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Modulation in Interannual Sea-Ice Patterns in the Southern Ocean
in Association with Large-Scale Atmospheric Mode Shift

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Abstract

We verified that the synchronous propagations of the spatial patterns of sea ice concentration (SIC) of wavenumber 2 around the Antarctic occurred only for the period 1984 to 1994. An empirical orthogonal function (EOF) analysis of satellite data for 1979–2003 objectively demonstrates that the spatial pattern of SIC propagated eastward only in 1984–1994, in other years, it did not. Our results show that interannual variations in SIC patterns are associated with differences in the dominant large-scale atmospheric patterns. In non-propagating years, variance of the tropospheric Antarctic oscillation (AAO) predominated. However, in propagating years, the AAO variance was subdominant to that of the Pacific South American (PSA) teleconnection pattern having a 4-year period. Such periodic PSA enables the SIC anomalies to propagate eastward with a periodically reinforced dipole pattern. The shift of large-scale atmospheric variability is one possible cause of the modulation in the SIC pattern. The switch of the atmospheric EOF leading mode from the PSA pattern to the AAO in the mid-1990s corresponded to the modulation in the SIC pattern and supports the presence of the atmospheric climate shifts.

1. Introduction

Previous studies have presented two views of circum-Antarctic interannual climatic variation. One view involves the Antarctic circumpolar wave (ACW) and eastward synchronous propagation of the spatial patterns of sea-ice extent, sea surface

1 temperature (SST), sea level pressure (SLP), and meridional wind stress anomalies with
2 wavenumber 2 around the Antarctic [e.g., White and Peterson, 1996; Motoi et al., 1998].
3 The atmospheric wave is also characterized by eastward propagation. Additionally sea
4 surface height (SSH) anomalies in the Southern Ocean synchronously propagate eastward
5 with the SST in association with the ACW, and the ocean plays an important role in
6 creating and maintaining the ACW [Jacobs and Mitchell, 1996]. Moreover, maintenance
7 of the ACW involves coupling between ocean and atmosphere. [Qiu and Jin, 1997, White
8 et al., 1998]. It is a remarkable example of self-organization between the global ocean and
9 the atmosphere. In contrast, the other view proposes that the circum-Antarctic climate is
10 governed by a geographically phase-locked quasi-stationary wave in sea-ice, SST, and
11 surface air temperature, which is linked to the El Niño–Southern Oscillation (ENSO)
12 variability [e.g. Yuan and Martinson, 2000, 2001, Kwok and Comiso, 2002, Kidson and
13 Renwick, 2002, Renwick 2002, Yuan, 2004]. This quasi-stationary wave is known as the
14 Antarctic Dipole (ADP) [Yuan and Martinson, 2000, 2001]. It is characterized by an
15 out-of-phase relationship between these anomalies in the central/eastern Pacific and
16 Atlantic sectors of the Antarctic. The dipole consists of a strong standing mode with weak
17 eastward propagation. The Antarctic sea-ice distribution is formed and maintained by an
18 atmospheric stationary or standing wave train that amplifies in association with
19 atmospheric blocking over the South Pacific [Renwick and Revell, 1999]. The stationary
20 wave train associated with the blocking is caused by the propagation of atmospheric

1 Rossby waves activated by ENSO [Karoly 1989, Trenberth et al., 1998, Kidson 1999, Mo
2 2000, Cai and Watterson, 2002, Kidson and Renwick, 2002] and is named the Pacific
3 South American (PSA) teleconnection pattern [Mo and Ghil, 1987]. Cai and Watterson
4 [2002] also demonstrated that ENSO forcing amplifies the PSA along with amplification
5 by internal atmospheric dynamics.

6 Park et al. [2004] showed that most of the Antarctic interannual variability can be
7 explained by a geographically phase-locked standing wave train linked to tropical ENSO
8 episodes using a Fourier decomposition into stationary and propagating components of
9 several oceanic and atmospheric variables (i.e., SST, SSH, and SLP). Although their work
10 involved the two views of circum-Antarctic interannual climatic variation, they did not
11 include sea-ice variability. To harmonize these different views and clarify the
12 circum-Antarctic interannual climatic variations, sea-ice studies, especially relating to its
13 interannual variability, are helpful because sea-ice functions as an interface between the
14 ocean and the atmosphere and is influenced by both. Present study will demonstrate the
15 spatial and temporal variations of sea-ice using newly available passive microwave
16 satellite data for 1979-2003.

17 Although numerous previous studies have described sea-ice variability in the
18 Southern Ocean in association with atmospheric surface conditions such as the SLP and
19 wind stresses, many have not discussed the relationship between sea-ice and the whole
20 troposphere. Bonekamp et al. [1999] and Connolley [2003], who demonstrated that

1 propagation of the SLP anomaly, i.e., ACW signal, is only present in the period of
2 1985–1994, have also made a remarkable contribution in trying to harmonize the different
3 views. However, their atmospheric analysis did not include the whole troposphere, but
4 rather was restricted to air in direct contact with the ocean. The action centers of
5 interannual atmospheric variability are usually located in the middle or upper troposphere,
6 rather than in the lower troposphere [Thompson and Wallace, 2000]. An example of
7 tropospheric variation is the Southern Hemisphere annular mode or the Antarctic
8 oscillation (SAM/AAO) [Thompson and Wallace, 2000] in which the AAO connects even
9 to the stratosphere. The PSA pattern appears in the middle or upper troposphere, but the
10 center of action of sea-ice is in the lower troposphere. Therefore a better understanding of
11 long-term whole tropospheric circulation in association with our long-term sea-ice
12 analysis should help clarify the Antarctic climate system. The knowledge about Antarctic
13 climate system can go one step further by looking at both of sea-ice and whole
14 tropospheric circulation.

15 We will address a new theory/hypothesis of circum-Antarctic interannual climatic
16 variations by focusing on sea-ice variations as revealed by statistical analyses of long-term,
17 satellite-derived sea-ice data and atmospheric reanalysis data. Bonekamp et al. [1999]
18 have pointed out the possibility of a regime shift in sea-ice variability in the Southern
19 Ocean, but its cause has not yet been understood. In this study, we will demonstrate that
20 shift of atmospheric variation controls whether the sea-ice propagates eastward or not. In

1 other words, the replacement of dominant atmospheric patterns modulates the sea-ice
2 variability.

3 Datasets and the statistical methods used in this study are described in sections 2
4 and 3, respectively. Results are described in Section 4, and discussion and concluding
5 remarks are in sections 5 and 6, respectively.

6

7

8 2. Data

9 Monthly sea ice concentration (SIC) data provided by the Oceans and Ice Branch,
10 Laboratory for Hydrospheric Processes at NASA Goddard Space Flight Center (GSFC,
11 NASA team algorithm) were used to investigate the interannual variability of sea-ice in the
12 Southern Ocean. The SIC data are derived from the Nimbus-7 Scanning Multichannel
13 Microwave Radiometer (SMMR) and the Defense Meteorological Satellite Program
14 (DMSP)-F8, -F11, and -F13 Special Sensor Microwave/Imagers (SSMIs). These two sets
15 of satellite data were combined by Cavalieri et al. [1996, 1997], and the combined data set
16 is available for the period of 1979–2003 with a spatial resolution of 25×25 km. This data
17 set is available from <http://nsidc.org/data/nsidc-0051.html>, and includes gridded daily and
18 monthly averaged sea ice concentrations for both the north and the south polar regions.
19 Two types of data are provided, final data and preliminary data. Final data are produced at
20 GSFC about once per year. Preliminary data are produced at The National Snow and Ice

1 Data Center (NSIDC) approximately every three months and include roughly the most
2 recent three to twelve months of processed data. The data we used is the final data, which
3 includes additional quality control, including temporal interpolation of large data gaps in
4 the daily data. Additionally particular care is needed to interpret the sea ice concentrations
5 during summer when the melt is present and in regions where new sea-ice makes up a
6 substantial part of the sea-ice cover. Some residual errors remain due to weather effects,
7 mixing of ocean and land area in the sensor field of view, and the differences of sensors. It
8 is recommended that sea-ice extent and area computed from daily maps of sea ice
9 concentrations be used to compute monthly averages of those parameters. In this paper, we
10 use monthly means on winter seasons, and so this error will not impact our analyses.

11 We also used monthly optimal-interpolation sea surface temperature (OISST,
12 hereafter SST) data compiled by the National Oceanic and Atmospheric Administration
13 (NOAA) on a 1.0×1.0 degree regular latitude–longitude global grid [Reynolds and Smith,
14 1994] and daily mean atmospheric reanalysis data provided by the National Centers for
15 Environmental Prediction/National Centers for Atmospheric Research (NCEP/NCAR)
16 [Kalnay et al., 1996] on a 2.5×2.5 degree regular latitude–longitude global grid. The
17 analysis period for all of the data sets was 1979 through 2003. The NCEP/NCAR
18 reanalysis data set, which is referred to as the NCEP1 data, was obtained from the National
19 Weather Service Climate Prediction Center reanalysis project (available online at
20 <http://www.ncep.noaa.gov/cdc/reanalysis/reanalysis.shtml>). We use 10m-wind data in

1 order to calculate the curl of the wind stress along with geopotential height and
2 temperature data at standard levels. For detailed calculations, see Section 3.

3 Bromwich and Fogt [2004] concluded that, for austral nonsummer climate studies
4 across Antarctica and the Southern Ocean, neither ECMWF (European Centre for
5 Medium-Range Weather Forecasts) 40 Year Re-analysis (ERA-40) data nor NCEP1 data
6 are reliable prior to the modern satellite era (before 1979), because the frequency of
7 ship-based observations in coastal Antarctica, which help to constrain the reanalysis,
8 decreases during winter. Also, Tennant [2004] pointed out that NCEP1 has areas of sparse
9 data coverage in the South Pacific and South Atlantic Oceans, and concluded that NCEP1
10 is not reliable during any season prior to 1979 in the Southern Hemisphere. Bromwich et al.
11 [2007] presented a wide review of recent knowledge regarding the status of the major
12 global reanalyses in the polar regions. They concluded that the beginning of the modern
13 satellite era in 1979, when new quantities of data were assimilated for the first time,
14 created a sudden adjustment in the Southern Ocean and Antarctica. Additionally, there was
15 a problem in assimilating bogus surface pressure observations in NCEP1 in Southern
16 Hemisphere, known as the PAOBS problem (see online at
17 <http://www.cpc.ncep.noaa.gov/products/wesley/paobs/paobs.html>). This error affects
18 1979-1992 (14years) in the 40°-60°S band on daily to weekly timescales. In this paper, we
19 use monthly means on pressure levels, and so this error will not impact our analyses. As
20 discussed above regarding the uncertainty of reanalysis data sets before satellite era, we

mainly use the reanalysis data sets from the satellite era (1979). Therefore, this problem will not impact our study.

3. Method

Wintertime seasonal averages of the SIC, SST, and atmospheric data were mainly used, with winter defined as July, August, September, and October (JASO) for SIC, and July, August, and September (JAS) for SST and atmospheric data. As there may be some lag in the response of sea-ice with large inertia to winter atmospheric variation, we have included October in the winter season only for the SIC data analysis. An empirical orthogonal function (EOF) analysis was applied to the covariance matrix of the winter-averaged SIC anomalies. The spatial coverage of the SIC-EOF analysis was the entire area of sea-ice around the Antarctic (from approximately 40° S to 90° S). The JASO mean data are used for the SIC-EOF calculation. We also applied an atmospheric EOF analysis to mass-weighted vertical average geopotential height anomaly data from 1000 to 300 hPa for the extraction of the dominant barotropic components. Note that there was not much difference between the result of analysis for the vertical averaged data and for the 500hPa data. Additionally, geopotential height data were weighted by area using the square root of the cosine of latitude to ensure equal area weighting for the covariance matrix. The atmospheric EOF analysis covered an area from 20 degrees S to 90 degrees S

so that a leading teleconnection pattern in the extratropic atmospheric circulation could be identified.

Temperature advection and the curl of wind stress were calculated for each day using the daily NCEP1 data. Data from 925 hPa were used to calculate temperature advection, and 10-m wind data were used to calculate wind stress. JAS and climatological means were then calculated.

4. Results

4.1 Sea-ice variability

Figure 1 shows the spatial SIC patterns of the first and second modes of the EOF (referred to as SIC-EOF1 and SIC-EOF2, respectively) and their PC scores. The analysis covered the period of 1979–2003. The SIC-EOF1 exhibits positive anomalies in the western Atlantic and western Pacific sectors, but negative anomalies in the Amundsen Sea, Ross Sea, the western Indian Ocean, and eastern Indian Ocean sectors. This spatial pattern looks like the Antarctic Dipole (ADP) [Yuan and Martinson, 2000, 2001, Yuan, 2004]. The SIC-EOF2 shows positive anomalies in the eastern Atlantic sector and central Pacific sector, but negative anomalies in the Bellingshausen Sea and the eastern Indian Ocean sector. The spatial patterns of both EOFs have wavenumber 2 and variances of 25.8% and 14.3%, respectively. SIC-EOF2 resembles SIC-EOF1, with the spatial pattern of

1 SIC-EOF2 appearing to shift eastward by about 45 degrees relative to that of SIC-EOF1.
 2 The interannual variation of the PC1 score also shows a striking resemblance to that of the
 3 PC2 score, but with a roughly one-year lag, especially during 1984 to 1994. These results
 4 indicate that the EOF decomposed an easterly propagating mode into the two standing
 5 modes. To confirm this, we examined the lag correlation of the PC scores. The
 6 simultaneous correlation coefficient is, by definition, zero. The correlation with a 1-year
 7 lag (lead) results in a coefficient of 0.57 (−0.48), which exceeds the 99% significance level
 8 based on t-tests. The correlation coefficient for a 2-year lag (lead) is −0.14 (−0.06).

9 These results indicate that the year of the prominent EOF2 spatial pattern tends to
 10 occur 1 year after the year of the prominent EOF1 spatial pattern. One year after the year of
 11 prominent EOF2, the EOF1 spatial pattern with negative sign occurs. The same pattern
 12 with the negative sign then repeats, with the prominent EOF1 spatial pattern reoccurring 4
 13 years later. Therefore the sea-ice spatial pattern with wavenumber 2 tends to propagate
 14 eastward in a 4-year period.

15 The PC scores are by definition orthogonal. To verify the rotation of the SIC
 16 spatial pattern, viewing the pattern from the polar coordinates is more advantageous than
 17 from the Cartesian coordinates (Figure 2). We viewed the two components based on their
 18 amplitude and the phase of interannual SIC variability. We defined the phase, θ , as

19
$$\text{phase } \theta = \tan^{-1}\left(\frac{PC2score}{PC1score}\right)$$

20 When the phase θ rotated counterclockwise in the field of Figure 2, i.e., increases with

1 time, the SIC propagates eastward.

2 Figure 3 shows the time evolution of the phase θ . Clearly, θ constantly increased
3 with time only between 1984 and 1994, indicating that the SIC anomalies propagated
4 eastward continuously in this period. The average slope of that increment signifies a
5 rotation cycle of about 4 years. However, for the other years, θ did not continuously
6 increase with time. Thus, the SIC anomalies did not propagate eastward from 1979 to 1984
7 or from 1994 to 2003. Figure 3 demonstrates that the spatial pattern of SIC anomalies with
8 wavenumber 2 propagated eastward only from 1984 to 1994. The ADP is composed of a
9 standing mode with weak eastward propagation [Yuan and Martinson, 2000, 2001, Yuan,
10 2004]. Our results show that the dipole structure is present, but also clearly show that it
11 propagates eastwards in the 1984–1994 period, meaning that during this period it is more
12 reasonable to regard the sea-ice variation as a visualization of a propagation signature by
13 the Antarctic circumpolar wave (ACW) than to regard it as a visualization of a standing
14 signature of the ADP. The period is the same as that shown by White and Peterson [1996].
15 However, the signal is clear only in the west Antarctic. Therefore, strictly speaking, this
16 signal is not exactly the same as the ACW. Also, our results are consistent with Connolley
17 [2003], in which the ACW was evident only from 1985 to 1994 using data analysis from
18 1968 to 1999. However, he did not determine why the ACW was prominent only in that
19 period, but simply speculated that it may be due to an external forcing, such as ENSO, or
20 intrinsic atmospheric variation. We will focus on discovering why the SIC anomaly only

propagates eastward in the years 1984–1994.

4.2 Atmospheric variability

Because the spatial SIC pattern during 1984–1994 differed from that in other years, the atmospheric variations that forced the sea-ice in those years may also have differed. In this subsection, we focus on differences in large-scale atmospheric patterns in association with the modulation in sea-ice variation. However, first, we describe the overall dominant atmospheric variations over and around the Antarctic from 1979 to 2003. Figure 4 shows the first and second EOFs of atmospheric spatial patterns and their corresponding time series. Hereafter, the spatial pattern of the atmospheric first mode and its time series are referred to as the ATM EOF1 and ATM EOF1 index (PC1 scores), respectively, and those of the second mode as the ATM EOF2 and ATM EOF2 index (PC2 scores). The variances contributed by ATM EOF1 and ATM EOF2 are 29.7% and 18.6%, respectively. We used the whole troposphere average for the analysis. This can filter out the variability that appears only within the lower troposphere. The spatial pattern of the first mode is similar to that of the AAO [Gong and Wang, 1999] / SAM [Thompson and Wallace, 2000], whereas the second mode exhibits positive anomalies in the western Atlantic sector and negative anomalies in the central Pacific sector. The second mode is similar to that shown by Karoly [1989], Cai and Baines [2001], and Cai and Watterson [2002]. In these studies, the largest variability with respect to the 200hPa

1 (Karoly [1989]) and 500hPa geopotential height was in the Pacific sector, with the second
2 largest peak in the western Atlantic sector; this pattern reflects a geographically
3 phase-locked standing wave. Significant action centers of our ATM EOF2 in the western
4 Atlantic sector, the Bellingshausen–Amundsen Seas, and the east South Pacific, i.e., to
5 the south of New Zealand, agree with those described in these articles. This is the
6 so-called PSA pattern, which is activated by tropical anomalous heating [Hoskins and
7 Karoly, 1981, Karoly, 1989]. Mo and Ghil [1987] discovered and defined the PSA pattern
8 for the first time. They define the second and third EOFs of 500hPa geopotential height
9 anomaly as the PSA pattern. Their PSA pattern has the strongest signature centered on the
10 Antarctic Peninsula. Our third EOF (figure is not shown) does not have such a feature as
11 theirs, and the corresponding contribution is as small as 11.9%. We therefore adopt our
12 EOF2 as the PSA pattern. As shown in Figure 4b, the strongest signature can be seen near
13 the Antarctic Peninsula. The amplitude of the ATM EOF1 index (PC1 scores) for
14 1984–1994 appears to be smaller than that for other periods, whereas the amplitude of the
15 ATM EOF2 index (PC2 scores) for 1984–1994 appears larger. Table 1 also suggests these
16 changes in variance. These results indicate the change/shift of large-scale atmospheric
17 variations.

18

19 4.3 Atmospheric variation from 1984 to 1994

20 If atmospheric factors cause the modulation in SIC variation, there must be some

1 signatures that differentiate the SIC variation in large-scale atmospheric patterns. To
2 identify the atmospheric patterns that modulate the SIC, we separately calculated
3 atmospheric first and second EOFs for the period 1984–1994 and for other years. We first
4 show the atmospheric variation, i.e. the atmospheric geopotential height field, only in
5 1984–1994, based on the same atmospheric EOF analysis as described above. Figure 5
6 shows the spatial patterns of the first and second modes and their corresponding time series.
7 The first and second modes contribute 28.7% and 25.0% of the variance, respectively. The
8 time variation of the first mode is obviously cyclic with an approximately 4-year period.
9 Further, the wavy structure of the first mode spatial pattern is quite similar to that of the
10 second mode for the whole period (Figure 4b). The correlation coefficient between the first
11 mode time series in this sub-period and the second mode time series in the whole period is
12 0.90. In this sub-period, the second mode is not similar to the first mode calculated for the
13 whole period. Thus, in this sub-period, the PSA pattern was dominant as the first mode.
14 The approximately 4-year cycle of the first mode, i.e., the PSA pattern, coincides with the
15 period of the eastward propagation of the SIC. This coincidence suggests that the
16 atmospheric shift should change/modulate the pattern of SIC variation. Hereafter, we
17 define the normalized time series of the first-mode EOF for 1984–1994 as the PSA index
18 (PC1 scores) and investigate the influence of the PSA on eastward SIC propagation. Note
19 that we normalize the time series divided by the standard deviation and the definition of
20 the positive PSA pattern in this paper is the pattern like Figure 5a. Although the time series

of the PSA index (PC1 scores) is 10 years long, an approximately 4-year cycle is resolvable. Therefore, the variance of a cyclic PSA pattern with an approximately 4-year cycle was predominant in the atmosphere in the period 1984–1994.

4.4 Atmospheric variation from 1979 to 1983 and 1995 to 2003

Here, we focus on atmospheric variations in the sub-periods 1979–1983 and 1995–2003, when SIC anomalies did not propagate eastward, using the same atmospheric EOF analysis. The spatial patterns of the first mode and the second mode and their corresponding time series are shown in Figure 6. The spatial patterns of both are quite similar to those of the first and second modes for the whole period shown in Figure 4. These modes again exhibit the AAO pattern and the PSA pattern, respectively. The variances contributed by the leading and second modes are 38.9% and 17.9%, respectively. The first mode (i.e., the AAO) is more predominant than that for the whole period. In addition, the spatial pattern of the second mode in Figure 6 (b) is quite similar to that of the first mode for the period 1984–1994, shown in Figure 5 (a), which exhibits the PSA pattern. The variances for Figures 6(b) and 5(a) are 17.9% and 28.1% respectively. This difference indicates that the PSA was damped in the periods 1979–1983 and 1995–2003 compared to the period 1984–1994. It is possible that the leading modes shown in Figure 6 are not real as disjointed timeseries were combined for use in an EOF analysis. To confirm the modes

1 in Figure 6 are real, we performed the EOF analysis on the individual time periods i.e.,
2 1979–1983 and 1995–2003 separately (Figures not shown). The spatial patterns of these
3 individual EOF analyses show the AAO and PSA patterns as first and second modes
4 respectively, corresponding to Figures 4 and 6. The timeseries of the individual EOFs were
5 also similar to those in Figures 4 and 6 for both periods 1979 to 1983 and 1995 to 2003.
6 Therefore, we consider the EOF results shown in Figure 6 to be valid.

9 5. Discussion

10 We determined a number of characteristics of large-scale atmospheric variability
11 associated with sea-ice variability. The spatial pattern of sea-ice with wavenumber 2
12 propagated eastward only in 1984–1994. In other years, no significant eastward
13 propagating features were signified. Differences in large-scale dominant atmospheric
14 patterns were also uncovered. In the non-propagating years, the AAO variance
15 predominated. In years of eastward SIC propagation, the variance of a cyclic PSA pattern
16 with an approximately 4-year cycle was predominant in the atmosphere.

17 Below, we examine the cause of the SIC modulation. We first describe the
18 external forcing of the PSA pattern that causes the eastward propagation of the SIC. We
19 then discuss the shift of atmospheric variation that determines the modulation in SIC
20 variation.

1

2 5.1 Propagation of the SIC and atmospheric PSA pattern

3 Figure 7 shows simultaneous and lagged regression patterns of the SIC with the
4 atmospheric PSA index (PC1 scores); each of the simultaneous, 1-year, and 2-year lagged
5 SIC patterns has a wavenumber of 2. Figure 7a shows an area of large negative (positive)
6 variability over the central Pacific sector (the western Atlantic sector). This spatial pattern
7 is quite similar to that of SIC-EOF1. In fact, the PSA index (PC1 scores) and SIC-EOF1
8 PC score have a correlation coefficient of 0.88 for the period of 1984–1994. The PSA
9 index (PC1 scores) is the time series of the first EOF executed only in 1984–1994. Also,
10 Figure 7 clearly shows that the areas of large positive and negative regression propagated
11 eastward year by year. Therefore, the PSA pattern somehow forced SIC anomalies to
12 propagate eastward.

13 Figure 8 shows the relation of atmospheric dynamic and thermodynamic forcing
14 with the PSA index (PC1 scores). Simultaneous patterns of temperature advection (Figure
15 8 top), curl τ (Figure 8 middle), and SST (Figure 8 bottom) commonly show a pair of
16 significant warm and cold anomalies in the central Pacific and Atlantic sectors. The warm
17 (cold) area, which signifies anomalous warm (cold) temperature advection, convergence
18 (divergence) of sea-ice, and anomalous warm (cold) SST, is favorable for the decrease
19 (increase) in sea-ice. The significant areas of the warm–cold pairs (Figure 8a) agree well
20 with those of the SIC anomalies (Figure 7a). Thus, these figures indicate that when the

1 index of the PSA pattern (PC1 scores) is large and positive, atmospheric dynamic and
2 thermodynamic external forcing by the PSA pattern amplify the SIC contrast between the
3 central Pacific sector and the Atlantic sector. This atmospheric forcing is favorable for the
4 formation of a dipole of SIC in these sectors. Therefore, the PSA pattern excites the dipole
5 pattern of the SIC in these areas. The atmospheric forcing 2 years later is in reverse
6 because the index of the PSA pattern (PC1 scores) has a 4-year cycle (Figures 7c and 8c).
7 In other words, the atmosphere periodically forces the formation of an SIC dipole, i.e.,
8 Antarctic Dipole [Yuan and Martinson, 2000, 2001], every other year with a reversed
9 phase. The atmospheric forcing mostly vanishes 1 year after the year having a large and
10 positive PSA index (PC1 scores, Figure 8b). However, a persistent signature can be seen in
11 the SST field, with positive anomalies in an area approximately 45 degrees eastward from
12 the significant dipole area of the simultaneous SST field. This suggests the presence of
13 eastward movement of the SST signature. Also, the positive and negative SIC patterns
14 located over the western Atlantic and central Pacific sector (Figure 7a) synchronously
15 move eastward 1 year later (Figure 7b). This synchronous SIC and SST propagation was
16 previously discussed by Martinson [1993] and Gloersen and White [2001]. They
17 demonstrated that the propagating wave of the sea-ice variability is carried from one
18 winter to the next winter by the thermal inertia of upper water neighboring the sea-ice. The
19 explanation of atmospheric dynamic and thermodynamic forcing with the simultaneous
20 PSA index (PC1 scores) is consistent with Raphael [2004, 2007], who examined the

1 relationship between the pattern of an atmospheric zonal wavenumber three and Antarctic
2 sea-ice by using an index of the zonal wave three. The zonal wave three possibly forces an
3 alternating pattern of equatorward (colder) and poleward (warmer) flow, which influences
4 sea-ice growth/expansion and decay/retrogression respectively. The basic mechanism
5 underlying the relationship between the atmospheric circulation pattern and sea-ice
6 variability via atmospheric dynamic and thermodynamic forcing in our results is consistent
7 with these papers. Raphael [2004, 2007], however, did not describe the relationship
8 between the atmospheric zonal wave three and the PSA pattern. The spatial pattern of their
9 atmospheric zonal wave three is different from our PSA pattern deviating/rotating by about
10 45° with respect to their zonal wave three.

11 Combining the present results with those of previous studies, we propose the
12 following scenario of eastward rotation of the SIC. The PSA pattern excites the negative
13 and positive dipole structure of the SIC in the central Pacific and western Atlantic sectors
14 in a year with a positive and large PSA index (PC1 scores). The dipole signature is retained
15 in the ocean by large thermal inertia, persisting until the next year. In the following winter,
16 this memorized signature moves eastward in association with the eastward oceanic
17 propagation, as reported by Martinson [1993] and Gloersen and White [2001]. Two years
18 later, the same atmospheric forcing as in the first year, but with reversed phase, again
19 excites the dipole of the SIC with reversed phase. The memorized signature also moves
20 further eastward toward the opposite side of the Antarctic Peninsula. Three years later, the

1 same oceanic propagation as in the second year, but having the reversed phase, occurs. In
2 the fourth year, the same atmospheric forcing as in the first year once again excites the
3 dipole of the SIC. This 4-year cycle of atmospheric forcing is probably the same as the
4 period of the oceanic signature that rounds the Antarctic. Therefore, this periodic
5 atmospheric forcing excites the dipole, and the ocean makes the dipole signature propagate
6 eastward. In other words, the atmosphere plays a role in creating the dipole, and the ocean
7 plays a role as a carrier of the dipole. The periodicity of this atmospheric forcing is
8 consistent with Mo [2000] and Rasmusson et al. [1990], who showed that the PSA has a
9 48-month cycle that is driven by the ENSO. Regarding the Antarctic dipole pattern of
10 sea-ice variability, Holland et al. [2005] focused on the standing wave pattern in sea-ice
11 anomaly associated with simulated Antarctic dipole variability and investigated the
12 mechanisms in detail using a climate coupled model. They showed that the Antarctic
13 dipole pattern of sea-ice variability was forced by a combination of both thermodynamics
14 (e.g., ice/ocean surface heat flux convergence analysis) and dynamical processes. Their
15 result is consistent with ours, in particular, with the role of the anomalously high SLP in
16 Figures 4(b), 5(a), and 6(b), in the Amundsen–Bellingshausen Sea.

17 As shown in Figures 7 and 8, the eastward propagation seems to only be visible
18 over the western part of the Southern ocean. To confirm this, we show that the Hovmöller
19 (longitude-time) diagram of JASO mean SIC anomalies averaged from 55° S to 70° S
20 around the Antarctic for 1979–2003 (Figure 9, top). This figure clearly demonstrates that

1 the signal of eastward propagation is only evident from 180° W to 60° E. The bottom panel
 2 of Figure 9 shows the simultaneous and lagged correlation of JASO mean SIC, averaged
 3 from 55° S to 70° S around the Antarctic for 1979–2003, along with the ATM-EOF2 index
 4 (PC2 scores) in the period 1979–2003 (as the atmospheric PSA index). Each of the
 5 simultaneous (black line), 1-year (green line), and 2-year (yellow line) lagged SIC patterns
 6 have two peaks that satisfy the statistical significance criteria. Blue dot-dash lines indicate
 7 90%, 95%, and 99% statistical significance based on *t*-tests, respectively. The
 8 simultaneous correlation pattern exhibits large negative and positive values over the area
 9 of 120° W, or the central Pacific sector, and the area of 60° W, or the western Atlantic sector.
 10 This spatial correlation pattern signifies the Antarctic dipole. In addition, the lag
 11 correlation lines clearly show that the areas of large positive and negative correlation
 12 coefficients propagated eastward year by year only over 180° W to 60° E. Yuan and
 13 Martinson (2000) indicated that the Antarctic dipole consists of a strong standing mode
 14 with a very weak propagating signature. As shown in Figure 9, however, we can
 15 demonstrate that in the period 1984–1994, the Antarctic dipole has a standing mode with a
 16 substantially strong propagating motion compared with other periods i.e. non-rotating
 17 years.

18

19 5.2 Non Propagation of the SIC and atmospheric AAO

20 Here, we propose an explanation for the SIC change/modulation. We calculated

1 the horizontal temperature advection field, the curl τ field, and the SST anomaly field
2 linearly regressed over the time series of the second EOF executed in the sub-periods of
3 non-rotation, as in Figure 6. Signatures that may induce eastward propagation of the SIC
4 could not be seen in any of the fields (figures not shown). Also, the top panel of Figure 9
5 shows no propagating signature of the SIC in these sub-periods. In addition, a 4-year cycle
6 was not dominant in the time series of the second mode in the sub-periods of non-rotation
7 (see Figure 6). The variance of the PSA in the sub-periods of non-rotation was, moreover,
8 smaller than that in the sub-period of rotation. In fact, the AAO overwhelmed the PSA
9 pattern in the sub-periods of non-rotation. This weak atmospheric external forcing made
10 the formation of the dipole pattern of the SIC difficult. The fact that 4-year cyclic
11 atmospheric forcing was not dominant also reduces the possibility of propagation of the
12 SIC. Therefore, the shift of the dominant atmospheric pattern is quite important for
13 determining whether the SIC propagates. In the non-rotating sub-periods, the AAO pattern
14 was predominant, whereas in the rotating period, the AAO pattern was subdominant.

15

16 5.3 Shift of the dominant atmospheric pattern

17 As discussed above, the shift of the dominant atmospheric pattern is quite
18 important for determining whether the SIC propagates. In this subsection, we focus on the
19 shift/change of the dominant atmospheric pattern for longer time period. To identify the
20 shift of the atmospheric patterns over a longer time period, we calculated atmospheric first

1 and second EOFs for the period 1958–2007 based on the same atmospheric EOF analysis
2 as described in Section 4.2 (figures not shown). The spatial pattern and corresponding time
3 series of the first (second) mode are quite similar to those of the AAO (PSA) mode, as
4 shown in Figure 4. Although the analysis period includes the era with no satellite data, i.e.,
5 before 1979, we consider that the patterns are realistic and have physical meaning because
6 these patterns are similar to those of the period 1979–2003. We further calculated
7 variances for each 11-year period for the time series of atmospheric EOFs in the period
8 1958–2007. The variance lines are shown in Figure 10; for example, the value in 1990
9 signifies the variance in the period 1985–1995. The variances of the PSA pattern are larger
10 than those of the AAO over the period 1984–1994. This period corresponds to the years of
11 sea-ice propagation, whereas in the non-propagating years (1979–1983 and 1995–2003),
12 variances of the AAO are more pronounced than those of the PSA pattern. Moreover,
13 Figure 10 demonstrates that the atmospheric shift of the dominant pattern occurred several
14 times from the 1960s to the 2000s: in the mid-1970s, -1980s, and -1990s.

15 Consequently, the amplitude and frequency shifts of the PSA pattern, as well as
16 the amplitude shift of the AAO, determine whether the SIC propagates. These shifts of
17 atmospheric patterns cause the modulation in sea-ice variation patterns in the Southern
18 Ocean. The viewpoint of sea-ice modulation enabled us to clarify the presence of the shifts
19 of the AAO and the PSA pattern.

20

1

2 6. Concluding remarks

3 We investigated the interannual variation in SIC anomalies around the Antarctic
4 using an EOF analysis for newly available passive satellite-derived microwave data for the
5 period of 1979–2003. The period of eastward propagation was only from 1984 to 1994,
6 with no significant eastward propagating features of the SIC in other years. This large
7 modulation in the SIC suggests that the change of a climate variability occurred. We also
8 clarified the difference in dominant large-scale atmospheric patterns in association with
9 the SIC modulation. In the non-propagating years, the variance of tropospheric AAO was
10 predominant. In the rotating years, the variance of the PSA pattern with a 4-year cycle in
11 the troposphere was predominant, whereas AAO variance was subdominant. Such
12 predominant periodic atmospheric external forcing allows the SIC to propagate eastward.

13 The causes of the modulation in the SIC pattern include the amplitude and
14 frequency shifts of large-scale atmospheric variability. The switch in the dominant
15 atmospheric pattern from the PSA to the AAO in the mid-1990s is synchronized with the
16 modulation in the SIC pattern. In addition, we can demonstrate that the shift of the
17 dominant atmospheric pattern between the AAO and PSA occurred in the mid-1970s,
18 -1980s, and -1990s. It is known that the PSA pattern is influenced by ENSO [e.g. Karoly
19 1989, Trenberth et al., 1998, Kidson 1999]. However, no significant modulations of the
20 ENSO cycle occurred in the mid-1970s, -1980s, and -1990s. This suggests that the

1 response of the high-latitude atmosphere to quasi-cyclic tropical forcing is not simple. The
2 causes of long-term shift of the AAO also require further research. Because the AAO and
3 the PSA are hemispheric-scale atmospheric phenomena, these shifts may influence other
4 climatic subsystems.

5

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2 We extend our thanks to S. Aoki, K. Ohshima, and Y. Fukamachi, for their useful
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5 used to draw the figures.

6

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6

1 Table and figure captions

2 Table 1. Variances of the time series of atmospheric EOFs in the sub-periods from 1984
3 through 1994 and in other sub-periods. ATM-EOF1 and ATM-EOF2 represent the first and
4 second modes of the atmospheric EOF, respectively. The SIC anomalies were
5 characterized by eastward propagation in 1984–1994. In the other years, the SIC
6 anomalies did not have any features of eastward propagation.

7

8 Figure 1. (top a, b) Spatial patterns of the first and second modes of JASO mean SIC
9 anomalies around the Antarctic for 1979–2003. (bottom) Corresponding time series of the
10 first (black line) and second (green line) modes. The indices are standardized. The shading
11 in a and b indicates linear regression coefficients of the SIC with the time series of the first
12 and second mode, respectively (unit is %). The gradation of the shading changes in
13 increments of 5%, but absolute values $<1\%$ are ignored. The contours indicate 95%
14 statistical confidence based on t-tests.

15

16 Figure 2. Schematic map showing the relationship between the indices (PC1 and 2 scores)
17 of the two leading SIC-EOFs and the phase, θ . Counterclockwise rotation of θ with time
18 defines the increment in θ . Thus, in the period in which θ increases (decreases), the SIC
19 anomalies propagate eastward (westward).

20

1 Figure 3. Year-to-year evolution of the phase, θ . Horizontal and vertical axes show the year
2 and the phase, respectively (phase unit = degrees). To illustrate the rotational status
3 schematically, even if the phase value exceeds 360 degrees, we did not reset the phase to
4 zero.

5
6 Figure 4. (top) The spatial patterns of (a) ATM EOF1 and (b) ATM EOF2 for the JAS mean
7 vertically integrated geopotential height anomalies from 20° S to 90° S for 1979–2003. See
8 the text for details on the calculation method. (bottom) Corresponding time series of the
9 first (black line) and second (green line) modes. The values are standardized. Shading in
10 (a) and (b) indicates the linear regression coefficients for the mass-weighted, vertically
11 integrated geopotential height field with the time series of the first and second modes,
12 respectively. The unit for the shading is m. The gradation of the shading changes every 10
13 m, but absolute values <5 m are ignored. The contours indicate 95% statistical confidence
14 based on t-tests.

15
16 Figure 5. The same as Figure 4, except for the EOF calculation only for the period of
17 1984–1994. (a) The black line at the bottom of the figure represents the first mode; (b) the
18 green line shows the second mode.

19
20 Figure 6. The same as Figure 4, except for the EOF calculation only for 1979–1983 and

1 1995–2003. The variances contributed by the EOF1 and the EOF2 are 38.9% and 17.9%,
2 respectively. (a) The black line at the bottom of the figure represents the first mode; (b) the
3 green line represents the second mode.

4
5 Figure 7. The SIC anomaly field linearly regressed on the standardized PSA index (PC1
6 scores) of 1984–1994. (a) Simultaneous regressed pattern (1984–1994), (b) 1-year-lagged
7 regressed pattern (1985–1995), and (c) 2-year-lagged regressed pattern (1986–1996).
8 Gradation of light, moderate, and heavy cold (warm) color shading indicates positive
9 (negative) correlations that respectively exceed 90%, 95%, and 99% statistical
10 significance based on *t*-tests. A positive correlation signifies heavier sea-ice than normal.
11 Contours indicate regression coefficients. The unit of the regression coefficient is %.

12
13 Figure 8. The same as Figure 7, except for (top) the horizontal temperature advection field
14 at 925 hPa, (middle) the curl τ field, and (bottom) the SST anomaly field. The warm color
15 indicates favorable conditions for reductions in sea-ice. The units of the regressions at the
16 top, middle, and bottom are, respectively, 10^6 K s^{-1} , 10^9 N m^{-3} , and K.

17
18 Figure 9. (top) Hovmöller diagram of JASO mean SIC anomalies averaged from 55° S to
19 70° S around the Antarctic for 1979–2003 (unit is %). (bottom) The meridional mean SIC
20 anomaly averaged from 55° S to 70° S linearly regressed on the standardized ATM-EOF2

index (PC2 scores) of 1979–2003. (black line) Simultaneous regressed SIC with respect to the longitude (1979–2003), (green line) 1-year-lagged regressed SIC (1980–2002), and (yellow line) 2-year-lagged regressed SIC (1981–2001). Blue dot-dash lines in the bottom figure indicate, respectively, 90%, 95%, and 99% statistical significance based on t-tests.

Figure 10. Variances of the time series of atmospheric EOFs on each 11 years between 1958 and 2007. ATM-EOF1 (AAO) and ATM-EOF2 (PSA) denote the variances of the first and second modes of the atmospheric EOF in the period from 1958 through 2007, respectively.

Table 1.

Index	1984-1994	1979-1983 and 1995-2003
ATM-EOF1	0.553	1.363
ATM-EOF2	1.311	0.914

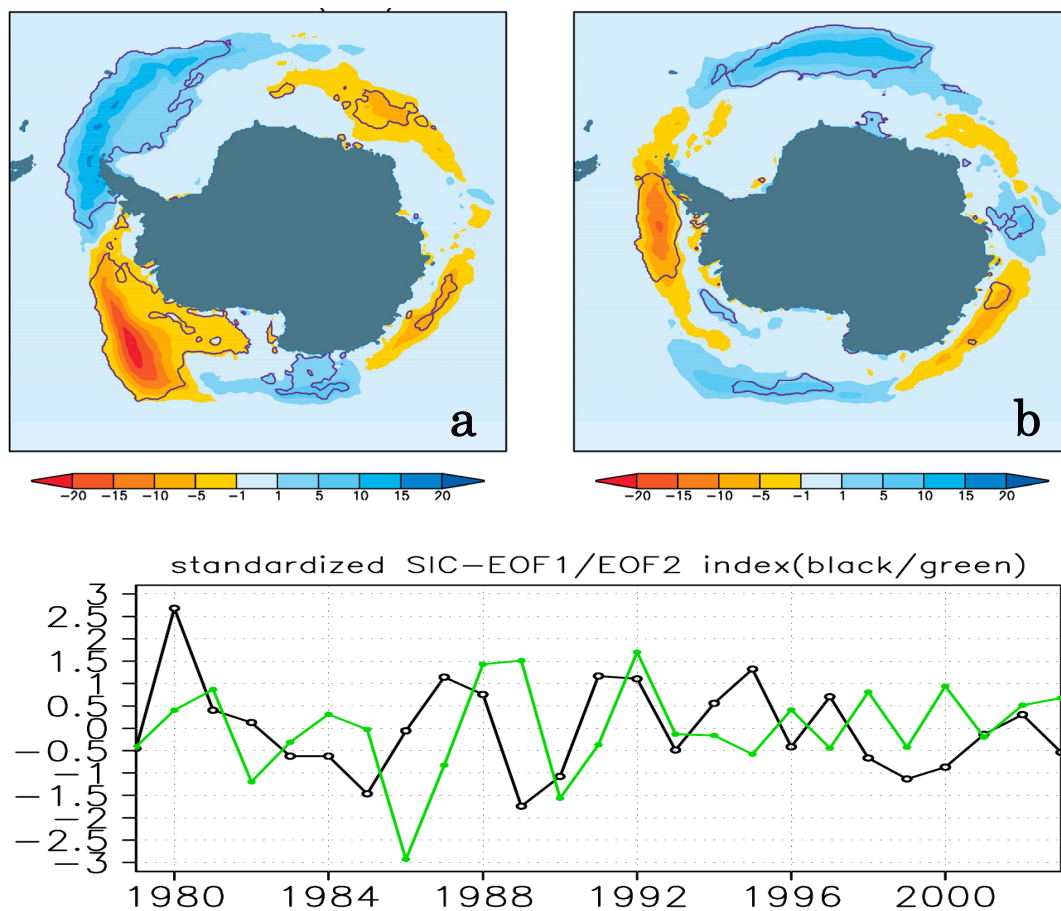


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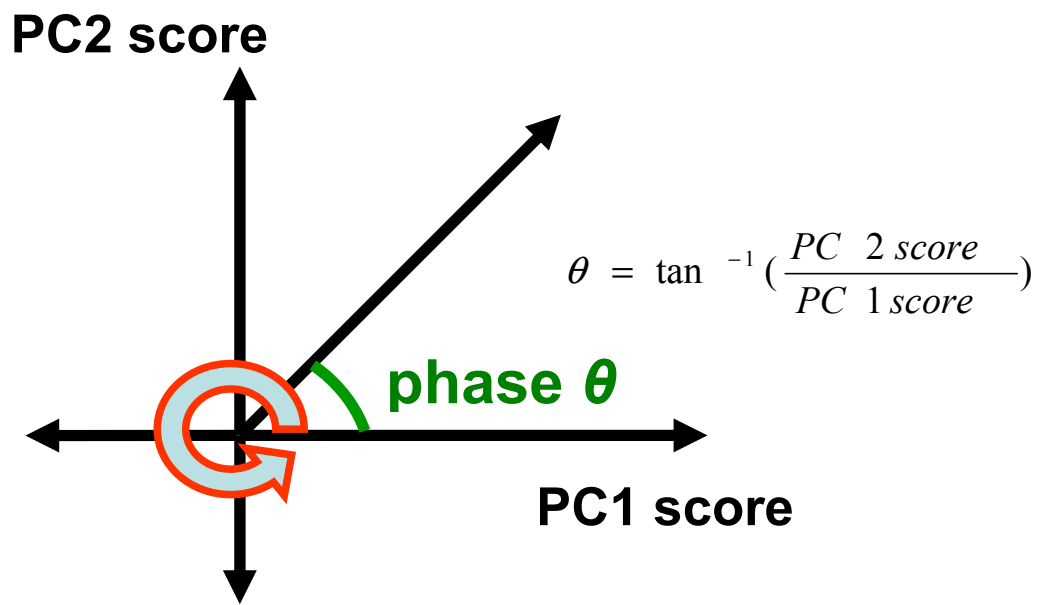


Figure 2 .

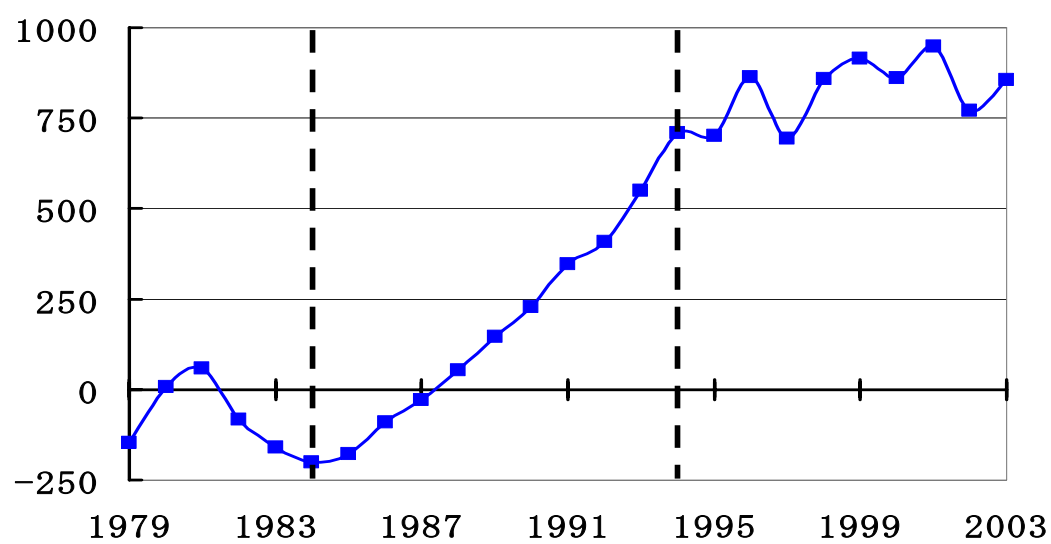


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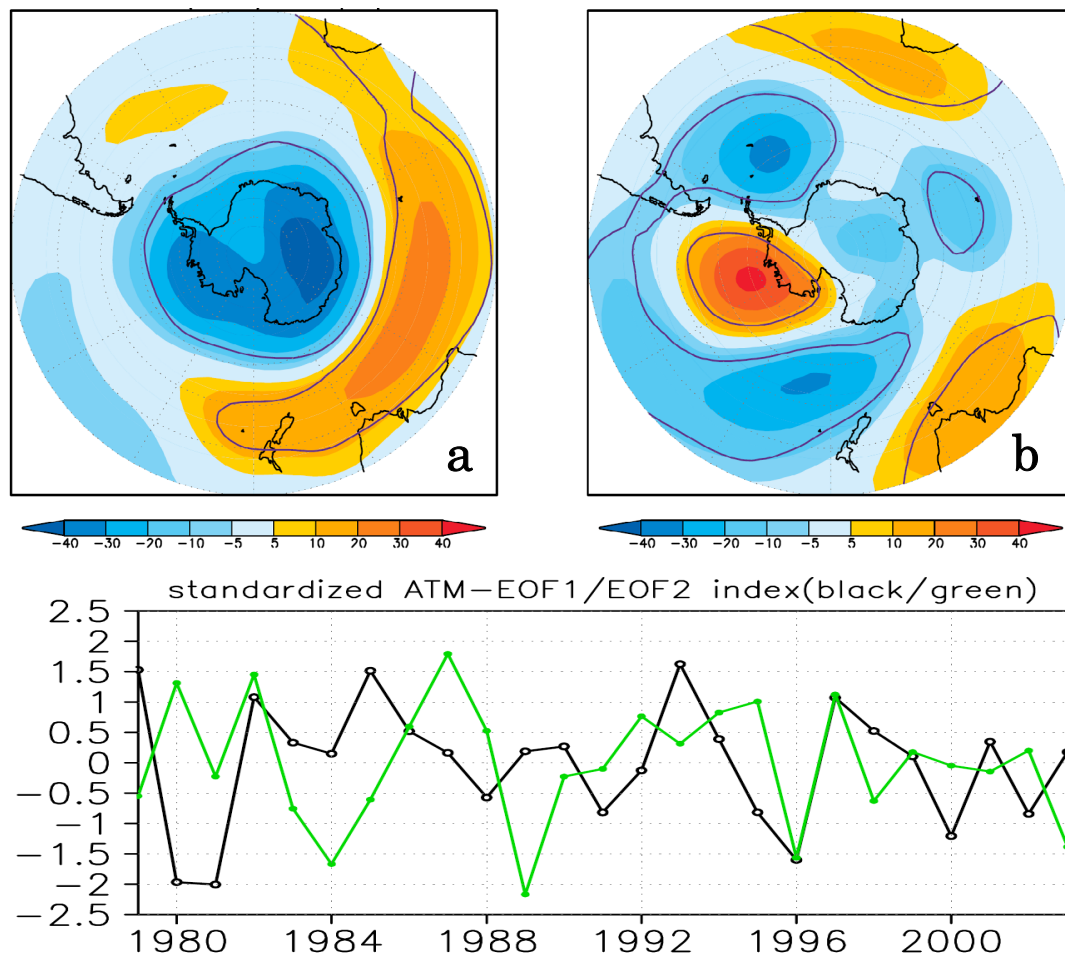


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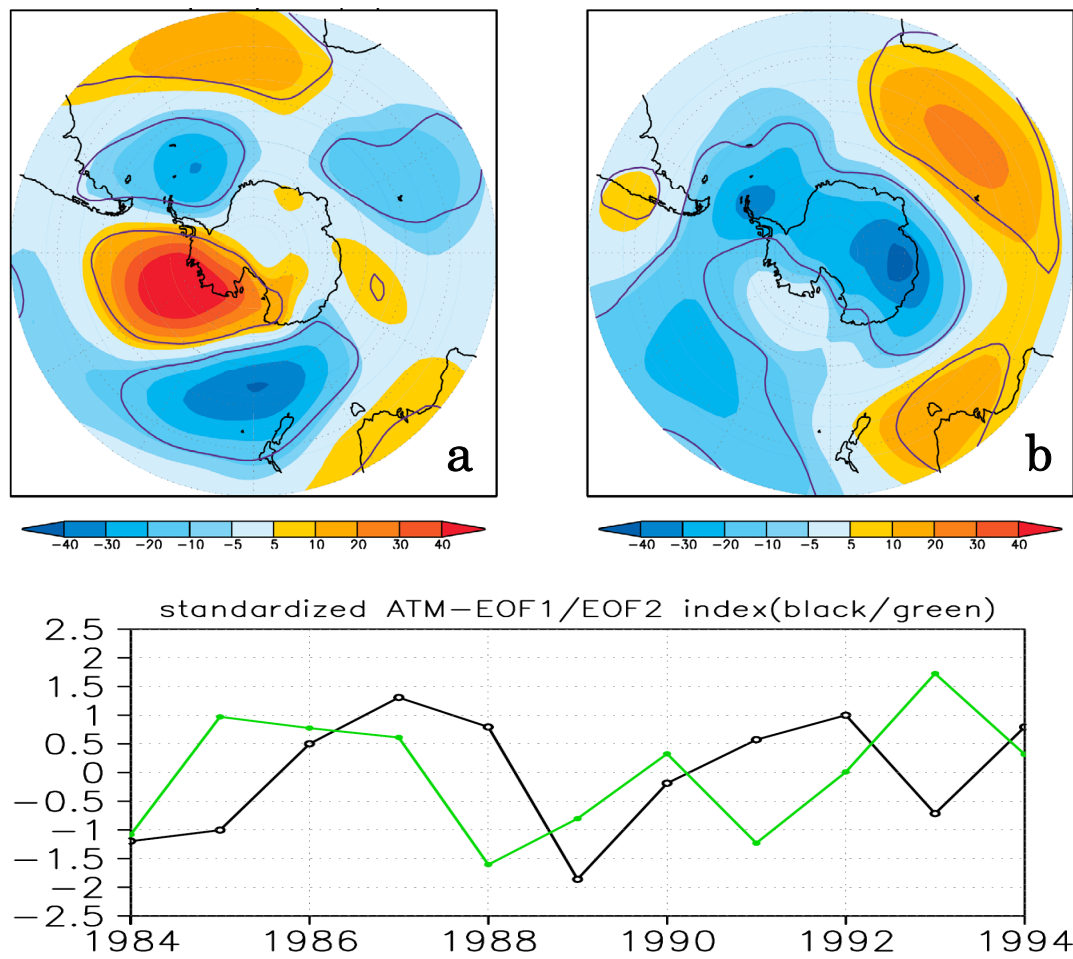


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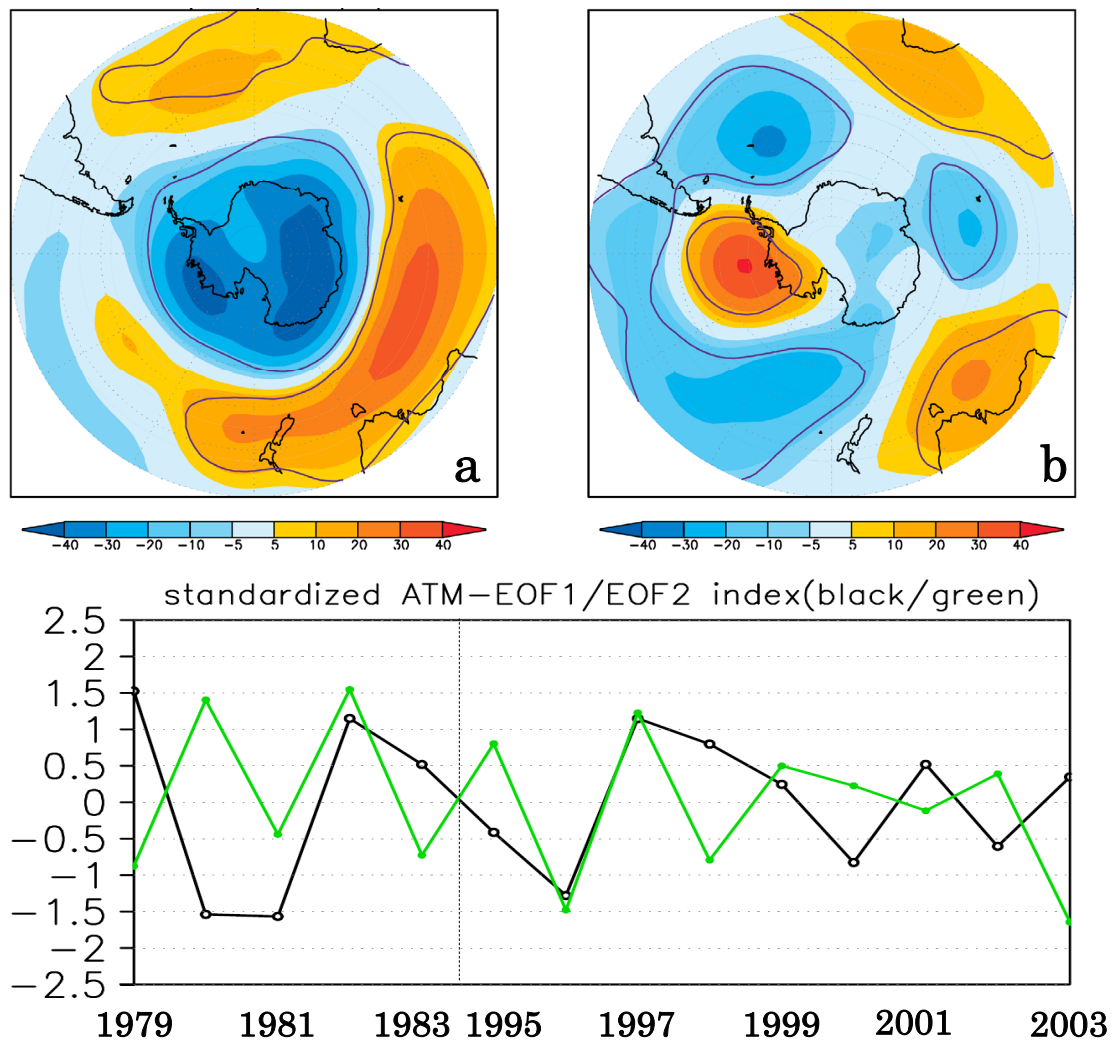


Figure 6.

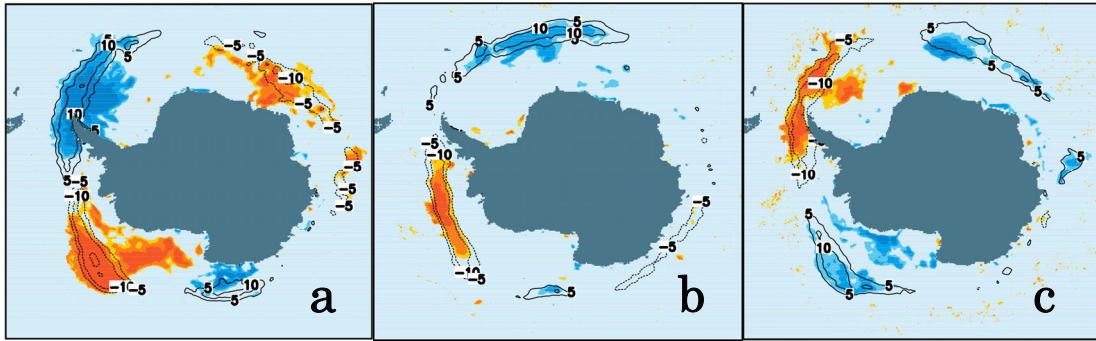


Figure 7.

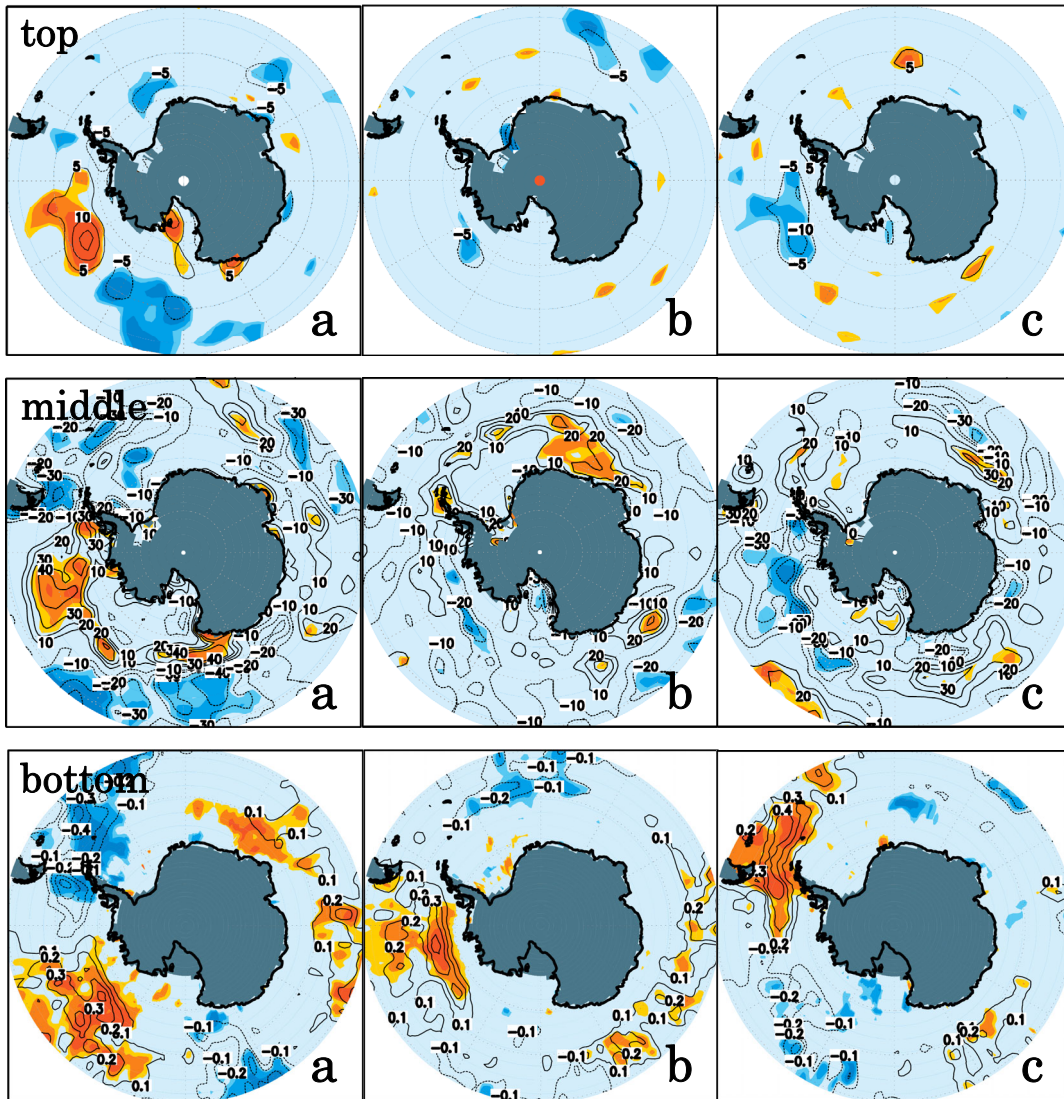


Figure 8.

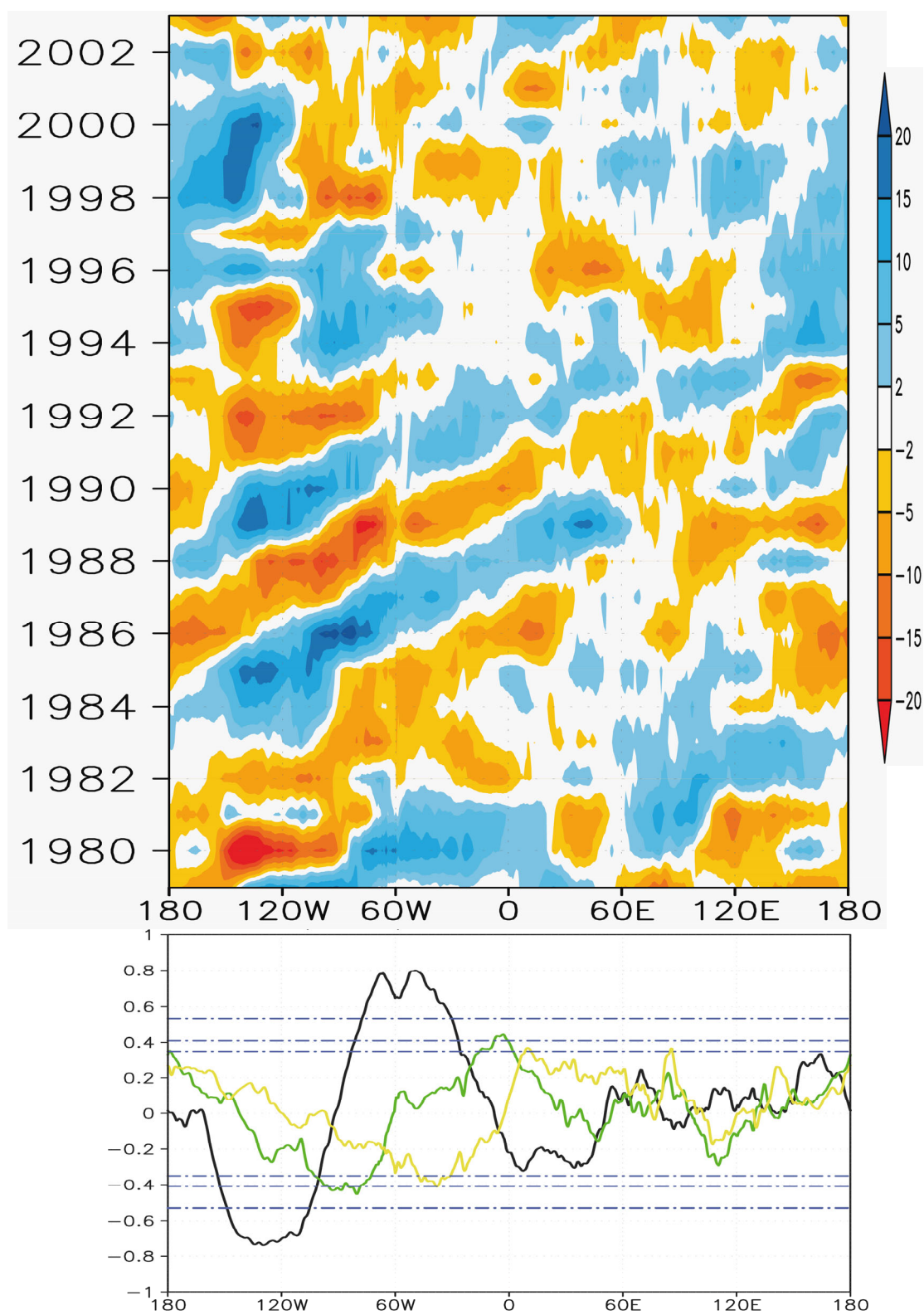


Figure 9.

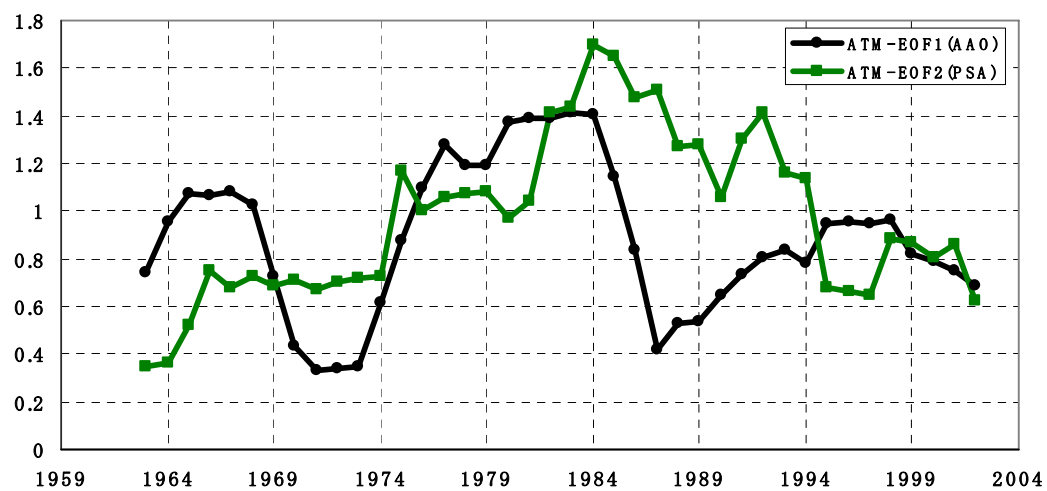


Figure 10.