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

Lejiang Yu\textsuperscript{1,}\textsuperscript{*}, Shiyuan Zhong\textsuperscript{2}, Timo Vihma\textsuperscript{3}, Cuijuan Sui\textsuperscript{4} and Bo Sun\textsuperscript{1}

\textsuperscript{1} MNR Key Laboratory for Polar Science, Polar Research Institute of China, Shanghai, People’s Republic of China
\textsuperscript{2} Department of Geography, Environment and Spatial Sciences, Michigan State University, East Lansing, MI, United States of America
\textsuperscript{3} Finnish Meteorological Institute, Helsinki, Finland
\textsuperscript{4} National Marine Environmental Forecasting Center, Beijing, People’s Republic of China

\textsuperscript{*} Author to whom any correspondence should be addressed.
E-mail: yulejiang@sina.com

Keywords: Antarctic, sea ice extent, trend, planetary wavetrain, sea surface temperature (SST)

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 \textit{et al} 2018) to regional weather (Uotila \textit{et al} 2011) and marine ecosystems (Norkko \textit{et al} 2007), and to global ocean circulation (Heuzé 2021) and radiation balance (Rihelä \textit{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 \textit{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 \textit{et al} 2013, Blanchard-Wrigglesworth \textit{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 \textit{et al} 2011, Marshall \textit{et al} 2015), and also to large-scale climate modes, represented mainly by the Southern Annular Mode (SAM) (Ferreira \textit{et al} 2015), the Amundsen Sea Low (ASL) (Raphael \textit{et al} 2017), the zonal wave three (ZW3) (Raphael 2007), the Pacific decadal oscillation (PDO) (Yu \textit{et al} 2017, 2022), the Atlantic Multidecadal Oscillation (AMO) (Li \textit{et al} 2014, Yu \textit{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, it is 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 (Cavaliere 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 × 10^6 km^2 yr^{-1} for austral summer, autumn, and spring, respectively) are an order of magnitude larger than the rates of expansion.
prior to 2014 ($2.4, 2.9, \text{ and } 2.2 \times 10^4 \text{ km}^2 \text{ yr}^{-1}$ 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 1. The time series of Antarctic sea ice extent for austral summer (JFM), autumn (AMJ) and spring (OND).](image-url)
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
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 southeasterwards 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 southwesternly 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
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 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.
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
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 southwestern Pacific and Indian Oceans through the formation...
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.
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.

Acknowledgments

The authors thank the European Centre for Medium-Range Weather Forecasts (ECMWF) for the ERA-5 data. This study is financially supported by the National Natural Science Foundation of China (41941009), the National Key R&D Program of China (2018YFA0605701), and the European Commission H2020 project Polar Regions in the Earth System (PolarRES; Grant 10100359).

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.

ORCID iDs

Shiyuan Zhong @ https://orcid.org/0000-0002-2287-7220
Timo Vihma @ https://orcid.org/0000-0002-6557-7084

References

Bintanja R, van Oldenborgh G J, Drijfhout S S, Wouters B and Katsman C A 2013 Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion Nat. Geosci. 6 376–9
Bintanja R, van Oldenborgh G J and Katsman C A 2015 The effect of increased fresh water from Antarctic ice shelves on future trends in Antarctic sea ice Ann. Glaciol. 56 120–6
Bitz C M and Polvani L M 2012 Antarctic climate response to stratospheric ozone depletion in a fine resolution ocean climate model Geophys. Res. Lett. 39 L20705
Blanchard-Wrigglesworth E, Roach L A, Donohoe A and Ding Q 2021 Impact of winds and Southern Ocean SSTs on Antarctic sea ice trends and variability J. Clim. 34 949–65
Cavaleri D J, Parkinson C L, Gloersen P and Zwally H J 1996 Updated yearly Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1 (Boulder, CO: NASA National Snow and Ice Data Center Distributed Active Archive Center) NASA (https://doi.org/10.5067/8GQ8LZQVL0VL) (Accessed 17 March 2021)
Chung E S, Kim S J, Timmermann A, Lee K J, Lee S K, Stuecker M F, Rodgers K B, Lee S-S and Huang L 2022 Antarctic sea-ice expansion and Southern Ocean cooling linked to tropical variability Nat. Clim. Change 12 461–8
Ding Q, Steig E J, Battisti D S and Kattel M 2011 Winter warming in West Antarctica caused by central tropical Pacific warming Nat. Geosci. 4 398–403
Dong X, Wang Y, Hou S, Ding M and Zhang Y 2020 Robustness of the recent global atmospheric reanalyses for Antarctic near-surface wind speed climatology J. Clim. 33 4027–43
Eayrs C, Li X, Raphael M N and Holland D M 2021 Rapid decline in Antarctic sea ice in recent years hints at future change Nat. Geosci. 14 160–4
Enfield D B, Mestas-Núñez A M and Trimble P J 2001 The Atlantic multidecadal oscillation and its relationship to rainfall and river flows in the continental U.S. Geophys. Res. Lett. 28 2077–80
Fan T, Deser C and Schneider D P 2014 Recent Antarctic sea ice trends in the context of Southern Ocean surface climate variations since 1950 Geophys. Res. Lett. 41 2419–26
Ferreira D, Marshall J, Bitz C M, Solomon S and Plumb A 2015 Antarctic ocean and sea ice response to ozone depletion: a two–time–scale problem J. Clim. 28 1206–26
Goosse H and Zunz V 2014 Decadal trends in the Antarctic sea ice extent ultimately controlled by ice–ocean feedback Cryosphere 8 453–70
Gossart A, Helsen S, Lenaerts J T M, Broucie S V, van Lipzig N P M and Souveniris N 2019 An evaluation of surface climatology in state–of–the–art reanalyses over the Antarctic ice sheet J. Clim. 32 6899–915
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 Geophys. Res. Lett. 31 L05206
Hersbach H et al 2020 The ERA5 global reanalysis Q. J. R. Meteorol. Soc. 146 1999–2049
Heuzé C 2021 Antarctic bottom water and North Atlantic deep water in CMIP6 models Ocean Sci. 17 59–90
Hobbs W R, Bindoff N L and Raphael M N 2015 New perspectives on observed and simulated Antarctic sea ice extent trends using optimal fingerprinting techniques J. Clim. 28 1543–60
Hobbs W R, Massom R, Stammerjohn S, Reid P A, Williams G and Meier W 2016 A review of recent changes in Southern
Ocean sea ice, their drivers and forcings Glob. Planet. Change 143 228–30
Holland P R and Kwok R 2012 Wind-driven trends in Antarctic sea-ice drift Nat. Geosci. 5 872–5
Huang B, Thorne P W, Banzon V F, Boyer T, Chepurin G, Lawrimore J H, Smith T M, Thorne P W, Woodruff S D and Zhang H-M 2017 Extended reconstructed sea surface temperature version 5 (ERSST v5), upgrades, validations, and intercomparisons J. Clim. 28 911–30
Kohyama T and Hartmann D L 2016 Antarctic sea ice response to weather and climate modes of variability J. Clim. 29 721–41
Landrum I L, Holland M M, Raphael M N and Polvani L M 2017 Stratospheric ozone depletion: an unlikely driver of the regional trends in Antarctic sea ice in Austral fall in the late twentieth century Geophys. Res. Lett. 44 11062–70
Li X et al 2021 Tropical teleconnection impacts on Antarctic climate changes Nat. Rev. Earth Environ. 2 680–98
Li X, Holland D M, Gerber E P and Yoo C 2014 Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice Nature 505 538–42
Mantua N J, Hare S R, Zhang Y, Wallace J M and Francis R C 1997 A Pacific interdecadal climate oscillation with impacts on salmon production Bull. Am. Meteorol. Soc. 78 1096–79
Marshall G J and Bracegirdle T J 2015 An examination of the relationship between the Southern Annular Mode and Antarctic surface air temperatures in the CMIP5 historical runs Clim. Dyn. 45 1513–35
Marshall J, Scott J R, Armour K C, Campin J-M, Kelley M and Romanou A 2015 The ocean’s role in the transient response of climate to abrupt greenhouse gas forcing Clim. Dyn. 44 2287–99
Massom R A, Scambos T A, Bennett I G, Reid P and Stammerjohn S E 2018 Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell Nature 558 383–9
Meeth G A, Arblaster J M, Chung C T Y, Holland M M, DuVivier A, Thompson L, Yang D and Bitz C M 2019 Sustained ocean changes contributed to sudden Antarctic sea ice retreat in the late 2016 Nat. Commun. 10 14
Norkko A, Thrush S F, Cummings V J, Gibbs M M, Andrew N L, Norkko J and Schwarz A-M 2007 Trophic structure of coastal Antarctic food webs associated with changes in sea ice and food supply Ecology 88 2810–20
North G R, Bell T L, Cahalan R F and Moeng F J 1982 Sampling errors in the estimation of empirical orthogonal functions Mon. Weather Rev. 11 699–706
O’Kane T J, Matear R J, Chamberlain M A, Risby J S, Sloyan B M and Horenko I 2013 Decadal variability in an OGCM Southern Ocean: intrinsic modes, forced modes and metastable states Ocean Model 69 1–21
Parkinson C L 2019 A 40-yr record reveals gradual Antarctic sea ice increases followed by decrease at rates far exceeding the rates seen in the Arctic Proc. Natl Acad. Sci. USA 116 14414–23
Polvani L M and Smith K L 2013 Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5 Geophys. Res. Lett. 40 3195–9
Power S, Casey T, Holland C, Colman A and Melta V 1999 Interdecadal modulation of the impact of ENSO on Australia Clim. Dyn. 15 319–31
Ramon J, Ledo L, Torralba V, Soret A and Doblas-Reyes F J 2019 What global reanalysis best represents near-surface winds? Q. J. R. Meteorol. Soc. 145 3236–51
Raphael M N 2007 The influence of atmospheric zonal wave three on Antarctic sea ice variability J. Geophys. Res. 112 D12112
Raphael M N, Marshall G J, Turner J, Fogt R L, Schneider D, Dixon D A, Hosking J S, Jones J M and Hobbs W R 2017 The Amundsen Sea low: variability, changes, and impact on Antarctic climate Bull. Am. Meteorol. Soc. 97 111–21
Rihelé A, Bright B M and Anttila K 2021 Recent strengthening of snow and ice albedo feedback driven by Antarctic sea-ice loss Nat. Geosci. 14 832–6
Roach L A et al 2020 Antarctic sea ice area in CMIP6 Geophys. Res. Lett. 47 e86729
Sardeshmukh P D and Hoskins B J 1988 The generation of global rotational flow by steady idealized tropical divergence J. Atmos. Sci. 45 1228–51
Schlosser E, Huermann F A and Raphael M N 2018 Atmospheric influences on the anomalous 2016 Antarctic sea ice decay Cryosphere 12 1103–19
Schneider D P and Deser C 2018 Tropical driven and externally forced patterns of Antarctic sea ice change: reconciling observed and modeled trends Clim. Dyn. 50 4599–618
Sidgmond M and Fyfe J C 2010 Has the ozone hole contributed to increased Antarctic sea ice extent? Geophys. Res. Lett. 37 L18502
Stammerjohn S E, Martinson D G, Smith R C, Yuan X and Rind D 2008 Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño—Southern Oscillation and Southern Annular mode variability J. Geophys. Res. 113 C03S90
Stuecker M F, Bitz C M and Armour K C 2017 Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring Geophys. Res. Lett. 44 9008–19
Sun S and Li X 2018 Surface temperature over Antarctica Antarctic sea ice expansion reproduced in a climate model after correcting biases in sea ice drift velocity Nat. Commun. 12 1–6
Takahaya K and Nakamura H A 2001 Formulation of a phase independent wave-activity flux for stationary and migratory quasi geostrophic eddies on a zonally varying basic flow J. Atmos. Sci. 58 608–27
Tzetzer D, Thomas E and Allen C 2019 A validation of ERA5 reanalysis data in the Southern Antarctic Peninsula-Ellsworth land region, and its implications for ice core studies Geosciences 9 289
Thompson D W J, Solomon S, Kushner P J, England M H, Grise K M and Karoly D 2011 2011 Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change Nat. Geosci. 4 741–9
Turner J et al 2020 Recent decrease of summer sea ice in the Weddell Sea, Antarctica Geophys. Res. Lett. 47 e2020GL087127
Turner J, Phillips T, Marshall G J, Hosking J S and Deb P 2017 Unprecedented springtime retreat of Antarctic sea ice in 2016 Geophys. Res. Lett. 44 6868–75
Uotila P, Vihma T, Pezza A B, Simmonds I, Keay K and Lynch A H 2011 Relationships between Antarctic cyclones and surface conditions as derived from high-resolution numerical weather prediction data J. Geophys. Res. 116 D07109
Wang G, Hendon H H, Arblaster J M, Lim E-P, Abhik S and van Rensch P 2019 Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016 Nat. Commun. 10 13
Wilks D S 2006 Statistical Methods in the Atmospheric Sciences (San Diego, CA: Academic) p 648
Yu L, Zhong S, A W J, Zhou M, H L D, Li B, Wang X and Yang Q 2017 Possible connection of the opposite trends in Arctic and Antarctic sea ice cover Sci. Rep. 7 43804
Yu L, Zhong S and Sun B 2022 Synchronous variation patterns of monthly sea ice anomalies at the Arctic and Antarctic J. Clim. 35 2823–47
Yu L, Zhong S, Vihma T, Sui C and Sun B 2021 Sea ice changes in the Pacific sector of the Southern Ocean in autumn closely associated with the negative polarity of the South Pacific Oscillation Geophys. Res. Lett. 48 e2021GL092409
Yu L, Zhong S, Zhou M, Sun B and Lenschow D H 2018 Antarctic summer sea ice trend in the context of high latitude atmospheric circulation changes J. Clim. 31 3909–20
Zambri B, Solomon S, Thompson D W J and Fu Q 2021 Emergence of Southern Hemisphere stratospheric circulation changes in response to ozone recovery Nat. Geosci. 14 638–44
Zhang J L 2007 Increasing Antarctic sea ice under warming atmospheric and oceanic conditions J. Clim. 20 2515–29
Zhang X, Deser C and Sun L 2021 Is there a tropical response to recent observed Southern Ocean cooling? Geophys. Res. Lett. 48 e2020GL091235
Zunz V, Goosse H and Massonnet F 2013 How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? Cryosphere 7 451–68