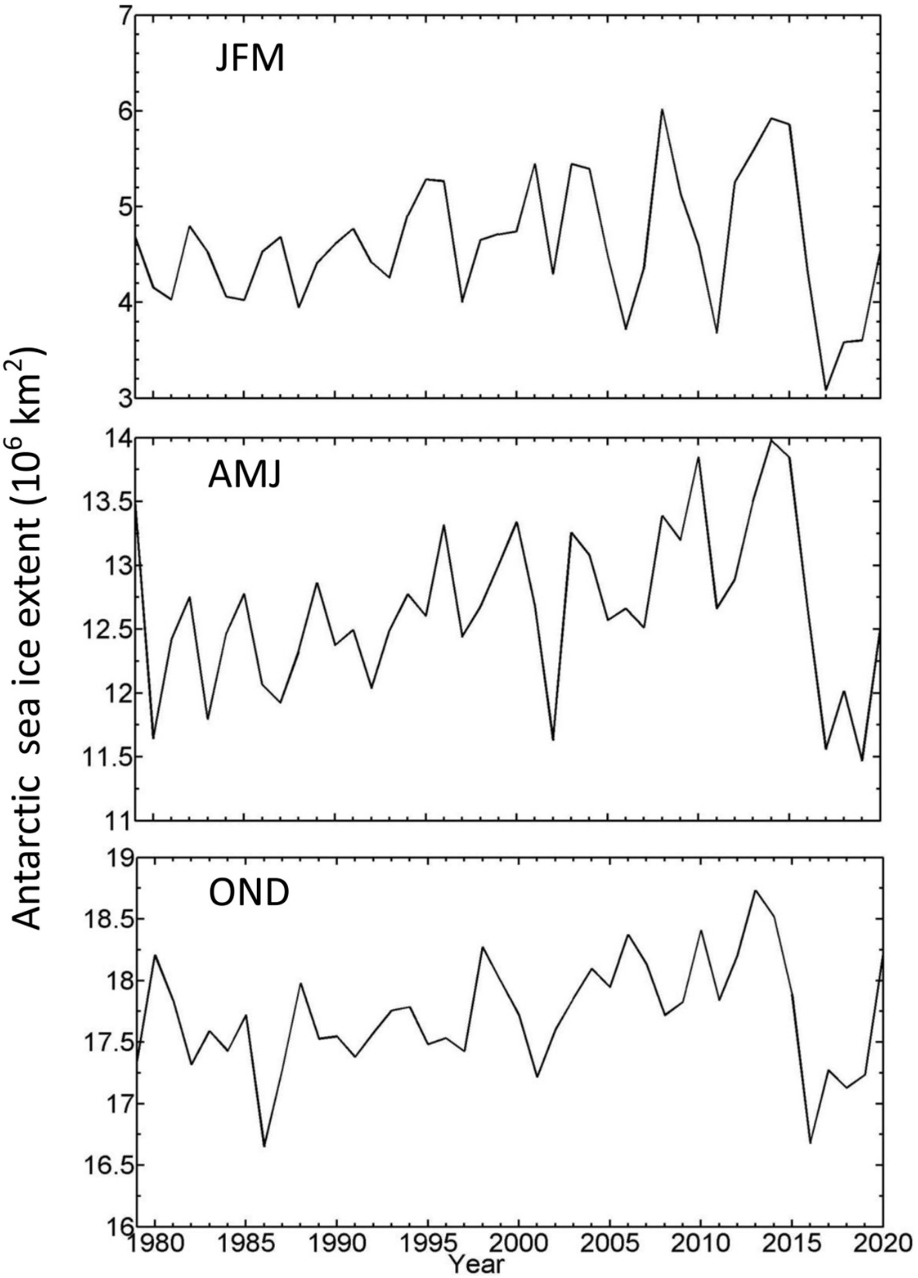

Figure 1. The time series of Antarctic sea ice extent for austral summer (JFM), autumn (AMJ) and spring (OND).

prior to 2014 (2.4, 2.9, and 2.2 × 10^4 km^2 yr^{-1} for austral summer, autumn, and spring, respectively). The results are in line with those of previous studies (Parkinson 2019).

Next, we determine if these trends and variations can be explained by the modes of the sea ice variability identified using EOF for the same season. The results reveal that the PC for some of the EOF modes exhibits a trend shift similar to that in the sea ice trends. In particular, the trend reversal around 2014 appears in the PC1 for austral summer, PC2 for austral autumn and PC4 for austral spring (figure 2 left panel). No such trend shift is present in the other PCs of the first four modes (supplement figure 1S). There are significant ($p < 0.01$) correlations between the time series of Antarctic sea ice extent and the PC1 in austral summer (0.66), PC2 in austral autumn (0.74), and PC4 in austral spring (0.76), which are the highest correlation coefficients among the first four modes for each season (supplement table 1S). The correlations indicate that 44%, 55% and 58% of the variance of the Antarctic sea ice extent in austral summer, autumn, and spring can be statistically explained by the first, second, and fourth modes of sea ice concentration, respectively. The high correlations between the times series for the sea ice extent and for the three EOF

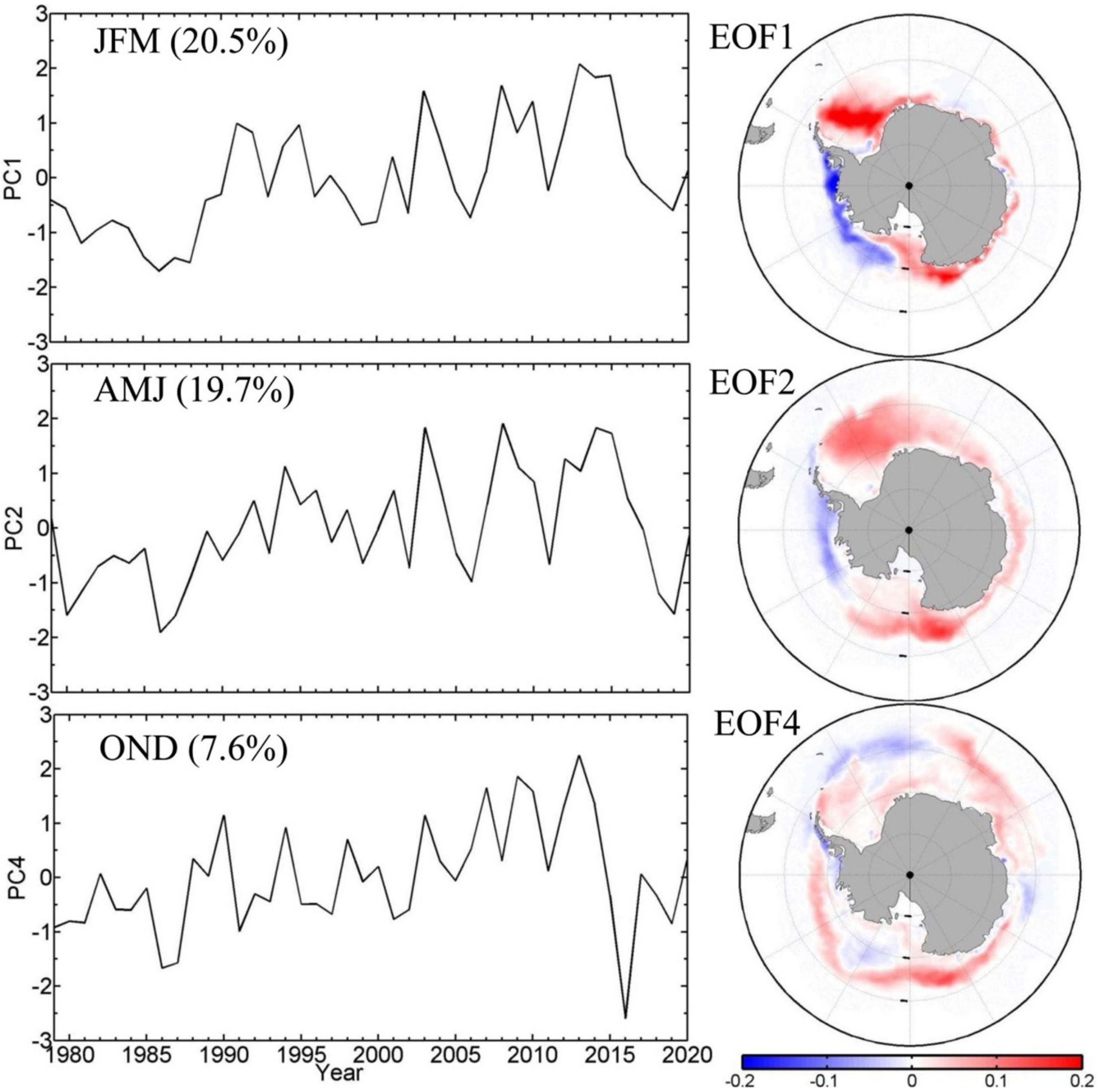

Figure 2. The time series (left) and spatial patterns (right) of the first mode of EOF analysis of summer sea ice concentration (top panels), the second mode of EOF analysis of autumn sea ice concentration (middle panels), and the fourth mode of EOF analysis of spring sea ice concentration (bottom panels). The numbers in brackets denote the percentages of sea ice variance explained by the modes.

modes also suggest that an examination of these EOF patterns and the changes in their frequency of occurrence over time may offer clues for the observed Antarctic sea ice evolution, particularly the trend reversal around 2014, and their regional variations.

The first mode (EOF1) in austral summer, which accounts for 20.5% of the variance of sea ice concentration for the season, displays a dipole structure of negative sea ice anomalies in the Bellingshausen, Amundsen, and the northern Ross Seas, in contrast to positive anomalies elsewhere in the Southern Ocean (figure 2). The EOF2 in austral autumn, which explains 19.7% of the variance of the autumn sea ice concentration, is also characterized by a dipole structure with opposite sea ice changes between the Bellingshausen and Amundsen Seas and the rest of the Southern Ocean (figure 2). The spatial pattern for the fourth spring mode (EOF4), accounting for 7.6% of spring sea ice concentration variance, is more complicated, showing negative sea ice anomalies in the northern parts of the Atlantic sector, northern Amundsen Sea, a portion of the Bellingshausen Sea and Davis Sea, and positive elsewhere (figure 2). Each of these spatial patterns (figure 2) bears a resemblance to that of the sea ice trend for the corresponding season (supplement figure 2S), as reflected by large spatial correlation coefficients of 0.86 and 0.81 ($p < 0.01$) for austral summer and autumn, and somewhat smaller coefficient of 0.59 ($p < 0.01$) for austral spring due mainly to the differences in the Weddell Sea. Despite the differences in their spatial structures, these three modes share a common feature in that the overall spatial pattern is related to the long-term increasing trend prior to 2014, whereas the opposite is associated with the period of rapid sea ice retreat.

We proceed to examine, through regression, the patterns of the anomalous atmospheric circulations and SST corresponding to the three EOF modes

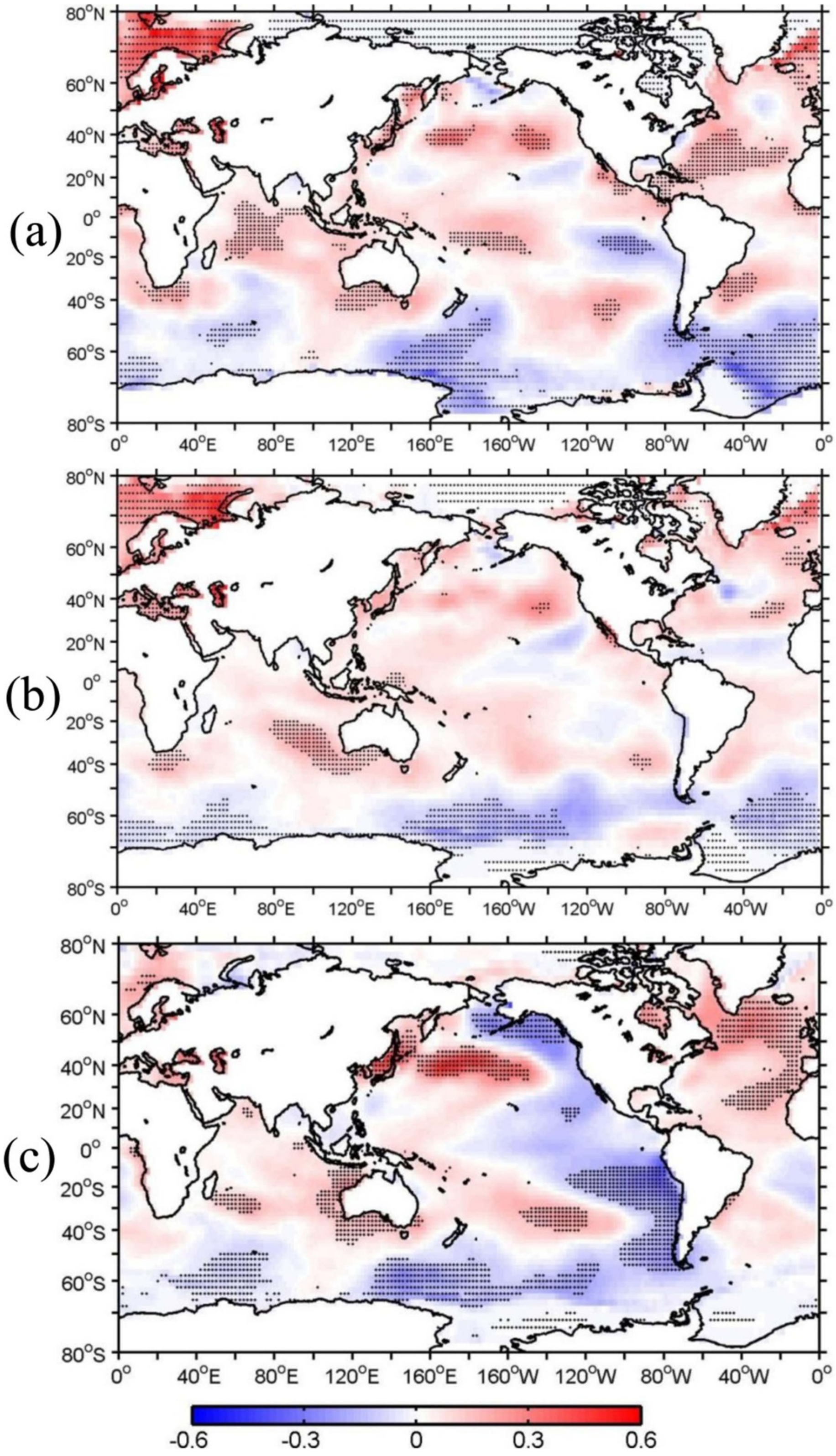

Figure 3. Regression maps of SST (°C) onto (a) the PC1 in austral summer (JFM), (b) the PC2 in austral autumn (AMJ), and (c) the PC4 in austral spring (OND). Dotted regions indicate above 95% confidence level.

(figures 3–9) to explain the anomalous sea ice distributions (figure 2). For austral summer, while the PC1 is positive, positive SST anomalies dominate the tropical Indian, the western tropical Pacific and northern Atlantic Oceans (figure 3(a)). The positive SST anomalies over the tropical western Pacific Ocean trigger more convective activities, as suggested by the negative anomalies in the top-of-the-atmosphere outgoing longwave radiation (OLR) (figure 4(a)) and the 200 hPa divergent wind (figure 4(c)). Strong convection activities produce high clouds with cold tops emitting little OLR, and diverging upper tropospheric

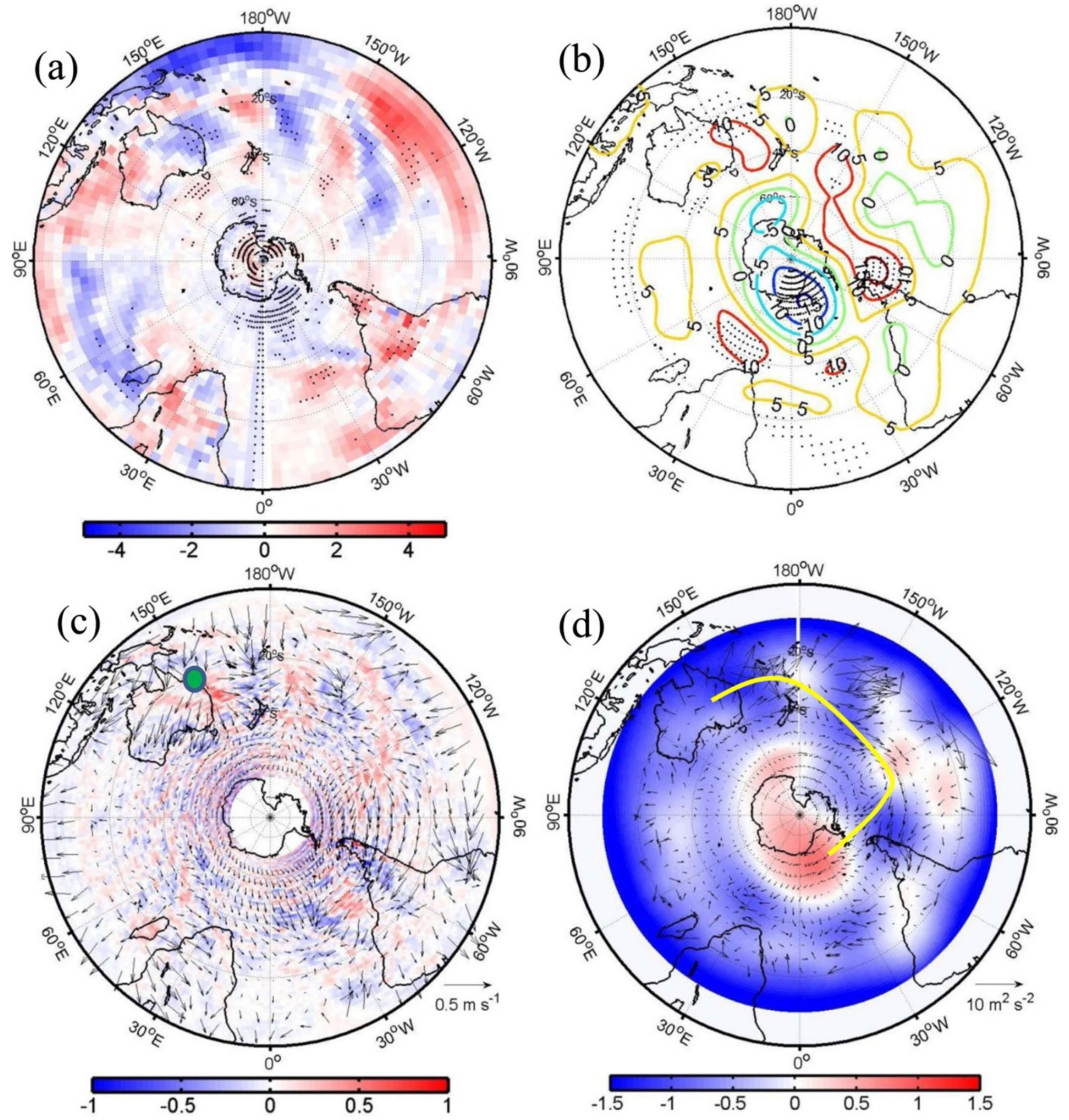

Figure 4. Regression maps of (a) OLR (W m^{-2}), (b) 200 hPa geopotential height (gpm), (c) 200 hPa divergent wind (vectors) and RWS (10^{-10} s^{-2}), and (d) streamfunction (10^7 m^2 s^{-1}) and WAF (vectors), onto the PC1 in austral summer (JFM). Dotted regions in panels (a) and (b) denote above 95% confidence level. Solid green circle in (c) denotes RWS. The yellow line in (d) denotes wavetrain propagating direction.

horizontal winds. The convective activity anomalies also occur over eastern Australia and the subtropical Southern Pacific Ocean. These convective activities generate positive anomalies in Rossby wave sources (figure 4(c)), which excite a wavetrain propagating eastwards and southeastwards into the Southern Ocean (figures 4(b) and (d)). The wavetrain weakens the ASL and strengthens the negative height anomalies over the Weddell Sea (figure 4(b)). Meanwhile, the convective activity anomalies over eastern Australia also produce a wavetrain propagating southwards into the Southern Ocean before turning eastwards into the Ross and Amundsen Seas, which leads to negative height anomalies over East Antarctica and positive height anomalies over the Ross and Amundsen Seas. The weakened summertime ASL produces zonal asymmetry of the positive SAM (figure 5(a)), which generates anomalous westerly surface winds over most of the Southern Ocean (figure 5(b)). The anomalous cyclonic circulation over the Ross Sea pushes sea ice onshore in the Amundsen Sea and eastern Ross Sea, but offshore in the western Ross Sea (figure 5(b)), which lead to negative sea ice anomalies in the Amundsen Sea, but predominantly positive ones in the Ross Sea (figure 2). The negative sea ice anomalies in the Amundsen and Bellingshausen Seas are partly due to the anomalous high north of these Seas (figure 5(a)). The anomalous southwesterly winds over the Weddell Sea increase sea ice cover there (figure 5). Besides mechanical sea ice transport, the anomalous atmospheric circulations also are related to sea ice anomalies through thermodynamic

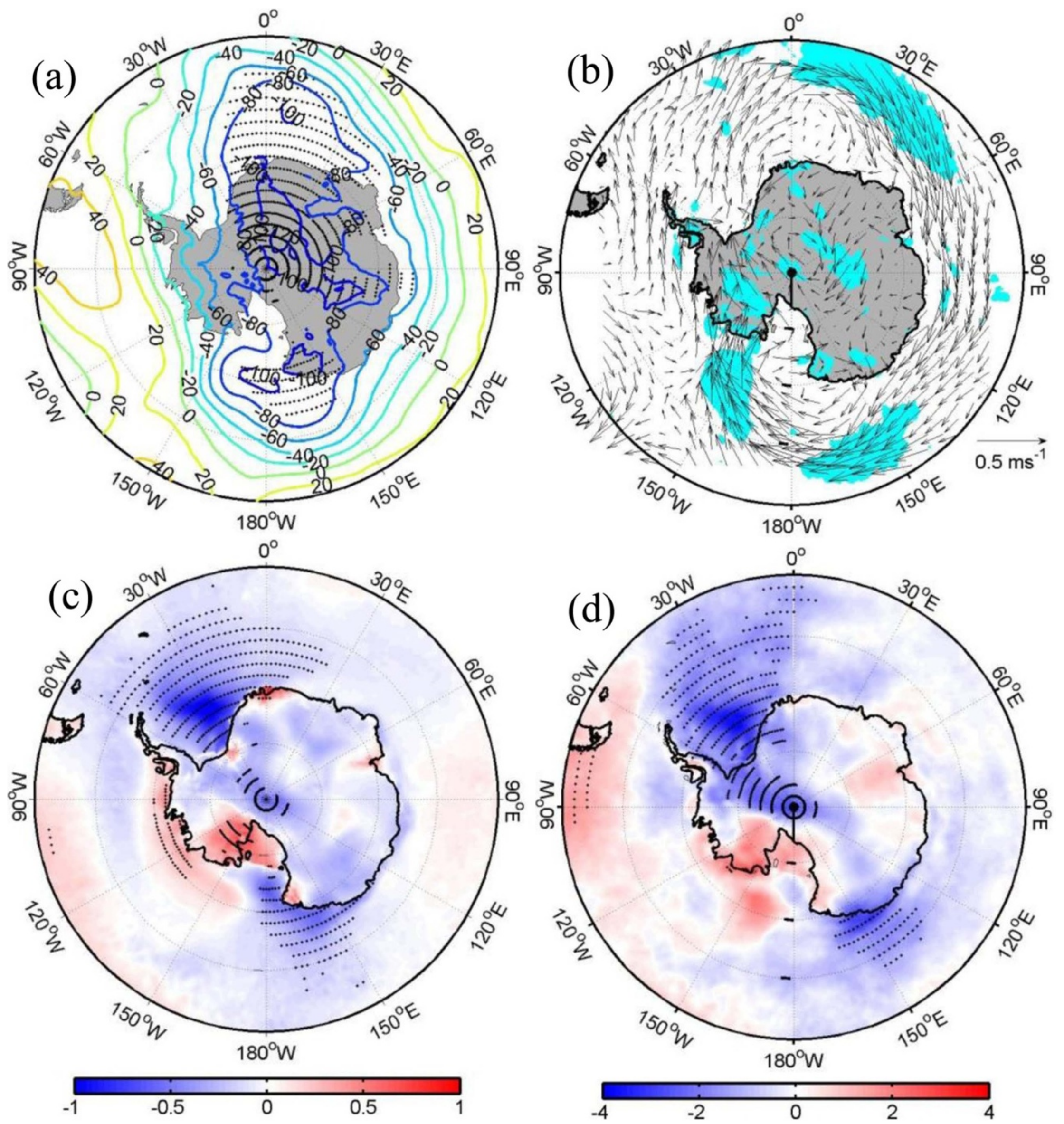

Figure 5. Regression map of (a) mean sea level pressure (Pascal), (b) 10 m wind field (vectors), (c) 2 m air temperature (°C), and (d) surface downward longwave radiation (10^5 W s^{-1}), onto the PC1 in austral summer (JFM). Dotted regions on panels (a), (c), (d) and shaded regions on panel (b) indicate above 95% confidence level.

processes. The asymmetric positive phase of SAM are associated with negative surface air temperature anomalies over most of East Antarctica as well as the Weddell and Ross Seas in summer (figure 5(c) and Marshall and Bracegirdle 2015), favoring positive sea ice anomalies (figure 2). In the Amundsen Sea and the southern Bellingshausen Sea, the positive anomalies in air temperature and surface downward longwave radiation (figure 5(d)) are in concert with the negative sea ice anomalies in the region (figure 2).

In austral autumn, SST anomalies associated with the second EOF mode have positive values in the low and mid latitudes of the Southern Hemisphere (figure 3(b)). The positive SST anomalies near New Zealand generate more convective activities reflected in negative anomalies in OLR and divergent wind (figures 6(a) and (c)). The convection excites a wavetrain propagating eastwards to South America and another wavetrain propagating southeastward to over the Southern Ocean (figures 6(b) and (d)). The atmospheric circulation anomalies induced by the second wavetrain display a strengthened ASL (figures 6(b) and 7(a)). The anomalous northerly winds over the eastern Amundsen and Bellingshausen Seas (figure 7(b)) decrease the regional sea ice cover (figure 2). The opposite occurs over the western Amundsen and Ross Seas. The southwesterly winds over the eastern Weddell Sea (figure 7(b)) also help expand sea ice cover there. The positive surface air temperature anomalies (figure 7(c)) related to the positive surface downward longwave radiation anomalies (figure 7(d)) over the Bellingshausen Sea correspond to the reduced sea ice extent in the region, and the opposite occurs in the rest of the Southern Ocean.

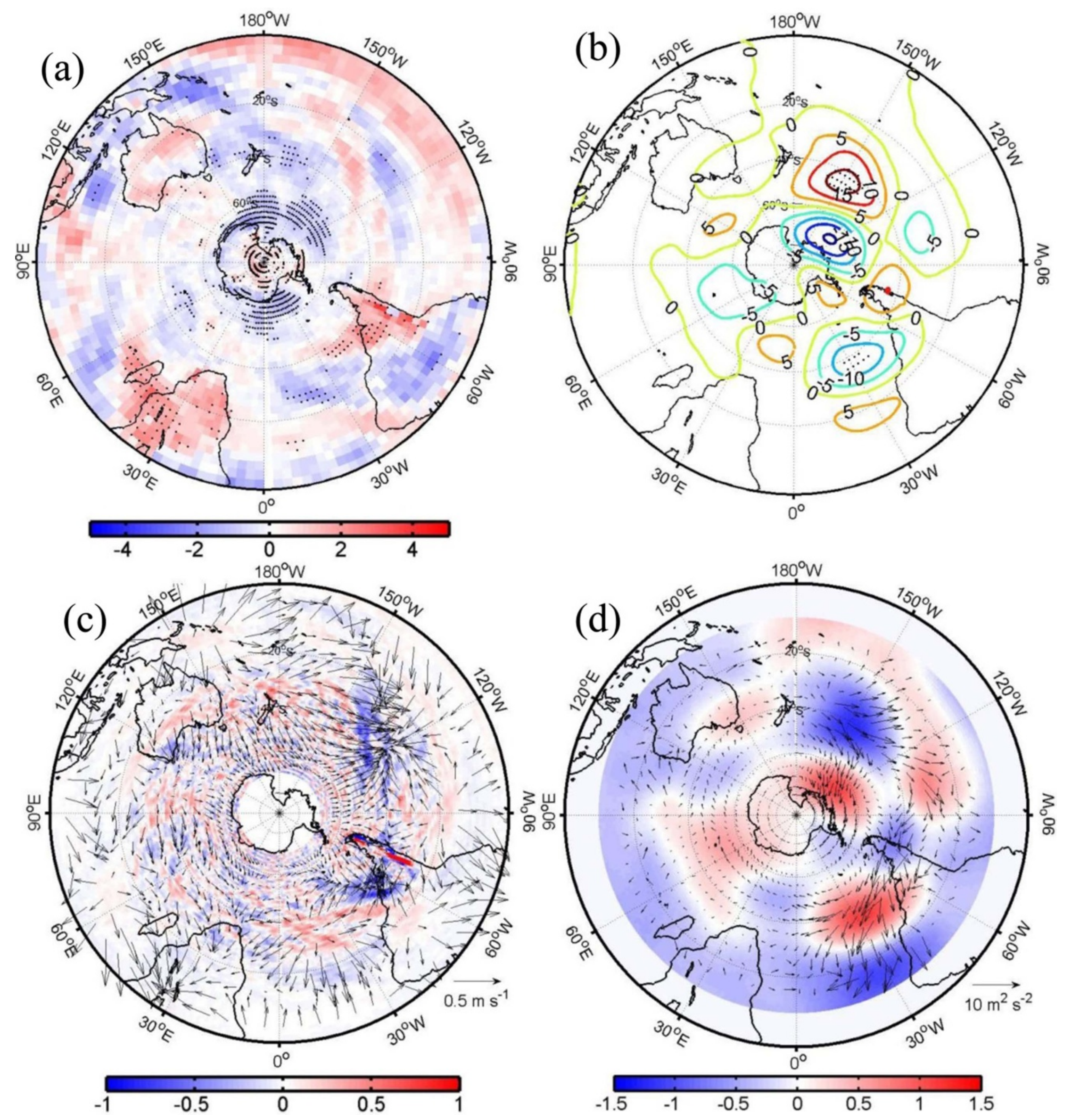

Figure 6. The same as figure 4, but for the PC2 in austral autumn (AMJ).

In austral spring, the SST anomalies related to the fourth EOF mode show a negative phase of the PDO (Mantua *et al* 1997) or Interdecadal Pacific Oscillation (Power *et al* 1999), a positive phase of the AMO (Enfield *et al* 2001), and positive values over the tropical Indian Ocean (figure 3(c)). The positive SST anomalies over the southwestern tropical Pacific Ocean generate negative OLR anomalies and 200 hPa divergent wind to the northeast of Australia (figure 8(a)) (figures 8(a) and (c)), which excite a planetary wavetrain propagating southeastwards to the Southern Ocean, forming the structure of the ZW3 mode (figures 8(b) and (d)). The suppressed convective activities over the southeastern Pacific Ocean favor northward propagation of the wavetrain into the tropics. The anomalous mean sea level pressure, surface wind, surface air temperature and surface downward longwave radiation also display the ZW3 structure (figure 9). Over the southwestern Pacific Ocean, anomalous southwesterly and southeasterly winds expand sea ice cover (figure 9(b)). Similarly, southerly winds over the Bellingshausen and western Weddell Seas also increase the regional sea ice cover. On the contrary, northerly wind anomalies over the eastern Weddell Sea diminish sea ice cover there. The anomalous surface air temperature and surface downward longwave radiation patterns are in agreement with the sea ice anomalies (figures 9(c) and (d)). For example, negative surface air temperature anomalies over the Southern Pacific Ocean are in concert with increased regional sea ice cover.

4. Summary

The Antarctic sea ice extent displayed an overall increasing trend from 1979 to 2014, followed by an

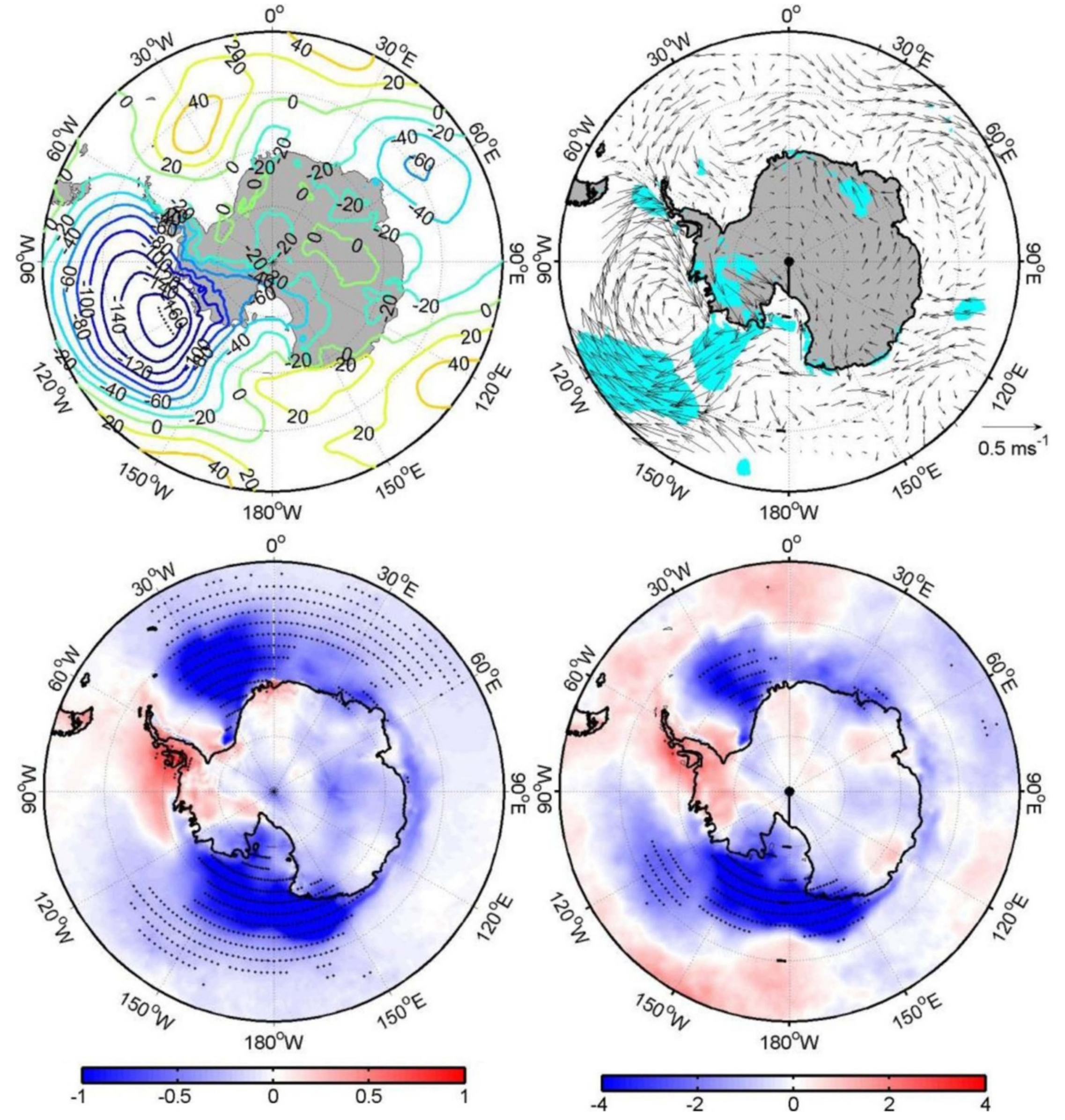

Figure 7. The same as figure 5, but for the PC2 in austral autumn (AMJ).

abrupt decrease over 2015–2017. We first showed that the 40 year (1979–2020) trends, including the recent reversal, in the sea ice extent in austral summer, autumn and spring are significantly correlated to the time series of the first, second and fourth modes of sea ice variability in the corresponding season, respectively, suggesting that the changes in the occurrences of the leading sea ice variability modes over the same time period may offer clues to the sea ice trends and their regional variations across the Southern Ocean. We next examined the spatial patterns of these three modes and the associated anomalous SST and atmospheric circulation patterns. The first mode in summer and the second mode in autumn display a dipole structure (negative anomalies in the Amundsen Sea in contrast to positive anomalies elsewhere in the Southern Ocean) and the fourth mode in spring is characterized by positive sea ice anomalies over most of the Southern Ocean. We demonstrated that these spatial patterns of sea ice variability are largely consistent with what is expected from the patterns of the anomalous surface wind fields and the resulting sea ice transport and heat advection in different regions of the Southern Ocean. We further showed that these atmospheric circulation anomalies are related to planetary wavetrains triggered by positive SST anomalies and enhanced convective activities over the southwestern Pacific Ocean. The SST and OLR anomalies over other regions also contribute to the wavetrains. These results suggest that both the long-term increasing trend and the abrupt change to a sharp decrease in the Antarctic sea ice extent are teleconnected to the SST anomalies in the southern Pacific and Indian Oceans through the formation

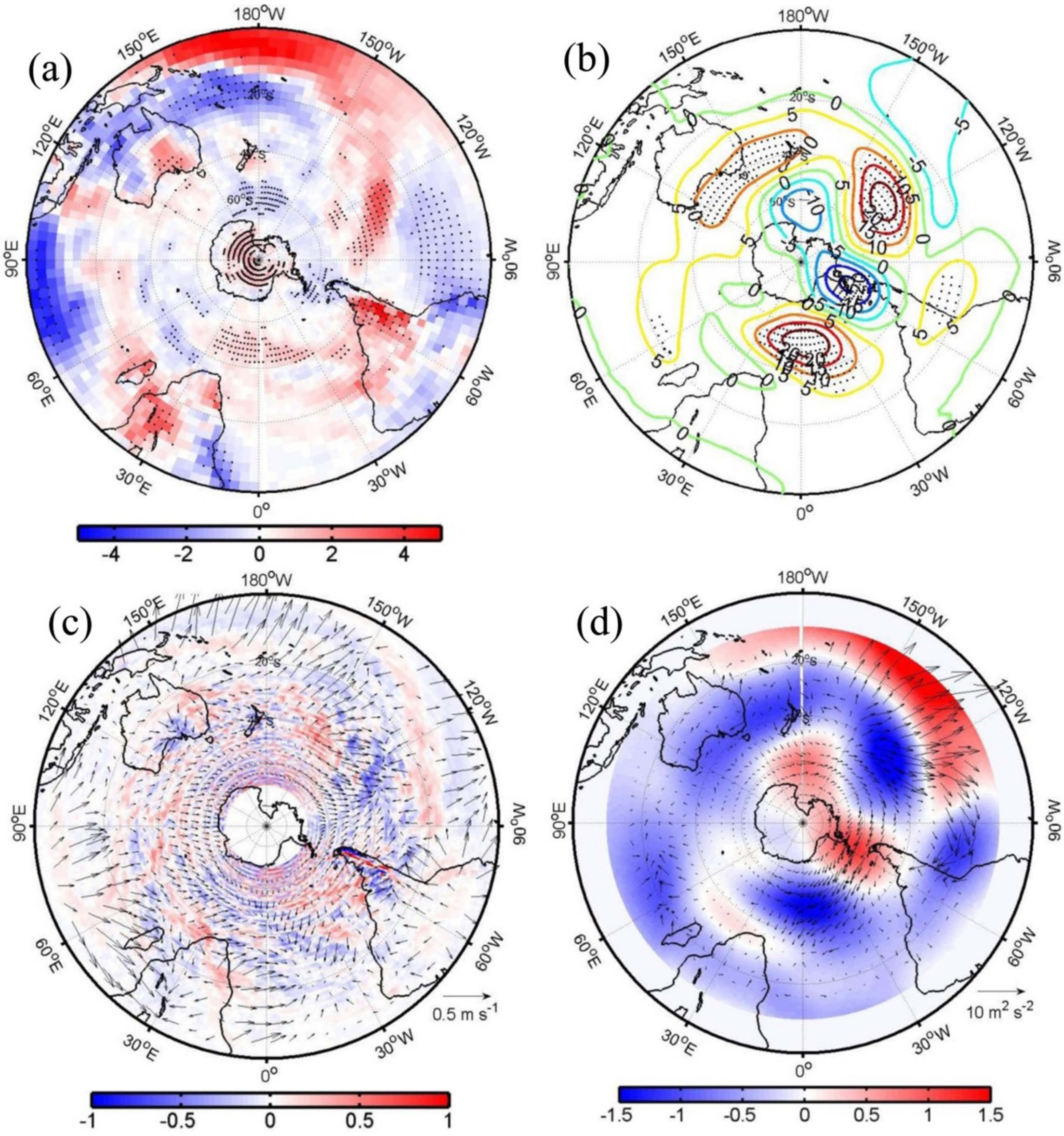

Figure 8. The same as figure 4, but for the PC4 in austral spring (OND).

and propagation of planetary wavetrains. Accordingly, the same mechanisms, in different phases, have been associated with the increasing trend and its reversal.

5. Discussion

Our statistical methods (regression and correlation analyses) cannot warrant the causality among the different variables. Zhang *et al* (2021) suggested that there is warming in the tropical Atlantic as a response to the recently observed Southern Ocean cooling, which is evident in figure 3. However, numerical experiments need to be carried out to confirm the cause and effects between SST anomalies in the Indian and Pacific Oceans and the Antarctic sea ice concentration anomalies. The modes displaying the changes in the Antarctic sea ice extent explain a maximum of 20% of the variability in the sea ice concentration. However, they explain 40%–60% of the decadal change in the Antarctic sea ice extent, which is our focus in this study. Other modes may account for the interannual variability of Antarctic ice concentration.

Yu *et al* (2018) noted previously that the positive phase SAM and a wavetrain originating over northern Australia, similar to the austral summer EOF1 here (figure 2), contributed to the increasing trend in Antarctic sea ice extent in austral summer. The positive SAM phase may be associated with ozone change in the southern stratosphere (Sigmond and Fyfe 2010, Bitz and Polvani 2012, Landrum *et al* 2017, Zambri *et al* 2021). From 2016 to 2019, the positive SST anomalies in the Weddell Sea in austral summer corroborated the decrease of sea ice in this region (Turner *et al* 2020), which is opposite to the pattern shown in figure 3.

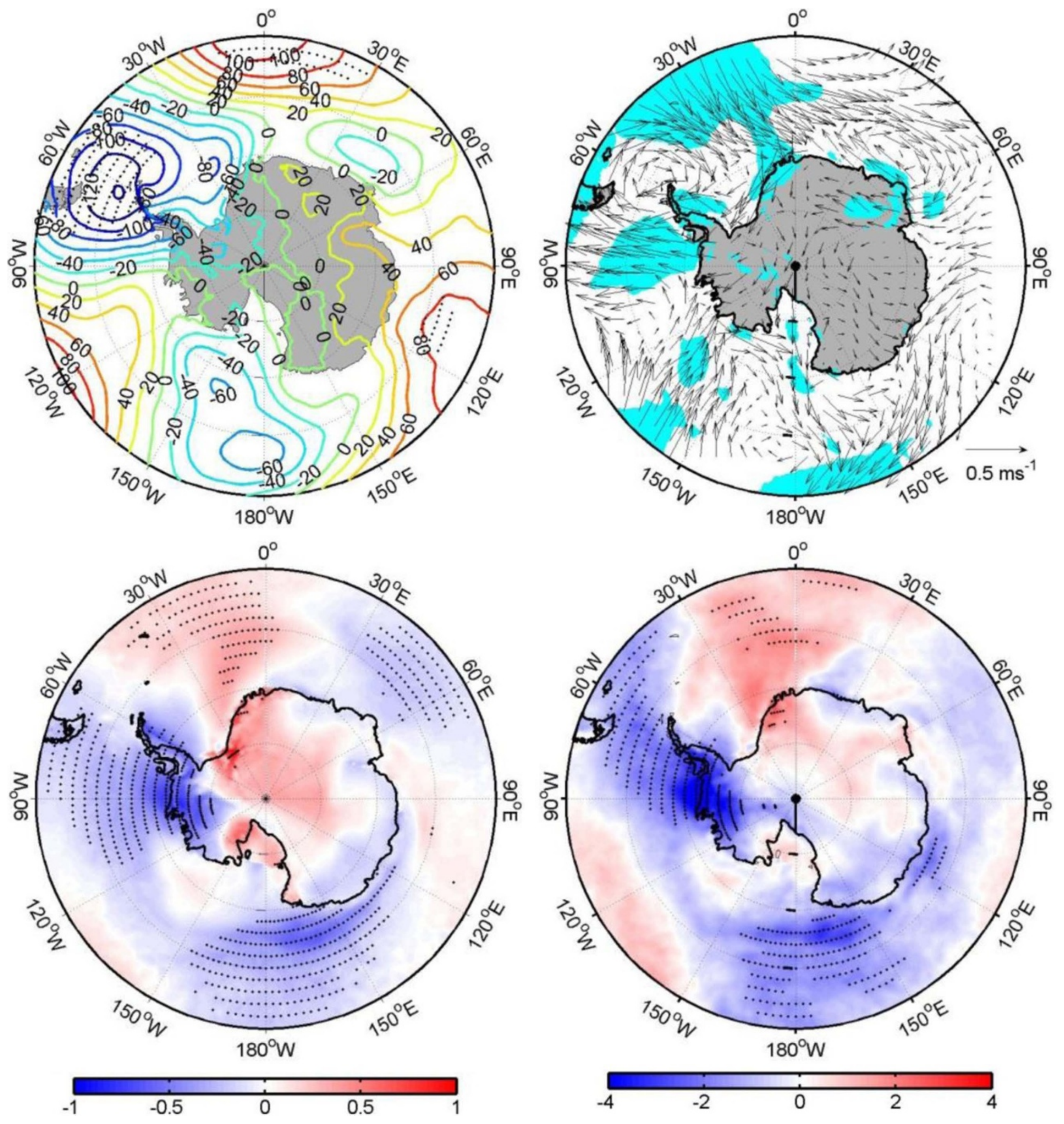

Figure 9. The same as figure 5, but for the PC4 in austral spring (OND).

For austral spring, the slow expansion of the overall Antarctic sea ice extent from 1979 until 2014 may be attributed to the PDO and AMO (Ding *et al* 2011, Hobbs *et al* 2015, Kohyama and Hartmann 2016, Raphael *et al* 2017, Schneider and Deser 2018, Li *et al* 2021, Chung *et al* 2022), which is evident in figure 3. If AMO is indeed a driver (Turner *et al* 2020), the variations in the SST often associated with AMO would have affected the Antarctic sea ice conditions in spring. For the period of sea ice decline since 2015, The 2015/2016 El Niño event produced the ZW3 mode (Meehl *et al* 2019, Eayrs *et al* 2021) and positive SST anomalies over the eastern Ross, Amundsen and Bellingshausen Seas (Bintanja *et al* 2015). In spring 2016, the anomalous high- and low-pressure pair over the Ross and Amundsen Seas and the associated wind fields help explain the unprecedented sea ice retreat (Stuecker *et al* 2017). The SST pattern for the case of 2016 is opposite to the pattern in figure 3. Harangozo (2004) noted that SST anomalies in the South Pacific Convergence Zone region do not tend to create Rossby wavetrains, which were not observed in this study.

Our results highlighted the important role internal climate system variability has played in the changes of Antarctic sea ice trend over the past four decades in all seasons but winter, confirming the findings from several previous studies (Polvani *et al* 2013, Zunz *et al* 2013, Fan *et al* 2014, Roach *et al* 2020). External forces, such as increases in the greenhouse gas emissions and ozone depletion, have also contributed to sea ice changes in the Antarctic, especially in austral summer (Sigmond and Fyfe 2010, Bitz and Polvani 2012, Landrum *et al* 2017). The close relationship established in this study between the shift of the trends in the Antarctic sea ice extent and the changes in the atmospheric circulations triggered by SST anomalies in the Indian Ocean and the tropical Pacific Ocean provide knowledge relevant for projections of possible future changes in Antarctic sea ice extent.

Data availability statement

The monthly Antarctic sea ice concentration data set is available from the U.S. National Snow and Ice Data Center (NSIDC) (http://nsidc.org/data/NSIDC-0051). Monthly mean atmospheric variables are provided by the European Centre for Medium Range Weather Forecasts (ECMWF) Reanalysis (ERA5) (www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production). The monthly sea surface temperature (SST) data are downloaded from the U.S. National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST data version 5 (https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html). The top-of-the-atmosphere outgoing longwave radiation (OLR) data are obtained from the NOAA Interpolated Outgoing Longwave Radiation (http://psl.noaa.gov/data/gridded/data.interp_OLR.html).

The data that support the findings of this study are openly available at the following URL/DOI: http://nsidc.org/data/NSIDC-0051.

Code availability

Computer code is available from the corresponding author upon reasonable request.

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Author contributions

L Y designed the story line, analyzed the data, and wrote the draft. S Z and T V contributed equally in writing and revising of the paper. C S plotted the wave activity fluxes. B S provided funding and offered suggestions.

Conflict of interest

The authors declare no competing interests.

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