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ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms

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Abstract: Many remote and local climate variabilities influence Antarctic sea ice at different time scales. The strongest sea ice teleconnection at the interannual time scale was found between El Niño–Southern Oscillation (ENSO) events and a high latitude climate mode named the Antarctic Dipole. The Antarctic Dipole is characterized by an out-of-phase relationship between sea ice and surface temperature anomalies in the South Pacific and South Atlantic, manifesting itself and persisting 3–4 seasons after being triggered by the ENSO forcing. This study examines the life cycles of ENSO warm and cold events in the tropics and associated evolution of the ADP in high latitudes of the Southern Hemisphere. In evaluating the mechanisms that form the ADP, the study suggests a synthesized scheme that links these high latitude processes with ENSO teleconnection in both the Pacific and Atlantic basins. The synthesized scheme suggests that the two main mechanisms responsible for the formation/maintenance of the Antarctic Dipole are the heat flux due to the mean meridional circulation of the regional Ferrel Cell and regional anomalous circulation generated by stationary eddies. The changes in the Hadley Cell, the jet stream in the subtropics, and the Rossby Wave train associated with ENSO link the tropical forcing to these high latitude processes. Moreover, these two mechanisms operate in phase and are comparable in magnitude. The positive feedback between the jet stream and stationary eddies in the atmosphere, the positive feedback within the air-sea-ice system, and the seasonality all reinforce the anomalies, resulting in persistent Antarctic Dipole anomalies.

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Key words: heat flux, jet stream, meridional circulation, Rossby Wave, the Southern Hemisphere, teleconnection

Introduction

The cryosphere in the Southern Ocean is an active component in global climate. It is also influenced by the many local, regional and remote climate variabilities at periods ranging from synoptic to geological timescales. Since satellite observations became available in the 1970s, many studies have investigated the interannual variability of sea ice and its covariation with global climate. A number of such studies suggested that the Antarctic sea ice fields linearly co-vary with the El Niño/Southern Oscillation (ENSO) phenomenon in the tropical Pacific (Chiu 1983, Carleton 1989, Simmonds & Jacka 1995, White & Peterson 1996, Yuan *et al*. 1996, Smith *et al*. 1996, Ledley & Huang 1997, Carleton *et al*. 1998, Yuan & Martinson 2000, 2001, Harangozo 2000, Kwok & Comiso 2002, Martinson & Iannuzzi 2003). These ENSO related sea ice variabilities mainly occurred in key regions, such as the Ross, Bellingshausen and Weddell seas, as well as the Southern Indian Ocean. Due to the limitation of the sea ice time series, some of the earlier studies were not able to evaluate the significance of the relationship or found that the relationship was insignificant. But with the accumulation of the sea ice time series, the sea ice/ENSO teleconnection has been found to be statistically significant in more recent studies, such as in Simmonds & Jacka (1995), Yuan & Martinson (2000) and Martinson & Iannuzzi (2003).

In addition to the ENSO variability, Antarctic sea ice was also linked to some other preferred climate patterns. Yuan & Martinson (2000) found that the sea ice is linked to an out-of-phase temperature pattern between the Drake Passage and the central tropical Pacific. The sea ice also has some statistically significant relationships with other extra-polar climate indices, such as the tropical Indian Ocean sea surface temperature (SST), the tropical land precipitation and the Pacific North America (PNA) index. Still, the ENSO teleconnection stands out as the most significant link of Antarctic sea ice with extra-polar climate variability.

Although ENSO influences have been found in sea ice of many regions around the Antarctic, only recent studies have identified the ENSO signal in Antarctic sea ice with remarkable temporal and spatial coherency. Two high latitude climate modes in southern subpolar regions were suggested linking to the ENSO variability in the tropics. White & Peterson (1996) reported that the sea ice anomaly, as well as anomalies in sea surface temperature, pressure and wind fields, propagate eastwards in a coherent pattern at ENSO time scales, referred to as the "Antarctic Circumpolar Wave". But, in the western hemisphere of the Antarctic, Yuan & Martinson (2000, 2001) found that a quasi-stationary wave in sea ice, SST, and SAT is strongly linked to the ENSO variability and also dominates the interannual variability of the sea ice field. This stationary wave was named the Antarctic Dipole (ADP).

Many aspects of extra-tropical atmospheric circulation change in response to ENSO forcing (see recent reviews by Carleton 2003 and Turner 2004). These changes are responsible for transporting the ENSO signal to mid-high latitudes. A number of studies (Karoly 1989, Mo & Higgins 1998, Kiladis & Mo 1998, Garreaud & Battisti 1999) have attributed the ENSO-polar teleconnection to the stationary Rossby Wave that propagates the tropical signal to southern high latitudes. The Rossby Wave train usually responds to the change of the tropical convection due to anomalous heating (Mo & Higgins 1998). This wave train is one predominant circulation pattern in the Southern Hemisphere (Kidson 1999), which forms the Pacific and South America (PSA) pattern (Mo & Higgins 1998), the counterpart of the PNA pattern in the Northern Hemisphere. In response to the warm ENSO events, the PSA pattern consists of a low-pressure centre east of New Zealand, a high pressure centre in the subpolar region of the south-east Pacific, and another low pressure centre over South America and the South Atlantic (Karoly 1989).

In association with the PSA and the Rossby Wave, blocking highs present another circulation characteristic in the south-east Pacific influenced by ENSO cycles (Rutllant & Fuenzalida 1991, Renwick 1998, Renwick & Revell 1999). The blocking events, usually identified by persistent anomalous high-pressure centres that interrupt the mean zonal flow, frequently occur in both the south-west Pacific and the south-east Pacific (Sinclair 1996). In the south-east Pacific, the blocking highs occur near the high-pressure centre of the PSA aforementioned during ENSO warm events. By contrast, low-pressure centres occur more frequently in the south-east Pacific in response to the ENSO cold events, as shown in Kiladis & Mo (1998).

The presence of a split jet stream during winter is a distinct climate feature in the South Pacific. The jet stream in the upper-level flow near Australia and New Zealand splits into the subtropical jet (STJ) centred near 25°S and polar front jet (PFJ) centred around 60°S. Although the locations of the STJ and PFJ do not change much, the strength of these jets change in response to ENSO cycles (Karoly 1989, Kitoh 1994, Chen *et al*. 1996, Bals-Elisholz *et al.* 2001). Furthermore, in a case study on a complete warm-to-cold ENSO cycle from 1986–89, Chen *et al.* (1996) revealed that the strong STJ and weak PFJ in the South Pacific are associated with the warm phase of the ENSO, while the weak STJ and strong PFJ are associated with the cold phase of the ENSO. As a consequence of the changes in the jet streams and storm tracks, changes in the distribution of cyclones and mesoscale weather systems are expected. Indeed, ENSO signals have been observed in the transient eddy activity in the Southern Ocean (Carleton & Carpenter 1990, Carleton & Fitch 1993, Sinclair *et al*. 1997, and Carleton & Song 2000).

By revealing the life cycles of ENSO warm and cold events in the tropics and the associated evolution of the ADP in high latitudes of the Southern Hemisphere, this study evaluates the mechanisms that form the ADP anomalies, and provides synthesized mechanisms that link these high latitude processes with ENSO teleconnection mechanisms in both the South Pacific and South Atlantic.

Data and process

This study used satellite-observed sea ice concentrations (SIC) from 1978 to 2002, provided by the National Snow and Ice Center. These remote passive microwave measurements of polar sea ice taken over more than twenty years provide observations of sea ice concentrations with a typical spatial resolution of 25 km and near daily temporal resolution, enabling us to study sea ice variabilities from synoptic to decadal time scales. This study used approximately 24 years of monthly sea ice concentration data derived from observed brightness temperatures by the bootstrap algorithm (Comiso 1999).

To investigate teleconnections between Antarctic sea ice and global climate, several variables from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay *et al*. 1996, Kistler, *et al*. 2001) were used, which include monthly SAT at 1000 mb, sea level pressure (SLP), vector winds at 10 m height, temperature and meridional winds at all pressure levels, and zonal wind at 300 mb. All of these variables except vector winds at 10 m are in class A of the reanalysis output, indicating that the variables are most strongly influenced by observation with minimal model impact. Vector winds at 10 m are classified into class B, indicating that the variable is strongly influenced by the model even though observational data exist. Besides inadequate observations input into the reanalysis in the Southern Ocean, a few known problems and errors exist in the NCEP/NCAR reanalysis, as discussed in Kistler *et al*. (2001). Among them, the PAOBs error has the most impact on the Southern Ocean assimilation. PAOBs are estimates of the SLP produced by the Australian Bureau of Meteorology. NCEP/NCAR reanalysis unfortunately shifted 180° of longitude in the use of the data for 1979–92. The problem is significant on a synoptic scale but becomes small in monthly mean fields (Kistler *et al*. 2001). Based on the comparison of results from different datasets including the Jones monthly near-surface temperature anomaly (Jones 1994, Parker *et al*. 1994, 1995) and the NASA Goddard Institute for Space Studies global surface air temperature anomaly data (Hansen & Lebedeff 1987, Reynolds & Smith 1994), Yuan & Martinson (2000) concluded that the NCEP/NCAR reanalysis monthly data in the Southern Hemisphere are reliable for the purpose of studying interannual variability and polar-extrapolar teleconnection.

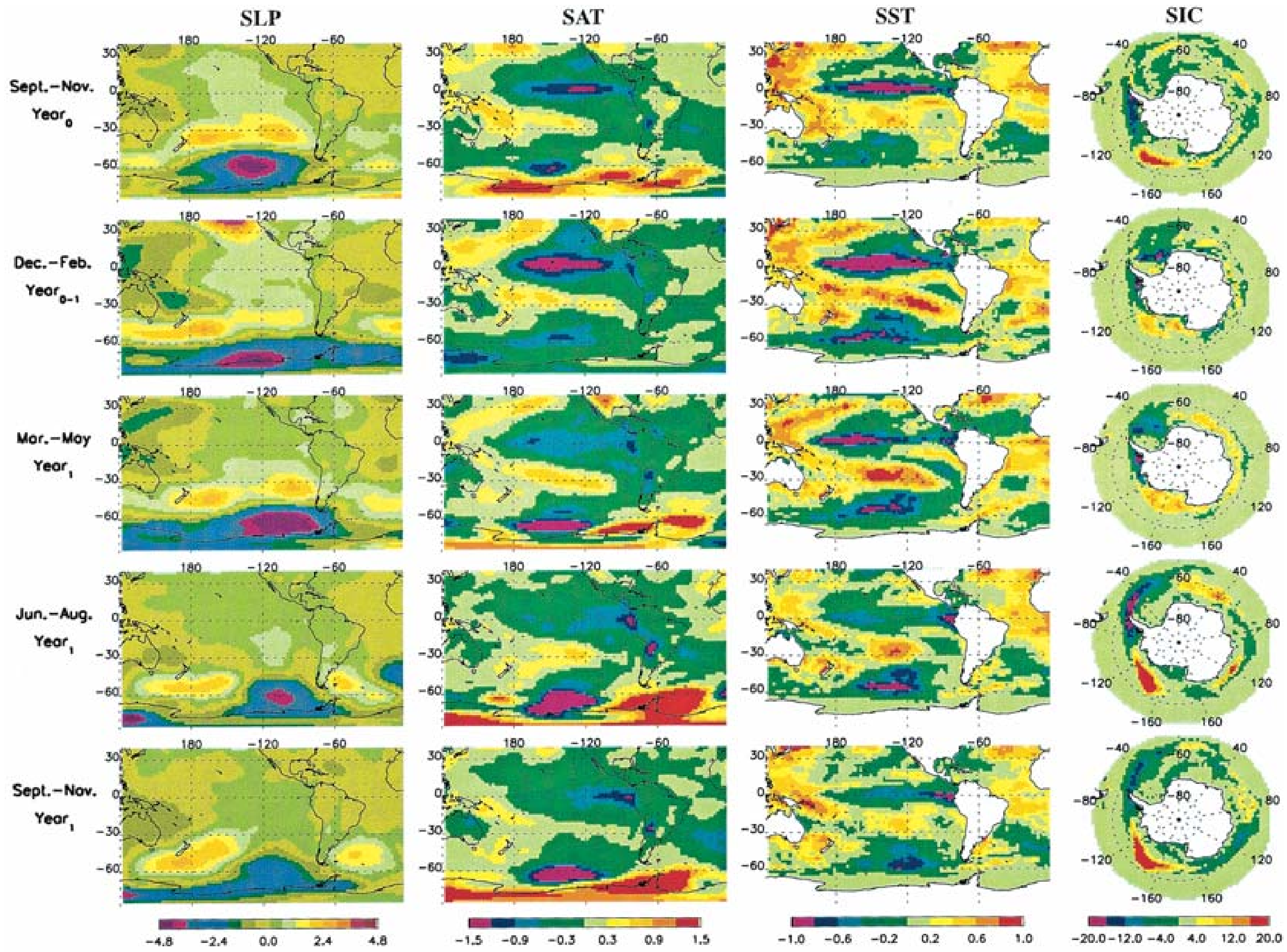

Fig. 1. Seasonal composites of SLP (mb), SAT (°C), SST (°C) and SIC (%) anomalies for five La Niña events (between 1984 and 2000) sequencing from the spring before the events matured to the spring after the events matured.

In addition, for the current study, monthly Reynolds & Smith (1994) SST anomalies from 1981–2003 were also used. These data were blended from ship, buoy and bias-corrected satellite data. Based on the Niño3.4 index from NCEP, five El Niño events (1982–83, 1986–87, 1987–88, 1991–92, 1997–98) and five La Niña events (1984–85, 1988–89, 1995–96, 1998–99, 1999–2000) were selected for composite analyses in the study. Some events may be different if Niño3 index is used.

The ENSO cycle and evolution of the Antarctic Dipole

The Antarctic Dipole (ADP) is a high-latitude climate variability in the air-sea-ice system that responds strongly to the ENSO forcing (Yuan & Martinson 2000, 2001, Renwick 2002, Kidson & Renwick 2002). Warm ENSO events usually generate positive (warm) temperature anomalies and negative (reduced) sea ice anomalies in the Pacific centre of the ADP, but generate an opposite response in the Atlantic centre of the ADP. By contrast, cold ENSO events are associated with colder temperatures and expanded sea ice in the Pacific centre of the dipole but with warmer temperatures and less sea ice in the Atlantic centre of the dipole. To examine the extent of the ENSO impact in global temperature fields, Liu *et al*. (2002) constructed the difference between the El Niño annual SAT composite and the La Niña annual SAT composite. The difference revealed that temperature anomalies in the ADP region are the largest ENSO anomalies outside of the tropical Pacific. It was concluded that the ADP is the ENSO footprint at southern high latitudes. However, high latitude processes significantly modulate this ENSO anomaly. The ADP has its own high latitude characteristics in space and time.

To investigate this tropical and polar teleconnection, the temporal evolution of ENSO events and associated development of ADP anomalies are examined by composites of SLP, SAT, SST and SIC anomalies. Figure 1 displays the seasonal evolution of La Niña events (illustrated by La Niña composites in respective fields) starting from the boreal autumn when a cold SST anomaly

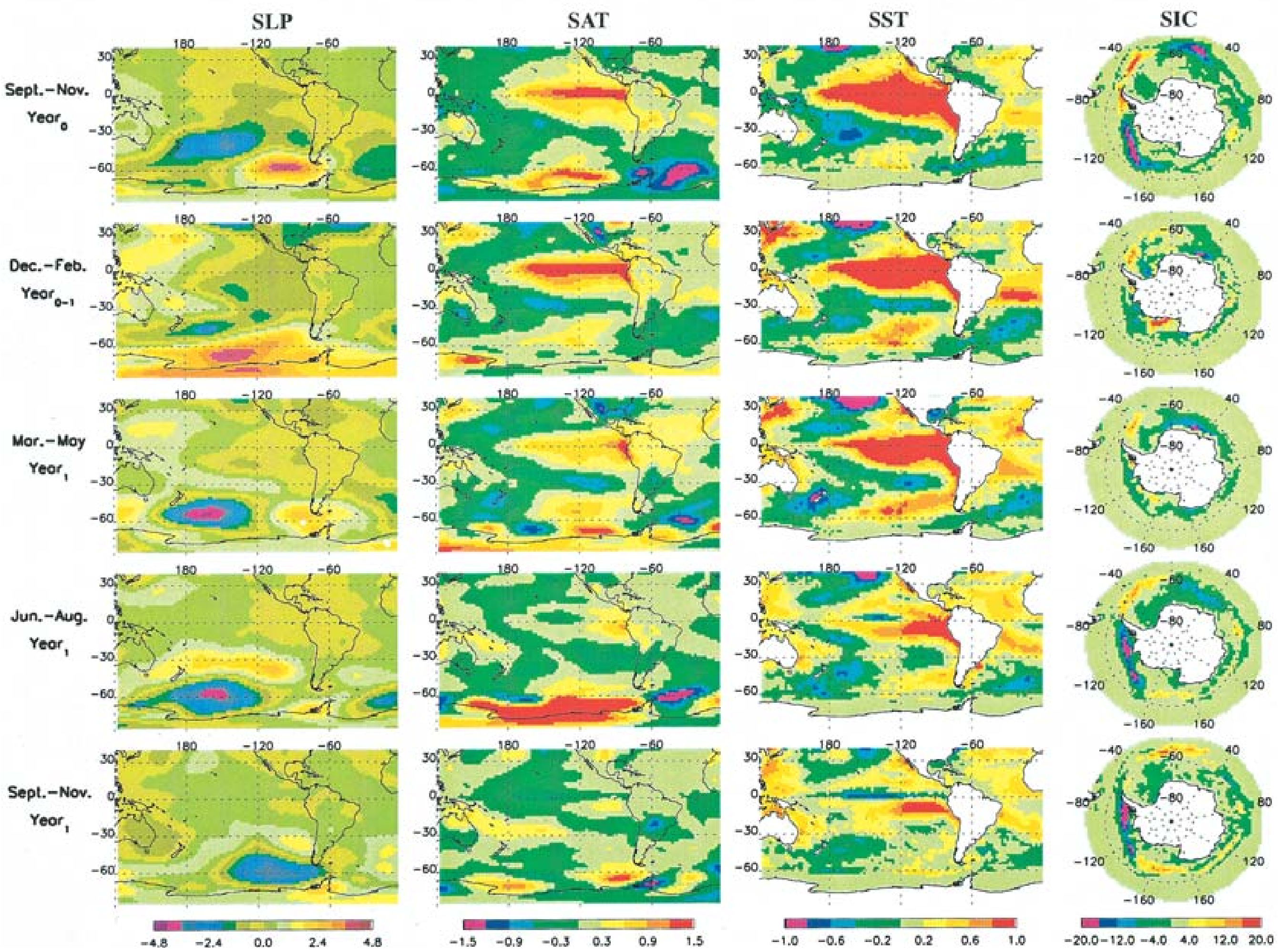

Fig. 2. Same as Fig. 2, except for El Niño composites.

has built up in the tropical Pacific. The Southern Ocean SST and ice field have not yet responded clearly to the forcing in a coherent pattern, although a low SLP centre develops in the Amundsen Sea. During the next season (December of year$_0$ to February of year$_1$), the cold events mature with large SAT and SST cold anomalies in the tropical Pacific. In the Southern Ocean, the low SLP centre moves eastward, while negative SAT/SST anomalies in the South Pacific and positive SAT/SST anomalies in the Weddell Sea start to become established. Sea ice cover is at its minimum in this austral summer season, though a weak positive anomaly east of the Ross Sea and a weak negative anomaly in the Weddell Sea already exist in the SIC field. In the following three seasons, the low SLP centre (that is a part of PSA pattern) establishes in the eastern South Pacific and persists. In the meantime, the ADP anomalies in the SAT, SST and SIC fields are fully developed, amplified and persist while the La Niña SST anomaly in the tropics is attenuated. The strongest anomalies in temperature and ice fields occur in the winter.

The evolution of the ADP during El Niño events is quite similar to that of La Niña events, but with opposite phase anomalies. The high-pressure centre in the Bellingshausen Sea established during warm events persists only two seasons after an El Niño matures at the tropics as opposed to three seasons in the La Niña phase. The high-pressure centre is weakened from autumn to winter after warm ENSO events, consistent with the finding of Garreaud & Battisti (1999). However, ADP anomalies in temperature and ice composite fields are still amplified and persist three seasons after warm events mature in the composite analysis (Fig. 2).

The evolution of the PSA centre in the south-east Pacific and development of ADP anomalies in temperature and sea ice fields presented in Figs 1 & 2 are consistent with the sequencing in the lagged correlation analysis presented by Kidson & Renwick (2002). The correlation analysis, however, produces smoother development while the composite analysis in this study reflects year to year variability in each season, producing less smooth development.

The development of ADP anomalies is different in ENSO

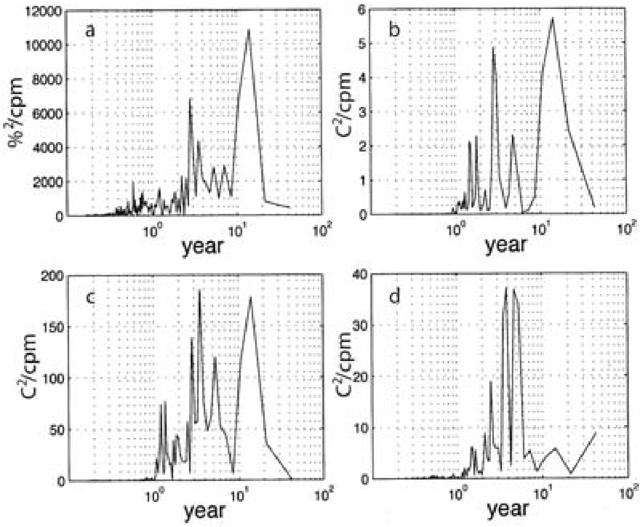

Fig. 3. Power spectra of **a.** DPI$_{ice}$, **b.** DPI$_{SAT}$, **c.** DPI$_{SST}$, and **d.** Niño3 index.

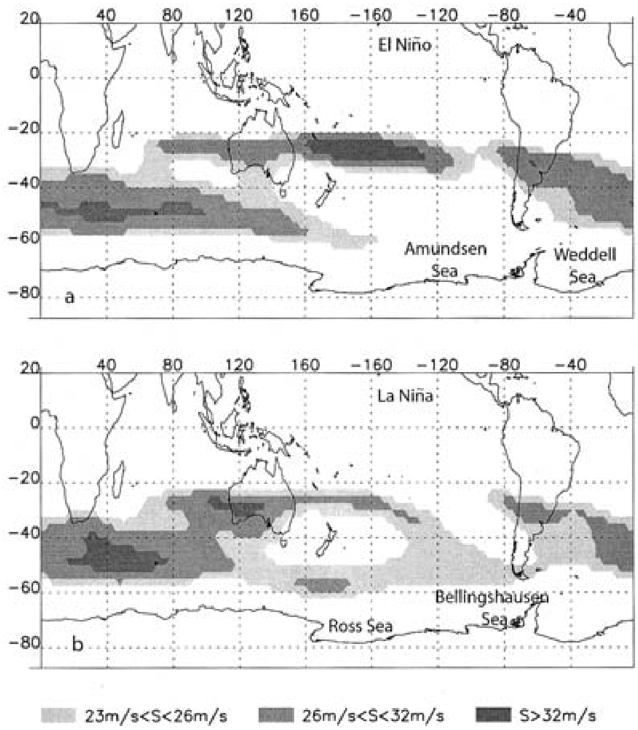

Fig. 4. a. El Niño composite, and **b.** La Niña composite of zonal winds (m s^{-1}) at 300 mb for the season of September to November.

warm and cold events in two ways. First, dipole temperature anomalies have a smoother temporal development and persist longer in the case of La Niña than in the case of El Niño, because El Niño has a larger variability in high latitude responses from event to event. Second, during spring (September, October and November) when El Niño is developing, the blocking high is quickly established in the south-east Pacific (Renwick & Revell 1999, 2000) and generates warm phase ADP anomalies in temperature and sea ice, as shown in Fig. 2. The cold phase ADP anomalies in SST and sea ice, however, are not established until summer due to large variability in all fields in this beginning phase of the development of cold ADP anomalies.

The ADP is not just a reflection of the ENSO variation at high latitudes. Apparently, the ENSO anomaly in the tropics changes the atmospheric circulation and starts to affect pressure and temperature fields at southern high latitudes in austral summer. As the Southern Hemisphere approaches austral winter, the ENSO anomaly in the air-sea-ice coupled system grows and persists, likely caused by a positive feedback among the atmosphere, ocean and cryosphere. Thus, the ADP evolves and develops its high latitude characteristics in the air-sea-ice coupled system after the tropical forcing is reduced.

ADP indices were constructed to examine their temporal variability in frequency domain. The SIC index (DPI$_{ice}$), SAT index (DPI$_{SAT}$) and SST index (DPI$_{SST}$) for the ADP were calculated by subtracting the mean monthly SIC, SAT and SST anomalies averaged in the Atlantic centre (40–60°W, 60–70°S) from those in the Pacific centre (130–150°W, 60–70°S), respectively. These three ADP indices were calculated from independent data sources. The power spectra of the Niño3 index of tropical SST and ADP indices reveal different characteristics of ENSO signals in the tropics and high latitudes (Fig. 3). In general, all three ADP indices have a strong variability near three year period. The DPI$_{SAT}$ also peaks at the four and five year periods, while the DPI$_{ice}$ has large interannual variance in the four year period too. The consistency of energy peaks in the interannual frequency band of the 3–5 year periods from all three sources suggests that those peaks probably represent the reality. On the other hand, the power spectrum of Niño3 has strong peaks in four and five years periods and a relatively weaker peak at the 2.5 year period. Apparently, ENSO and ADP closely share interannual variance in periods from 3–5 year, although they do not mirror each other exactly.

Synthesis of ENSO-ADP observations

In order to provide a synthesis of ENSO-ADP teleconnection phenomenon, we need to examine further the response of the jet stream to ENSO events in the context of teleconnection. Here I expand the analysis in Chen *et al.* (1996) by including the entire Southern Ocean, five ENSO warm events and five cold events and conducting a composite analysis (Fig. 4). During the warm ENSO phase, we see the strong STJ centred near 25°S between 160°E and 120°W extends across the South Pacific to South America. This STJ turns southward in the South Atlantic and becomes a single jet stream there. Tracking the PFJ we see it is very strong in the South Indian Ocean but becomes quite weak in

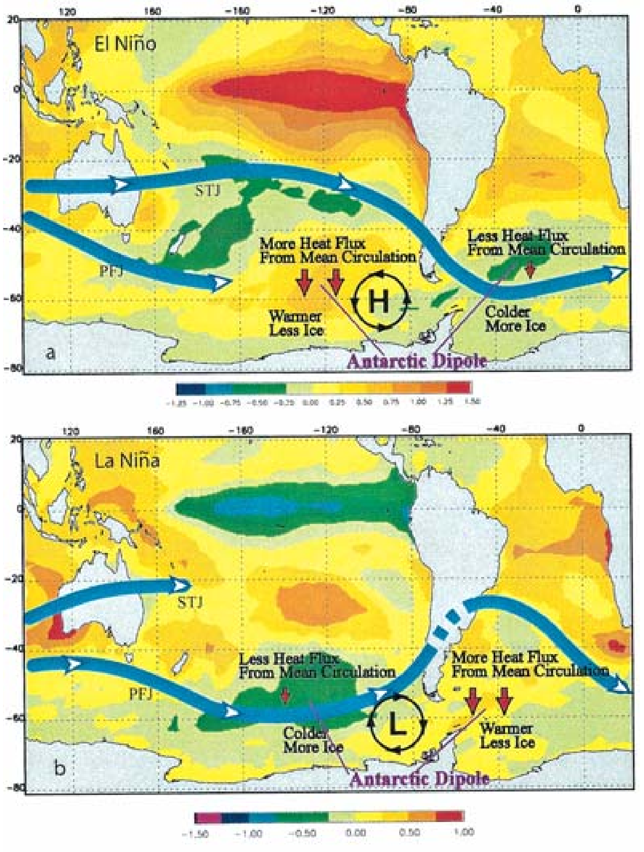

Fig. 5. SST anomaly composites (°C) for **a.** the El Niño condition, and **b.** La Niña condition. The composites were the results of averaging SST from May before ENSO events matured to the following April, and over five El Niño events and five La Niña events, respectively. Schematic jet stream (STJ and PFJ), persistent anomalous high and low pressure centres, and anomalous heat fluxes due to mean meridional circulations are marked in corresponding SST composites.

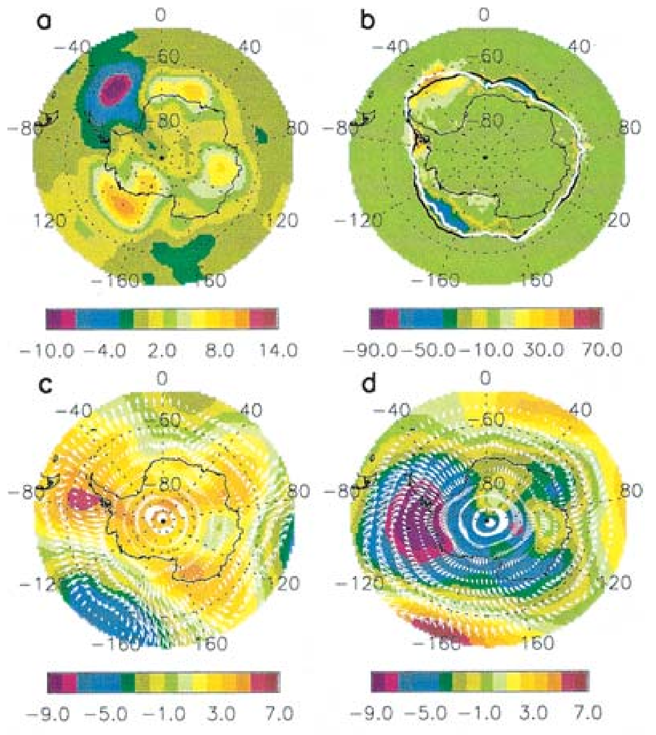

Fig. 6. a. Differences between El Niño composite and La Niña composite in the SAT anomaly, **b.** sea ice concentration and ice edge anomalies in May after ENSO events matured at the tropics. The white (black) line represents ice edge composite for the warm (cold) ENSO events. The **c.** El Niño composites, and **d.** La Niña composites of the SLP and surface wind anomalies are plotted for the same month.

the South Pacific. The split jet then ends in South America. During the cold ENSO phase, the PFJ is greatly enhanced in the South Pacific and extends all the way across the tip of South America, where it joins the single jet stream in the South Atlantic. The STJ in the South Pacific is much weaker, turning southward and joining the PFJ in the south-eastern Pacific. The result confirms the finding from the modelling study by Rind *et al.* (2001), in which they found that the storm track shifts equatorward in the South Pacific and poleward in the South Atlantic in response to ENSO warm events. Importantly, even though the double-jets are not profound in the south-eastern Pacific, the location and structure of the jet there varies significantly from the El Niño condition to the La Niña condition.

Before addressing the mechanisms of the ENSO-ADP teleconnection, I would like to synthesize what we have learnt about this phenomenon. Figure 5 summarizes the current knowledge about the ENSO in the tropics, the ADP mode at southern high latitudes and the associated atmospheric circulation patterns from an observational point of view. For ENSO warm events, higher temperatures and less sea ice occur in the Pacific centre of the Dipole while colder temperatures and more sea ice occur in the Atlantic centre of the Dipole simultaneously. The spinning up of the Weddell Gyre was shown by Martinson & Iannuzzi (2003) to be a consequence of this ENSO impact. A persistent high-pressure centre exists in the Bellingshausen Sea accompanying Dipole anomalies in temperature and ice fields for warm events. In the South Pacific, the subtropical jet is strengthened and the polar front jet is weakened. At the same time the strong jet stream swings poleward in the South Atlantic. In addition, poleward heat flux from the regional mean meridional circulation is strengthened in the South Pacific but weakened in the South Atlantic. The ADP anomalies and associated atmospheric circulation patterns for La Niña events are effectively mirror images of those for El Niño events.

Formation of the Antarctic Dipole

In general, the air-sea-ice system is highly coupled in the Southern Ocean. The ADP represents such a coupled

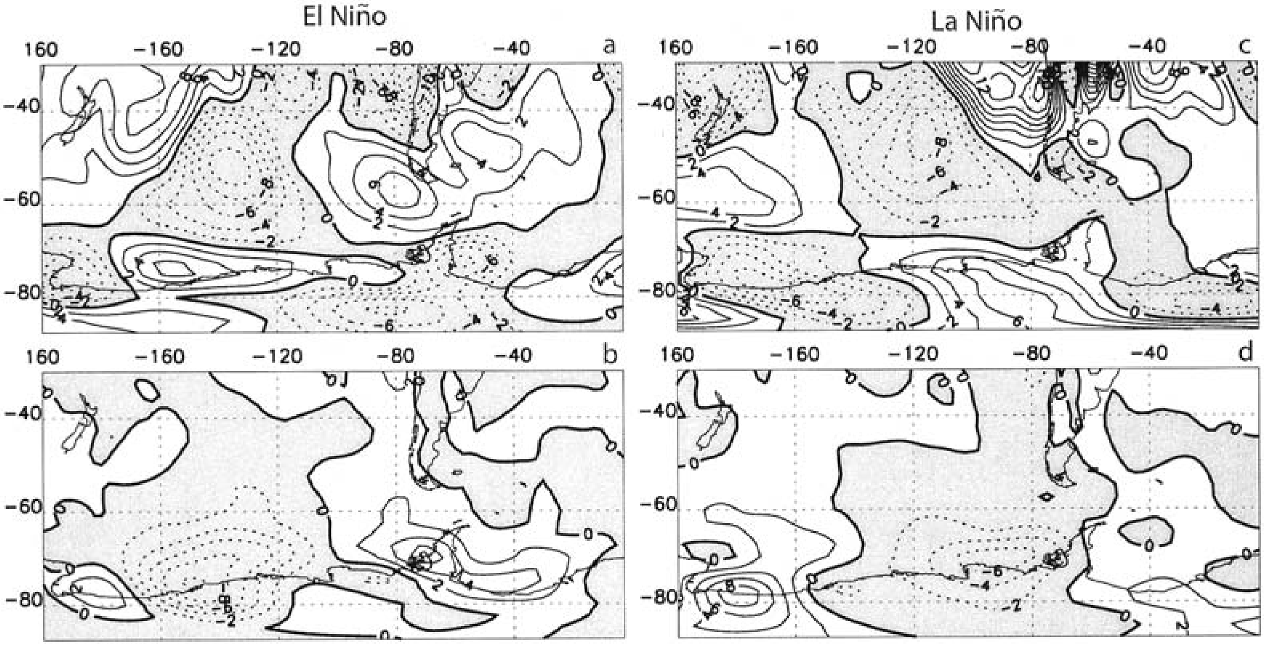

Fig. 7. El Niño and La Niña composites of heat flux anomalies at low-level atmosphere by the mean meridional circulation (a for El Niño, c for La Niña), and stationary eddies (b for El Niño, d for La Niña) in ºKms^{-1}. The heat fluxes were averaged from 1000 mb to 850 mb. Negative values are shaded and indicate polarward heat fluxes in the Southern Hemisphere.

climate mode, particularly at the ENSO time scale. To illustrate relationships between the atmosphere and cryosphere, monthly composites of SAT, SIC, ice edge, SLP and surface wind anomalies were constructed for warm and cold ENSO events, respectively. As an example, Fig. 6 shows the differences between El Niño composites and La Niña composites in temperature and sea ice fields in May after the ENSO matured in the tropics. The figure shows that the largest ENSO anomalies appear in the ADP region. Clearly SAT and ice fields synchronize responses to the ENSO. Notice that the main ENSO impact on sea ice concentration occurs near the ice edge. The corresponding SLP anomaly field is characterized by a high (low) anomaly pressure centre in the Bellingshausen Sea for the warm (cold) events. The prevailing high pressure centre during ENSO warm events brings warm air from lower latitudes to the polar region east of the Ross Sea and Amundsen Sea, and cold air from the Antarctic continent to the open ocean in the Weddell Sea, creating Dipole anomalies in these two regions simultaneously (Fig. 6c). The exact opposite situation occurs for ENSO cold events (Fig. 6d). The anomalous high and low pressure centres in Fig. 6c & d are part of the PSA pattern in response to ENSO warm and cold events, respectively. Such observed anomalies in SAT, SIC, SLP, and surface winds suggest a thermodynamic relationship between the atmosphere and cryosphere, and also show the relationship between the PSA in pressure field and the ADP in temperature and sea ice fields. This result is consistent with earlier studies (Kwok & Comiso 2002, Kidson & Renwick 2002, Renwick 2002).

In other research, correlations between the Niño3 index and mean meridional heat flux indicated that poleward heat flux has opposite anomalies in the South Pacific and South Atlantic basins (Liu *et al*. 2002). The research showed that the stronger regional Ferrel Cell in the Pacific and the weaker Ferrel Cell in the Atlantic in response to the ENSO warm events cause such heat flux distribution. Therefore we can say that the mean regional meridional circulation directly contributes to the formation of the ADP anomalies in temperature and sea ice. Although the eddy heat fluxes do not directly influence sea ice anomalies, their convergence in the subpolar region and divergence in the polar region strengthen the Ferrel Cell in the South Pacific, and vice versa for the South Atlantic (Liu *et al*. 2002).

To evaluate the relative importance of two mechanisms that form the ADP anomalies, I investigate meridional heat transports due to these two processes. The total atmospheric meridional heat transport (F_T) can be represented as:

$$F_T = <\overline{VT}> + <V^*T^*> + <V'T'> \qquad (1)$$

where the right-hand side terms represent the heat transport by the mean circulation, the stationary eddies (such as the Rossby wave train/PSA pattern) and transient eddies, respectively, and < > indicates the zonal mean (Peixoto & Oort 1992). Since the sea ice distribution seems unrelated to transient eddies (Simmonds 1996, Liu *et al* 2002), emphasis here is given to the heat transports induced by the mean meridional circulation and stationary eddies. The heat flux due to the mean meridional circulation $(\overline{VT})$ is calculated by monthly meridional wind and monthly temperature

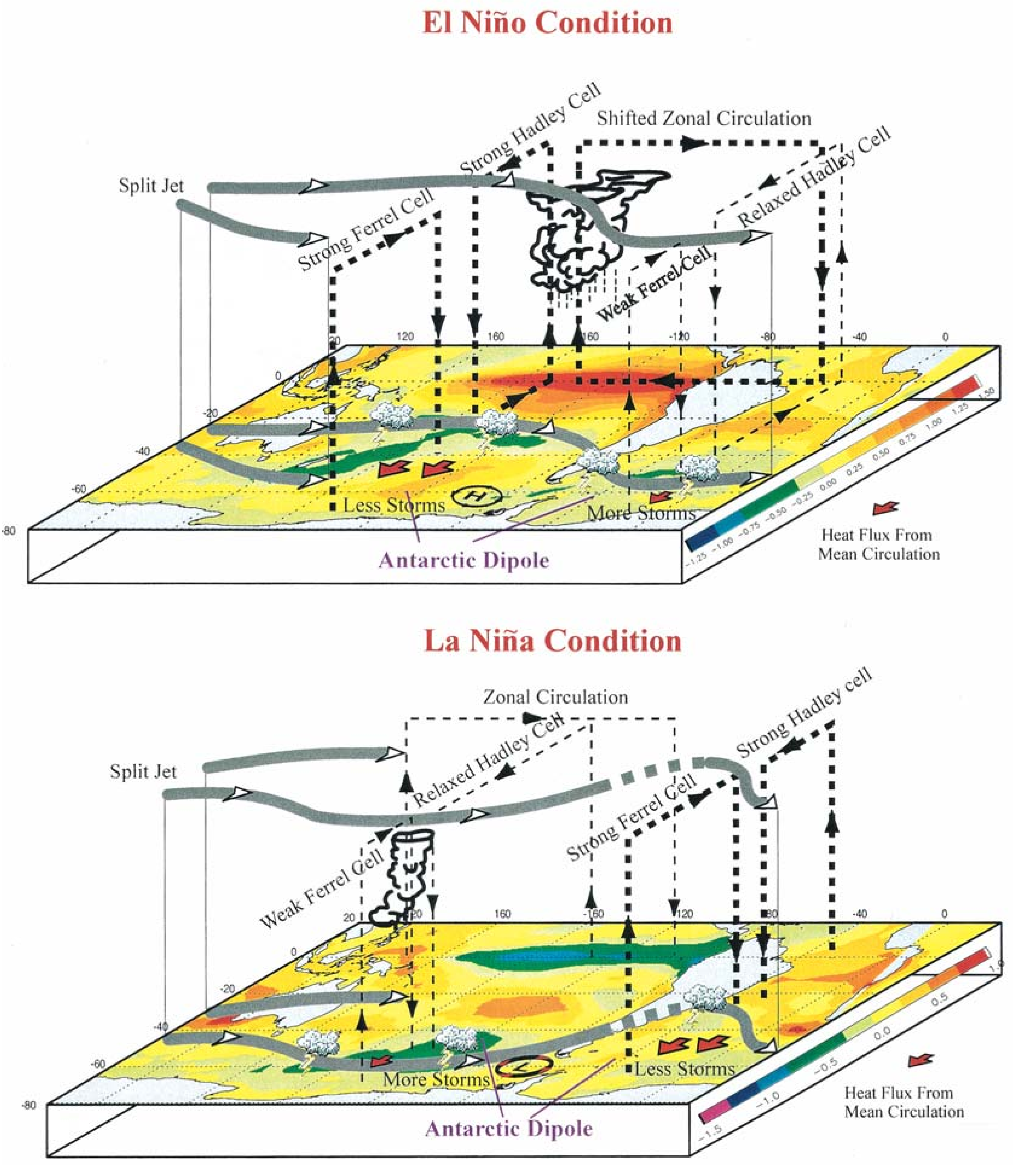

Fig. 8. Schematic atmospheric circulation pattern in response to ENSO warm (top) and cold (bottom) events superimposed on the corresponding SST composites, respectively.

minus a global mean temperature. The stationary eddy heat flux (V^*T^*) is calculated by the monthly mean meridional wind and temperature minus their zonal mean respectively at each grid point. In terms of zonal mean heat transport climatology, the mean circulation transports an order of magnitude more heat than do stationary eddies (Peixoto &

Oort 1992). However, the interannual variability of these heat fluxes is quite different.

Figure 7 displays ENSO composites of meridional heat flux anomalies due to these two processes in the western hemisphere. In the El Niño situation, the anomalous heat flux from the mean circulation is negative (poleward) in the subpolar regions north of the Ross Sea and Amundsen Sea and positive (equatorward) north of the Bellingshausen Sea and Weddell Sea. The heat flux reverses its sign in both basins south of 70ºS, which probably reflects anomalous heat flux by the Polar Cell. The stationary eddy heat flux has the same phase of anomaly pattern and similar magnitudes of the anomalies as the mean circulation heat flux in the subpolar regions, except its anomaly centres occur further south than that of the mean heat flux. In polar regions south of 70ºS, the mean and stationary eddy heat fluxes have opposite signs. Averaging the heat fluxes over seasonal ice zone from 55ºS to 75ºS near the Dipole Pacific centre (~140°W) yields a maximum poleward heat flux anomaly of 5ºK ms^{-1} for the mean circulation and 3.5ºK ms^{-1} for stationary eddies, respectively. The maximum equatorward heat flux anomaly over the seasonal ice zone occurs near the 70ºW and is about 3ºK ms^{-1} for both the mean circulation and stationary eddies. In the La Niña situation, the distribution of heat flux anomalies is in quadrature with the El Niño condition for both the mean flow and stationary eddies. Averaging the heat flux over the seasonal ice zone does not reveal a clear pattern for the mean circulation, but shows two reversed sign heat flux maxima for stationary eddies (both about 3ºK ms^{-1}) near 170ºW and 90ºW, respectively. Apparently, the heat flux during La Niña condition is not a clean linear sign change from El Niño condition. Nevertheless, heat flux anomalies from the mean circulation and stationary eddies are in phase and comparable in magnitude over the seasonal ice zone. These two processes actually supplement each other on influencing the sea ice field: the mean circulation heat flux dominates the subpolar regions while the stationary eddy heat flux dominates the polar seas.

Synthesis of ENSO-teleconnection mechanisms

With clear evidence of the ENSO-ADP teleconnection from observations and current understanding of tropical-polar teleconnection mechanisms, a coherent scheme has evolved illustrating how the tropical anomalous signal is transported to the polar region through an atmospheric bridge and creates ADP anomalies during ENSO events (Fig. 8). In the case of an El Niño, the warm SST in the tropical Pacific enhances tropical convection and the meridional equator-to-polar thermal gradient in the Pacific. This strengthens and contracts the Hadley Cell (Rind *et al*. 2001). As a consequence, the subtropical jet is strengthened and the storm track is shifted equatorward in the South Pacific. The same tropical warming shifts the zonal circulation eastward so that its descending branch takes place in the tropical Atlantic, which relaxes and expands the Hadley Cell there. Consequently, the storm track shifts polarward in the South Atlantic (Rind *et al*. 2001). The changes in the jet stream and the regional Hadley Cells apparently result in an enhanced Ferrel Cell in the South Pacific and weakened Ferrel Cell in the South Atlantic. Consequently, more (less) heat is transported into the polar region in the South Pacific (South Atlantic) in the lower level atmosphere (Liu *et al*. 2002). Therefore, the variation of poleward heat transport due to the regional mean meridional circulation directly contributes to the formation of out-of-phase temperature anomalies in the South Pacific and South Atlantic.

In the meantime, the same tropical warming can trigger the stationary Rossby Wave train that results in the PSA pattern in mid–high latitudes. In response to the warm event, an anomalous high-pressure centre of the PSA sits in the Bellingshausen Sea and creates a regional circulation that brings warm air from lower latitudes to the polar region in the South Pacific and cold Antarctic air out to the open ocean in the Weddell Sea. This regional anomalous circulation is clearly capable of generating ADP anomalies simultaneously in these two basins (Kwok & Comiso 2002, Renwick 2002). Moreover, the weakened PFJ means less cyclone activity in the Southeast Pacific region, which encourages persistent high pressure anomalies in this polar region. In addition, frequent cyclones in the Atlantic basin, which are usually accompanied by ridges in the upstream, favour the high pressure centre in the Bellingshausen Sea too. This not only implies that the variation of the jet stream indirectly contributes to the ADP formation, but also suggests that the positive feedback among the jet stream, storm distribution and stationary eddy activity in this particular region prolongs and maintains the high pressure centre of the PSA.

The atmospheric circulation in the La Niña condition is the opposite of the El Niño condition. Figure 8 shows that the tropical cooling relaxes the Hadley Cell and weakens the Ferrel Cell in the Pacific. The zonal circulation shifts westward in the tropics due to the shrunken warm pool, so the descending branch is located in the eastern tropical Pacific. Therefore, the Hadley Cell is relatively strong in the South Atlantic due to the warm SST in the tropics and the lack of competition from the descending branch of the zonal circulation. The strong Ferrel Cell is observed in the South Atlantic too. As a consequence, the PFJ is enhanced in the South Pacific and the jet stream shifts equatorward in the South Atlantic, creating a reversed alternating storm distribution in these two basins. The changes in the regional Ferrel Cell generate more poleward heat flux in the Atlantic and less poleward heat flux in the Pacific, creating ADP anomalies for the cold ENSO phase. The Rossby Wave train creates a cold phase PSA pattern with a low pressure centre in the Bellingshausen Sea. This low pressure centre is reinforced by the rich cyclone activity associated with the strong PFJ there.

Discussion and summary

Characterized by out-of-phase anomaly centres in the South Pacific and South Atlantic synchronized in the atmosphere, cryosphere and ocean, the Antarctic Dipole is a predominant climate mode in the Western Hemisphere and is closely related to the ENSO variation in the tropics. This study finds that the ADP manifests itself and grows in high latitudes after being triggered by the tropical forcing. It also develops a strong high latitude characteristic - a highly coupled mode in the air-sea-ice system. The ADP anomalies in temperature and sea ice usually persist three to four seasons after the ENSO events mature in the tropics.

Many studies in the last two decades have rapidly advanced our understanding of the elements of the ENSO teleconnection in the Southern Ocean. This study establishes the connection between these results and provides a synthesis of ENSO teleconnection mechanisms that linked the tropics with polar seas for both the South Pacific and the South Atlantic. The synthesized mechanistic scheme not only describes the ENSO teleconnection in the context of the ADP formation but also explains the persistence and manifestation of the ADP in polar seas. Two dynamic processes in the atmosphere are critical in the formation of the ADP. First, the stationary Rossby Wave creates a persistent anomalous high (low) pressure centre in the vicinity of the Bellingshausen Sea in response to warm (cold) ENSO events, generating opposite phase temperature and sea ice anomalies in the South Pacific and South Atlantic simultaneously. Second, the regional mean meridional circulation, namely the regional Ferrel Cell, creates out-of-phase poleward heat flux anomalies in the South Pacific and in the South Atlantic in response to ENSO events. Variation of the Hadley Cell and split jet streams in response to ENSO events connects the tropical forcing and these two high latitude processes. Moreover, this study finds that these two processes work in phase to produce the Dipole anomalies, and their contributions to the Dipole formation in terms of heat flux are comparable in magnitude. The positive feedback between the polar front jet and stationary waves in the atmosphere enhances the Dipole formation mechanism. On the other hand, the positive feedback within the air-sea-ice system also reinforces the existing anomalies: higher air temperatures results in more leads sea ice and allow more heat to be vented from the ocean to the atmosphere, which warms the air even more. These positive feedbacks in the atmospheric circulation and within the air-sea-ice coupled system are probably the reasons for the persistent anomalies in the ADP regions long after the tropical forcing has diminished.

Seasonality of the Southern Hemisphere also plays a critical role in the phenomenon of the long-lasting ADP. In the tropics, ENSO events mature in austral summer when sea ice cover is at its minimum in high latitudes. The weak temperature gradient across the air-sea interface limits heat and momentum fluxes between the atmosphere and ocean during this season. Although an anomalous ENSO signal could already be transferred to southern high latitudes through the atmospheric bridge, the ADP anomalies are weak. When the Southern Hemisphere approaches austral autumn and winter, air-sea-ice interaction intensifies from a drop in air temperature and growth of sea ice. Consequently, the ADP anomalies start to amplify because of positive feedback within the air-sea-ice coupled system, even though the tropical forcing is diminished.

This study provides comprehensive information regarding the ENSO-ADP teleconnection. The synthesis of ENSO Southern Ocean teleconnection mechanisms presented here is consistent with Carleton's (2003) summary but with an emphasis on the formation and maintenance of the ADP. In high latitudes, the ENSO-ADP relationship has been studied through analyzing atmospheric variables, SST and sea ice observations. The role of the upper ocean in this coupled system still remains unknown. With its large heat content, the upper ocean has a longer memory and much larger heat capacity for storing the anomalous climate signals than the atmosphere, which potentially can modulate the coupled system significantly. It deserves future study.

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