Influence of the tropics on the Southern Annular Mode

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Abstract

Perturbations in the Southern Annular Mode (SAM) are shown to be significantly correlated with SST anomalies in the tropical central Pacific during austral winter, and SST anomalies in the tropical eastern Pacific during austral summer. The SAM signature in the Pacific sector resembles a tropically-forced Rossby wave train, the so-called Pacific–South American pattern, while the signature in the Indian Ocean sector is a zonally elongated meridional dipole. Thus, the SAM tends to behave differently in the Eastern and Western Hemispheres, with internal dynamics prevailing in the Indian Ocean sector and the forced response to tropical SST anomalies exerting a strong influence in the Pacific sector. The tropically-forced component of the SAM in the Pacific Sector is related to a geographically fixed active Rossby wave source to the east of Australia within the core of the subtropical jet. In addition to the well-documented positive trend in summer, the SAM also exhibits a significant negative wintertime trend since 1979, characterized by prominent geopotential height increases over the high latitudes. In both seasons, SAM trends are closely linked to long term trends in tropical Pacific SST. Although the SAM is an intrinsic feature of high-latitude variability, maintained by wave mean flow interactions, the SAM index reflects the superposition of both high latitude and tropically forced variability.
1. Introduction

The variability of Southern Hemisphere (SH) atmospheric circulation is dominated by an approximately zonally symmetric pattern, referred as the Southern Annular Mode (SAM), characterized by a dipole in the zonal wind strength with opposing centers of action near 40° and 65°S, and an equivalent barotropic structure in the vertical (Kidson 1988; Karoly 1990; Shiotani 1990; Hartmann and Lo 1998; Feldstein and Lee 1998; Limpasuvan and Hartmann 2000; Thompson and Wallace 2000; Lorenz and Hartmann 2001; Vallis et al. 2004; Rashid and Simmonds 2004). The SAM, which accounts for 20%–30% of the total monthly sea level pressure (SLP) or geopotential height variability south of 20°S (Thompson and Wallace 2000), was previously referred to as the “high-latitude mode” (e.g., Karoly 1990; Kidson 1999) and the “Antarctic Oscillation (AAO)” (Thompson and Wallace 2000).

The storm track in the SH exhibits substantial north–south migration in association with variations of the SAM (Kidson and Sinclair 1995; Codron 2005), which have been related to variations in sea surface temperature (Mo 2000; Hall and Visbeck 2002; Screen et al. 2009), ocean circulation (e.g., Hall and Visbeck 2002; Sen Gupta and England 2006), sea ice (Lefebvre et al. 2004; Stammerjohn et al. 2008), biological productivity (Lovenduski and Gruber 2005), the carbon cycle (Butler et al. 2007; Lovenduski et al. 2007), and mid-latitude precipitation (e.g., Silvestri and Vera 2003; Gillett et al. 2006; Hendon et al. 2007).

Observational and modeling studies suggest that the SAM is maintained by a positive feedback of the high-frequency transient eddies in the storm track upon the zonally averaged zonal flow (e.g., Karoly 1990; Robinson 1991; Hartmann and Lo 1998;
Limpasuvan and Hartmann 2000; Lorenz and Hartmann 2001; Codron 2005). It is thus widely accepted that the SAM owes its existence to internal atmospheric dynamics, although interactions with the surface ocean and stratosphere may contribute to its variance (Watterson 2001; Thompson et al. 2005; Sen Gupta and England 2007). Long-term variability in the SAM has generally been attributed to the direct impact of radiative forcing. In particular, in recent decades, the SAM has exhibited a trend toward positive polarity during summer, manifested as a strengthening of the circumpolar westerlies along 60°S, which has been attributed both to stratospheric ozone depletion and to increased greenhouse gas concentrations (Thompson and Solomon 2002; Gillett and Thompson 2003; Marshall et al. 2004; Shindell and Schmidt 2004; Arblaster and Meehl 2005; Miller et al. 2006).

In contrast to the perspective in which the SAM is viewed primarily as an intrinsic feature of high-latitude atmospheric dynamics, a few studies have suggested that tropical sea surface temperature (SST) forcing has a significant impact on the SAM. For example, L’heureux and Thompson (2006) found that SAM and El Niño Southern Oscillation (ENSO)-related circulation anomalies exhibit common features during austral summer (DJF) and that about 25% of variance of the SAM index is related to ENSO variations. Similarly, Fogt and Bromwich (2006) found that the occurrence of a positive SAM index is more likely during strong La Niña years. The most recent example of the concurrence of ENSO- and SAM-related anomalies is in 2010. Both widely used SAM indices (the NOAA AAO index and the Marshall (2003) SAM index) show an extreme positive phase of the SAM, characterized by negative height anomalies over Antarctica and positive anomalies in midlatitudes, in 2010 winter (JJA) and spring (SON) (Blunden et al. 2011).
Simultaneous with the extreme in the SAM index, there was a significant La Niña event in the tropics (Kim et al. 2011). Although ENSO and the SAM tend to be viewed as independently driving circulation, temperature and precipitation changes in the SH, these observations suggest that the SAM, as conventionally defined, may comprise a superposition of tropically forced variability upon intrinsic high-latitude variability. The focus of this paper is the role of tropical forcing in shaping the SAM, with emphasis on seasons other than summer, which have received relatively little attention in previous work.

2. Data

We use atmospheric fields from ECMWF, a combination of the ERA-40 (1979-2002) and ERA-Interim (2003-2009) reanalysis data (Uppala et al. 2005). The two data sets show no discontinuities in the overlapping period of record (1988-2002). Because NCEP2 reanalysis data (Kanamitsu et al 2002) yield very similar results to those obtained using ECWMF data, we show only results derived from ECWMF in this study. We use sea surface temperature from ERSSTv3 (Smith et al. 2008). Outgoing longwave radiation (OLR), obtained from the National Oceanic and Atmospheric Administration satellites, is used as a proxy for large-scale convective activity over the tropical regions (Liebmann and Smith 1996). In all calculations based on monthly mean data, the annual cycle is removed. Note that for summer (DJF) the year label refers to January-February. To investigate the SAM pattern on intraseasonal time scales, pentad (5 day)-mean circulation anomaly fields, from which the climatological annual (or seasonal) cycle and mean of each year (or season) have been removed, are used.

3. Interannual variability of The SAM
3.1 Canonical SAM pattern at 200hPa

The canonical SAM pattern is usually defined as the first empirical orthogonal function (EOF) of sea level pressure or lower troposphere geopotential height fields in the SH (Hartmann and Lo 1998; Thompson and Wallace 2000; Lorenz and Hartmann 2001; Sen Gupta and England 2007). The projection of SLP or geopotential anomalies onto this EOF1 pattern then defines the time-varying SAM index. This is the method used by NOAA (http://www.cpc.ncep.noaa.gov) to define its AAO index (first EOF of 700 hPa geopotential heights poleward of 20ºS using NCEP/NCAR 1979-2000 reanalysis data).

Alternatively, the SAM index can be simply defined as the difference in the normalized zonally averaged anomalies between 40ºS and 65ºS (Gong and Wang 1999). This approach has been used by Marshall (2003) in defining the SAM (the difference of zonal mean SLP at 40ºS and 65ºS based on data from the twelve stations with the longest and most complete records).

Here, we use 200 hPa geopotential heights (Z200) to define the SAM, because 200hPa corresponds to the core of the tropospheric jetstream, where the circulation variance is greatest. The maximum variability of monthly Z200 can be seen over West Antarctica and the Amundsen Sea while weaker amplitudes are observed over continental East Antarctica (Fig. 1). The strong center of action off the coast of West Antarctica, which is observed in all seasons, was noted by Connolley (1997), who referred to it as “the pole of variability”. The concentration of variance in a single center of action over West Antarctica in the SH is distinct from the distribution of Z200 variance in the NH, which shows three centers of action of comparable strength: one over Greenland, one over the central North Pacific and one over the North Pole.
The leading EOF of monthly Z200, with the data weighted by the square root of cosine of latitude to provide equal weighting of equal areas, explains 21% of the month-to-month variance south of 20°S and is well separated from the remaining eigenvectors according to the North et al. (1982) criterion (Fig. 2a). This pattern is very similar to EOF1 of either monthly 850hPa height (Z850) or sea level pressure (SLP) anomalies in the same domain. The principal component (PC) associated with EOF1 of Z200, defined here as the SAM index (Fig. 2b), is highly correlated with the PC1 derived from Z850 or SLP and other two commonly-used indices (Table 1). Hence, the definition of the SAM is not highly sensitive to the level at which the index is defined.

A dipole pattern with centers of action near 40°S and 65°S is the most obvious feature of the SAM. It is approximately zonally symmetric, but the zonal asymmetries are notable, and their configuration differs between the high and mid latitudes. The high latitude band consists of two centers of variability: one over East Antarctica and one over West Antarctica, while the midlatitude outer ring is dominated by a zonal wavenumber three structure. A wavenumber three pattern is also prominent at midlatitude in the climatology (van Loon and Jenne 1972). The strongest loading occurs over the Amundsen Sea, where the month-to-month variability is also the greatest.

Prominent features of the Z200 SAM pattern are the occurrence of two anomalous highs over the south Pacific and south Atlantic, with an anomalous low between them. Together, these form an arching wave train reminiscent of the Pacific-South American (PSA) teleconnection pattern that is commonly regarded as being associated with ENSO (Karoly, 1989). The apparent connection with the tropical Pacific is further illustrated by the associated stationary wave activity flux, computed according to Plumb (1985)
Appendix A. As shown in Figure 2a, a prominent arc-shaped stream of wave activity flux clearly propagates away from subtropical Australia toward West Antarctica and returns to the tropics over South America, suggestive of a forced wave train embedded within the SAM.

3.2 Seasonality of the SAM and its correlation with tropical SST

The linkage between tropical forcing and the SAM index can also be observed in the pattern of correlations between the SAM index and SST anomalies. Figure 2c shows the correlation between the monthly SAM index and monthly SST data, while Figure 3 shows the correlation between the seasonal mean SAM index and seasonal mean SST. (Note that the seasonal mean SAM index is simply the three month average of the monthly PC in each year). The most significant correlations between the SAM and tropical SST occur during austral winter and summer, although the specific tropical region with which the SAM is most strongly correlated varies from season to season (Fig. 3). During JJA, the maximum correlation between SAM and the SST variability is in the western-central Pacific, in the region of the subtropical convergence zone (SPCZ). In DJF, the far eastern Pacific is the key region linked with the SAM. In the monthly mean data for all calendar months (Fig. 2c), the strongest correlation occurs in the central Pacific from 180°E to 240°E.

We estimate the significance of the correlations in Figs. 2c and 3 taking into account the autocorrelation inherent in the data, which reduces the number of degrees of freedom. For the correlation of monthly data (Fig. 2c), the effective sample size \( N^* \) is computed by considering the lag-one auto-correlations of the SAM index (\( r_1 = 0.4 \)) and tropical SST (1.0 > \( r_2 > 0.9 \) in most of tropical grids) following Bretherton et al. (1999):
\[ N^* = N \frac{1 - r_1 r_2}{1 + r_1 r_2} \]

where \( N \) is the number of available time steps and \( r_1 \) and \( r_2 \) are lag-one autocorrelation of monthly SAM index and tropical SST. The corrected sample size for the 372-month (31 years) time series is about 160. Based on this estimate, the correlations over the central Pacific from 180°E to 240°E are significant at the 99% confidence level (Fig. 2c). Correlations in the west central Pacific in JJA and east-central Pacific in DJF are also significant, at >95% confidence.

The seasonality of the amplitude and structure of the SAM can be assessed by calculating EOFs for each season individually. The annual cycle of the absolute value of the conventional monthly SAM index (inset in Fig. 2b) exhibits a pronounced maximum in the austral winter. Consistent with this result, EOF1 of monthly Z200 primarily captures the characteristics of the SAM pattern in JJA. Likewise, of the dominant EOFs for the individual seasons, EOF1 for JJA is most similar to EOF1 of the monthly data (Fig. 4). In all seasons except summer (DJF), the pattern of EOF1 exhibits strong zonal asymmetries with the largest loading over the Amundsen Sea and neighboring regions, where the largest monthly and seasonal variability in Z200 is observed (Fig. 1).

Let us consider how the Z200 variability over this region of high variability is linked with the SH circulation as a whole. Regression maps between the point with the largest variance (denoted as “AS”, at 67.5°S, 240°E, in Fig. 1) and SH Z200 display a prominent wave train pattern emanating from the tropical central Pacific and propagating to the Amundsen Sea (Fig. 5). These one-point regression maps strongly resemble the corresponding leading EOF for the respective seasons, thus suggesting that the EOFs are dominated by the circulation variability over the Amundsen Sea. As shown in Fig. 5,
Z200 over the Amundsen Sea is also significantly correlated with tropical Pacific SST in all seasons. The related SST pattern is very similar to that associated with the seasonal SAM index (Fig. 3). The region of maximum correlation in the SST field appears in each season to be directly associated with the wave-train-like pattern in Z200. In DJF, the strongest correlation with SST occurs in the eastern tropical Pacific, and the wave train pattern in Z200 assumes the form of a meridionally oriented dipole, whereas in the other seasons, the wave train pattern follows a “great circle” path emanating from the central tropical Pacific, and in each of those seasons, the maximum correlation with SST is also located in the tropical central Pacific.

The pattern of SST and Z200 correlations in Figure 5 suggests that the regions of maximum SST correlation (denoted by the boxes in Fig. 5) are key regions in the tropical Pacific for exciting the Rossby-wave response that characterizes the PSA pattern, as has been shown previously e.g. by Karoly (1989). This relationship is further illustrated in Fig. 6, which shows the correlation between tropical Pacific SST over these key regions and SLP. The correlation between those tropical SST anomalies and the low level circulation exhibits a PSA-like wave train structure in the extratropics, with a phase reversal between the upper and lower troposphere over the tropical Pacific, indicative of a stationary Rossby wave response to tropical SST forcing.

3.3 Decomposition of the SAM into regional patterns

To isolate the component of the SAM that is mainly driven by extratropical wave-mean flow interaction, we attempt to remove the impact of the tropically-forced wave train upon the SAM to the extent that this is possible. For this purpose, the variability that is linearly related to Z200 at the point “AS” in Fig. 1 is removed from the monthly Z200
time series at each SH grid point using the least squares fitting method (e.g. see Van Den Dool et al. 2000). This is equivalent to removing a PSA-shaped wave train from each monthly Z200 field. By construction, the variability over the AS point and the neighboring region is almost entirely eliminated while the variability over remote areas that is unrelated to the AS point is retained. On average, 13% of the total variability south of 20°S is removed by this procedure. EOF1 of the residual monthly data exhibits a pattern that is distinct from EOF1 of the raw data, with a zonal pattern that is well defined only in the Eastern Hemisphere (Fig. 7a).

The time-varying index of the pattern in Fig. 7a exhibits strongest variability during the cold season (Fig. 7b). The correlation between the seasonal-mean index of this pattern and simultaneous SST anomalies (Fig. 8) reveals a close connection between this regional SAM and tropical SST anomalies in the warm pool and SPCZ region in JJA and SON. In the other two seasons, the connection with the tropics is very weak. Thus, the SAM in the Indian Ocean sector is also related to tropical SST anomalies in winter and spring, although the key region is located to the west of the region of SST anomalies that are related to the PSA, as shown in Fig. 5c.

The foregoing analysis suggests that the SAM patterns in the Eastern and Western Hemispheres are largely independent. To further test this idea, the difference between the normalized zonal mean Z200 anomalies along 40°S and 65°S is computed separately for the Eastern and Western Hemispheres bounded by 180°E and 0°E. As shown in Table 2, the correlation between the indices for the Eastern and Western Hemispheres is weak and varies erratically from one calendar month to the next. In a seasonal mean sense, the connection between the SAM-related variability in the two sectors is significant in
summer (DJF) and spring (SON), but not in fall (MAM) and winter (JJA). Analogous tables (not shown) were constructed using other longitudes for partitioning the two hemispheres. The weakest interhemispheric correlations are obtained when the Pacific sector is separated from the Indian Ocean sector. Thus, the zonal homogeneity and coherence of the SAM are not robust throughout the year.

The SAM-related fluctuations over the Pacific and Indian Ocean sector have a stronger tendency to behave independently in the upper troposphere than at lower levels. Analogous calculations based on the Z500 field indicate that the regional SAM indices exhibit similar independence in the mid-troposphere. At the surface the zonal coupling is somewhat stronger. However, the strong zonal symmetry of SAM in the SLP field is mainly a reflection of the zonal coherence of SLP primarily at high latitudes. At midlatitudes, (e.g. along 40°S), SLP is not significantly correlated between the two sectors except during DJF (Table 3).

These findings are in agreement with results of Barnes and Hartmann (2010), who found that in JJA a positive eddy feedback that acts to sustain the SAM is observed over the Indian Ocean sector but not over the Pacific sector. The results presented above indicate that the leading mode of SH circulation variability, conventionally defined as the SAM, owes its existence to a superposition of two largely independent patterns: a tropically-forced wave train over the Pacific sector that projects upon the zonally-symmetric SAM signature and a north-south shifting of the jetstream and storm track over the Indian Ocean sector that is a reflection of extratropical eddy-mean flow interaction. Only during DJF is a significant relationship detectable between the tropically forced wave contribution to the SAM in the Pacific sector and the
A meridionally-oscillating contribution to the SAM in the Indian Ocean sector. A positive feedback of the stationary waves upon zonal-mean flow, as suggested by DeWeaver and Nigam (2000), is one mechanism that might cause these two separate patterns to occasionally vary in tandem.

4. Trends involving the covariability of the SAM and tropical SST

4.1 Epochal differences in the SH circulation and the tropical SST field

Most research on the trend in the SAM thus far has focused on the observed positive trend during austral summer and its association with both global tropospheric greenhouse gas forcing and high latitude SH stratospheric ozone forcing (Thompson and Solomon 2002; Gillett and Thompson 2003; Marshall et al. 2004; Shindell and Schmidt 2004; Arblaster and Meehl 2005; Miller et al. 2006). In view of the close connection between variations in tropical SST and the SAM discussed above, it is of interest to explore the possible role of trends in tropical SST in contributing to the observed trend in the SAM.

The monthly index of the SAM derived from EOF1 of Z200 for all calendar months exhibit no significant trend since 1979 (Fig. 2a). However, a positive trend is clearly discernible in the seasonal index for DJF (Fig. 9a), in agreement with previous work. The shift in the SAM index mainly occurs in the mid-1990s. In contrast, a decreasing trend is observed in JJA, marginally significant at the 95% confidence level, that has not heretofore been discussed in the literature (Fig. 9c). Much of the decrease in the index in JJA occurred around 1990. During spring and fall, there is no apparent trend in the SAM index.

To examine the spatial patterns of the trends in winter and summer, based on the corresponding seasonal SAM index, the 1979-2009 period of record can be divided
subjectively into the two epochs that exhibit the largest contrast. Epochal differences in
Z200 between 1979-1993 and 1994-2009 for DJF and between 1979-1989 and 1990-
2009 for JJA are shown in Fig. 10. The Z200 epochal differences in Fig. 10 exhibit
contrasting polarities of the SAM. In DJF, a pronounced zonally symmetric dipole
dominates the circulation difference (Fig. 10a). In JJA, Z200 increases almost
everywhere in the SH from the earlier to the later epoch, with the greatest increases
occurring over the Amundsen Sea and West Antarctica (Fig. 10b). The PSA wave train
pattern that was noted in the interannual variability can be traced from West Antarctica
back to subtropical Australia in the Z200 difference pattern for JJA. Similar changes are
observed in the middle troposphere and at the surface, as shown in Ding et al. (2011, their
Fig. 1).

The tropical SST change between the two selected epochs shows a significant warming
in the central Pacific/SPCZ in JJA and a cooling in the eastern Pacific in DJF (Figs. 10c,
10d). These two tropical regions with significant SST trend in JJA and DJF, respectively,
are also the regions in which the interannual SST anomalies are closely coupled with the
Pacific component of the SAM in the corresponding seasons. On the interannual time
scales, the positive SST anomalies over these two regions corresponds to the negative
polarity of the SAM, Thus, the sign of the SST trends in these regions matches the sign of
the SH circulation trends, consistent with the relationships for the year-to-year variability
discussed in the previous section.

The upper tropospheric circulation is more sensitive to the subtle change in the tropics
than the flow at lower levels; hence the upper level divergence associated with the
tropical forcing plays a key role in driving tropical-extratropical teleconnections (Hoskins
and Karoly 1981; Sardeshmukh and Hoskins 1988; Trenberth et al. 1998). The trends in tropical outgoing longwave radiation (OLR) and velocity potential that are coincident with the trend in the SAM are plotted in Fig. 10 (e, f). Accompanying the JJA SST warming in the tropical central Pacific and SPCZ region, an increase in convection and upper level divergence took place from the 1980s to the subsequent two decades, while in DJF, convection and upper level divergence decreased over the SST cooling region in the central eastern Pacific. These long term changes in upper level divergence, which appears to be directly driven by the forcing at the lower boundary, may play a key role in forcing the extratropical trends.

Although reanalysis data prior to 1979 are not generally considered reliable in the southern high latitudes, analysis of the SST and circulation fields from the late 1950s onwards enables us to examine whether the observed trend of JJA SAM in recent decades and its relationship with the tropical SST is consistent with relationships prior to 1979. Epochal differences between the periods 1958-83 and 1984-2009 are marked by changes in Z200 in JJA in West Antarctica and SST in the equatorial central Pacific that are very similar to the more recent patterns of interdecadal changes (Fig. 11). The tropical central Pacific is the region with the most pronounced SST warming in the past 52 years and the Amundsen Sea is the region with the largest height increases. Over the past 31 years, the variations in Z200 over the Amundsen Sea have closely paralleled variations in the JJA seasonal index of the SAM (Fig. 11c). Z200 over West Antarctica has been higher during the past 20 years than at any earlier time since 1958. Thus, tendency toward more negative values of the SAM index in JJA, which is dominated by the height rise over the
Amundsen Sea is a prominent feature of the SH circulation that has prevailed over at least the past 50 years.

4.2 MCA analysis

To confirm the relationships in the previous section, we employ maximum covariance analysis (MCA, see Appendix b for details) of seasonal mean tropical SST and SH Z200 for the period 1979-2009 carried out separately for JJA and DJF. Results obtained from MCA consist of modes comprising paired spatial patterns of SST and Z200 and the corresponding expansion coefficient time series. The leading mode indicates the pattern of tropical SST anomalies that is most strongly coupled with the SH circulation, and the SH circulation anomalies associated with that pattern.

For both seasons, the leading MCA modes are dominated by an ENSO-related coupled pattern, which is particularly strong during DJF (Figs. 12 and 13). The corresponding time series are dominated by interannual variability and they exhibit little, if any linear trend over the 31-year record. Hence, the canonical eastern Pacific ENSO-related variability doesn’t contribute to the observed long term changes in the SH circulation. The second MCA modes in both seasons capture the long term trends in the circulation and the related trends in tropical SST. In summer (DJF), SST cooling over the eastern Pacific and warming over most of the remainder of the tropics occurs in association with an annular trend in Z200 (Fig. 12b). In winter (JJA), a PSA-like trend in Z200 occurs in association with a significant warming of SST over the tropical central Pacific/SPCZ region (Fig. 13b), as shown previously by Ding et al. (2011). The Z200 and SST patterns in the second mode closely resemble the epochal differences in Z200 and SST, respectively, in both JJA and DJF as shown in Fig. 10. The associated time series exhibit
significant long term trends very similar to those in the respective time series of the seasonal SAM index shown in Fig. 9. In particular, the time series of SST and Z200 in the JJA mode exhibit a steady increase during the first half of the record and SST and Z200 in the DJF mode both show a shift around the mid-1990s. The MCA thus captures the salient features of the covariability between the SH circulation trend and concurrent changes in the tropical SST, and further supports our interpretation of their statistical relationship.

5. Dynamical interpretation

5.1 Dynamics of interannual variability of the SAM in the Pacific sector

The empirical evidence presented in sections 3 and 4 shows that the low frequency variability in SAM pattern – as conventionally defined – is tropically forced. To better understand the underlying dynamics, we calculate the Rossby Wave Source (RWS), as defined in Sardeshmukh and Hoskins (1988), $-\nabla \cdot (\nabla \times \zeta)$, where $\zeta$ is the absolute vorticity and $\nabla \times$ is the divergent component of the horizontal velocity field. The core of the climatological-mean subtropical jet is located to the east of Australia along 30°S (Figure 14). The tight vorticity gradient associated with the jet and the strong variability of upper level divergent flow over the warm pool should favor the generation of an active Rossby wave source over the jet core region (Lachlan-Cope and Connolley 2006). Indeed, as shown in Fig. 14, the year-to-year variability of seasonal mean RWS exhibits an active source region along the subtropical jet with the maximum to the east of Australia. Thus, the most active RWS in the subtropical SH is confined to a fairly small geographic region. The resulting wave train from this location tends to propagate along a “great circle” path to West Antarctica because the path of an extratropical wave train is largely determined
by the properties of the basic state flow. The strong wave flux emanating from subtropical Australia toward West Antarctica that projects upon the SAM pattern (Fig. 2a) is further evidence that the “pole of variability” over the Amundsen Sea is related to the characteristics of the basic state in the tropics and subtropics. It has also been suggested that the circulation variability over the Amundsen Sea reflects the zonally asymmetric Antarctic orography (Lachlan-Cope et al. 2001). Our results do not contradict this interpretation: as shown in Fig. 15, the Antarctic continent is also a major source of wave activity.

The most active source occurs in JJA when the jet itself is strongest (Fig. 14c). When the subtropical jet along 30°S almost disappears in the austral summer, the variability of the RWS is only half as large (Fig. 14a), but this is the time when the SST variability over the tropical Pacific is strongest. Thus, the location and seasonality of RWS activity appears to be mainly determined by the seasonal evolution of the intensity and shape of the jet stream, rather than by the strength of the variability of tropical SST. When the RWS activity over the core of the jet is weakest in DJF, the circulation variability over the Amundsen Sea is also relatively weak. This is additional evidence that the interannual variability of the high latitude SH circulation in the Pacific sector is more directly related to conditions in the tropics than to eddy-mean flow interactions or high latitude orographic effects.

Because the circulation response to tropical SST forcing yields a pair of Rossby wave gyres residing to the west and poleward of the forcing, whose divergent wind field has a much larger meridional width and a stronger intensity than that associated with Kelvin waves (Gill 1980), the tropical SST anomalies to the east of Australia are efficient in
triggering an active RWS in the core region of the subtropical jet. This is consistent with the correlation analysis in section 3.2, which shows that Z200 variations over the Amundsen Sea are more strongly correlated with SST anomalies over the central and eastern Pacific than with SST anomalies over the Indian Ocean and Western Pacific.

Considering the very active RWS along the core of subtropical jet, tropical internal instability largely unrelated to tropical SST anomalies could also excite fluctuations resembling the PSA wave train if it were able to generate a strong wave source over the jet core region. If this were the case, then one would expect the PSA signature to be prominent in the SH circulation variability, not only on interannual timescales but also intraseasonally. To explore this possibility, EOF analysis was performed on pentad-mean SH Z200 anomalies separately for each season and for the year as a whole. In MAM and DJF, the leading two EOFs are not statistically separable according to the North et al (1982) criterion (figures not shown). Possibly meaningful EOF1 patterns that are well separated from the second EOF are observed only in the calculation based on pentad anomalies for JJA, SON and for the entire year. The leading EOFs for JJA, SON and for the year, shown in Fig. 15, are very much alike and all bear a strong resemblance to their counterparts derived from monthly or seasonal mean data shown in Fig. 4. The PSA wave train is even more pronounced in the intraseasonal EOF1 than in the interannual EOF1. Because tropical SST fluctuations should be very small on the intraseasonal time scale, this suggests that the PSA-like pattern obtained from pentad data reflects an extratropical response to tropical internal variability rather than an SST-forced response. It thus appears that the PSA pattern is a preferred mode of the extratropical basic state that is very sensitive to small variations in the tropical convection; tropical SST forcing is one
way to force such variations, but it is not a requirement. This explains why SAM, as conventionally defined, strongly projects on the PSA pattern over a broad range of frequencies.

5.2 Dynamics of the SAM trend

The summer (DJF) trend in the SAM over the past 30 years has been most commonly attributed to the direct influence of radiative forcing from both greenhouse gases and ozone depletion (Thompson and Solomon 2002; Gillett and Thompson 2003; Marshall et al. 2004; Shindell and Schmidt 2004; Arblaster and Meehl 2005; Miller et al. 2006), but the winter trend, which is of the opposite sign, cannot be readily explained by the same forcing. The long term change of JJA SST in the tropics, as revealed by MCA, is an obvious candidate. The abrupt rise in the summertime SAM index in the mid 1990s may have also been at least partly due to the abrupt change of DJF SST in the tropical Pacific, which occurred around the same time.

Ding et al (2011) used a general circulation model to show that the JJA SST warming trend in the tropical central Pacific/SPCZ region generates a PSA-shaped trend in the SH circulation. Given the strong projection of the PSA pattern upon the SAM, we suggest that the forcing attributable to SST warming in the tropical central Pacific explains a substantial part of the observed trend in the SAM in winter. Similarly, the DJF SST warming over most of the tropics along with cooling in the Eastern Pacific also has the potential to excite a zonally-symmetric response in the extratropics by changing the Hadley cell and the midlatitude jetstream (Seager et al. 2003 and L’heureux and Thompson 2006), suggesting a further possible contribution of tropical SST to the SAM summer trend.
6. Summary and conclusions

The focus of this study is to examine the relationship between the SAM and SST variability in the tropics. Analyses based on EOF1 of monthly geopotential height at 200hPa show that the SAM pattern in the Pacific and Atlantic sector projects strongly upon the PSA wave train that is mainly forced by SST anomalies in the equatorial central-eastern Pacific. It follows that the SAM variability is related to tropical Pacific SST variability, as confirmed by the significant correlation of SAM index with tropical central Pacific SST in JJA, and tropical central and eastern Pacific SST in DJF.

The PSA pattern arises from a Rossby wave source in the upper troposphere to the east of Australia along 30ºS, which is active throughout the year. The intensity of this Rossby wave source is mainly determined by the strength and sharpness of the subtropical jet in the basic state flow. This geographically fixed wave source may play an important role in anchoring the PSA wave train and favoring the recurrence of the PSA, with its primary center of action off the West Antarctic coast, even in the absence of a spatially coherent pattern of SST variability over the central Pacific.

When circulation variability associated with the PSA in the SH circulation is regressed out of the hemispheric 200hPa height field, the leading EOF exhibits a ring-like SAM pattern in the Indian Ocean sector, suggesting that the behavior of the SAM over the Indian Ocean sector and Pacific sector is fundamentally different. In combination, these results indicate that the SAM, which has conventionally been regarded as the leading mode of SH circulation variability, in fact represents the superposition of a PSA type wave train in the Pacific sector and a meridional dipole pattern in the Indian Ocean sector. Although eddy-mean flow interaction in the extratropics is widely believed to be the
primary source of SAM variability, our study shows that planetary waves emanating from the tropical Pacific also strongly contribute to the variability of the SAM.

The long term trend in the SAM over the past three decades is also examined with emphasis on its connection with tropical SST. The SAM trend in summer is well known and has already been extensively discussed in previous work. The SAM index also exhibits a detectable downward trend in winter and the associated upper tropospheric geopotential height pattern in the Pacific sector projects strongly onto the PSA wave train. The interdecadal changes in the SAM in winter and summer are of opposing sign, and their time history is different. The summer SAM index exhibited an abrupt shift in the mid-1990s, whereas the main shift in the winter SAM began a decade earlier and was more gradual. In both winter and summer, a close association is observed between the change in the SAM index and tropical SST changes. In JJA, central Pacific SST experienced a rapid warming from the 1980s to the 1990s, accompanied by a downward trend in the SAM index, while in DJF, eastern Pacific SST exhibited a sudden cooling around the middle of the 1990s, coincident with a rise in the SAM index.

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Appendix a: Plumb (1985) wave activity analysis

The Plumb’s (1985) wave activity analysis is used to reveal stationary Rossby wave energy propagation. In spherical coordinates,

\[
\text{Plumb flux} = \frac{p \cos \phi}{p_0} \times \left\{ \frac{1}{2\Omega a \sin \phi \sin \lambda} \frac{\partial (v' \Phi')}{\partial \lambda} - u' v' + \frac{1}{2\Omega a \sin \phi \sin \lambda} \frac{\partial (u' \Phi')}{\partial \lambda} \right\} \quad \text{(Eq.2)}
\]

Where \((\phi, \lambda)\) are the coordinates (latitude, longitude); \(p\) is pressure; \(p_0 = 1000mb\); \(u', v', \) and \(\Phi'\) are the stationary disturbance’s zonal wind, meridional wind, and geopotential height, respectively; and \(a\) and \(\Omega\) are the earth’s radius and rotation rate, respectively. The Plumb flux provides direct information on the flux of wave activity, which is parallel to the group velocity of quasi-stationary Rossby waves. This diagnostic tool is well suited for detection of propagation characteristics of large scale quasi-stationary Rossby waves.

Appendix b: MCA analysis

We use maximum covariance analysis (MCA) to capture the dominant coupled modes between Southern Hemisphere Z200 (equator to 87.5°S) and tropical SST (20°N to 20°S). MCA between the Z200 and SST field is achieved by performing singular value decomposition on the temporal covariance matrix (Bretherton et al. 1992; Wallace et al. 1992), using equal area (square root of cosine of latitude) weighting. The pairs of singular vectors describe the spatial patterns of the respective fields. The corresponding squared singular value divided by the sum of the squares of the singular values represents the squared covariance fraction (SCF) and thus indicates the relative importance of that pair of vectors in relationship to the total squared covariance between the two fields. The
expansion coefficients obtained by projecting the singular vectors onto the original data fields depict the temporal variations in amplitude and polarity of the spatial patterns.
References


Table 1. Correlation coefficient between PC1 of monthly Z200 in the SH (87.5°S-20°S) and PC1 of monthly Z850 and PC1 of SLP in the same domain, and monthly SAM indices derived from NOAA and Marshall (2003) for the period 1979-2009.

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<tr>
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<th>PC1 of Z850</th>
<th>PC1 of SLP</th>
<th>NOAA AAO index</th>
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<td>PC1 of Z200</td>
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Table 2. Correlation between Eastern and Western Hemisphere components of the difference between normalized zonal mean Z200 (ECMWF reanalysis data, 1979-2009) at 40°S and 65°S. Significant correlations above 95% confidence level are bolded.

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Table 3. Correlation between Eastern and Western Hemisphere components of the zonal mean normalized SLP (ECMWF reanalysis data, 1979-2009) along 40°S. Significant correlations above 95% confidence level are bolded.

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Figure caption

Fig. 1 Standard deviation of 200 hPa geopotential height (Z200) anomalies, 1979-2009 (ECMWF reanalysis data) for (a) monthly mean for all calendar months (b) DJF seasonal mean, (c) MAM seasonal mean, (d) JJA seasonal mean and (e) SON seasonal mean. Contour interval 10 m. Cross denote the location (240ºE, 67.5ºS, defined as the AS point hereafter) in the Amundsen Sea, where the variability of Z200 is the largest in the SH in most seasons.

Fig. 2 a) EOF1 of 31-yr (1979-2009) monthly mean SH 200hPa height anomalies based on data for all calendar months (contour interval 10 m). EOF1, explaining 21% of total variance, has been scaled by one standard deviation of the corresponding principal component. The red vectors (unit: \(10^6\text{m}^2\text{s}^{-2}\)) denote the wave activity flux associated with the EOF1 pattern. (see Appendix a for details). Wave vectors with both components less than \(0.1 \times 10^6\text{m}^2\text{s}^{-2}\) are omitted. b) Principal component of EOF1 (PC1). The inset shows the annual cycle of the amplitude of PC1 defined as 31 year average of absolute value of PC1 for each month. The solid line denotes the mean of the annual cycle. c) Correlation between PC1 and global monthly mean SST for the period 1979-2009. Significant correlations above 99% confidence level are highlighted by shading.

Fig. 3 Regression of the seasonal mean SAM index against seasonal mean SST anomalies (contour interval 0.1 degree) for a) DJF, b) MAM, c) JJA and d) DJF. Shading denotes regions in which correlation is significant at or above the 95% confidence level.

Fig. 4 EOF1 of 31-yr (1979-2009) a) DJF, b) MAM, c) JJA and d) SON seasonal mean SH 200hPa height anomalies (contour interval 10m). EOF1 has been scaled by one
standard deviation of the corresponding principal component. The percentage of the total variance explained by EOF1 is indicated on the top of each panel.

**Fig. 5** Regression of Z200 over the AS point (67.5ºS, 240ºE) in the Amundsen Sea against tropical SST (upper panels, contour interval 0.1 degree) and SH Z200 (lower panels, contour interval 10 m) for a) DJF, b) MAM, c) JJA and d) DJF. Shading denotes regions in which correlation is significant at or above the 95% confidence level.

**Fig. 6** Regression of tropical SST over the key region (denoted as the box in Fig. 5 in the corresponding season) against SH SLP anomalies (contour interval 0.5 hPa) for a) DJF, b) MAM, c) JJA and d) DJF. Shading denotes regions in which correlation is significant at or above the 95% confidence level.

**Fig. 7** a) EOF1 of 31-yr (1979-2009) residual monthly mean SH 200hPa height anomalies (contour interval 10m). EOF1 has been scaled by one standard deviation of the corresponding principal component. b) Annual cycle in the amplitude of associated PC1 defined as the 31 year average of absolute value of PC1 in each month. Dashed line denotes the mean of the annual cycle.

**Fig. 8** Regression of seasonal mean PC1 of residual monthly mean SH 200hPa height anomalies (Fig. 7) against seasonal mean SST anomalies (contour interval 0.1 degree) for a) DJF, b) MAM, c) JJA and d) DJF. Shading denotes regions in which correlation is significant at or above the 95% confidence level.

**Fig. 9** Seasonal mean SAM index derived from PC1 of original monthly EOF1 (Fig. 2) for a) DJF, b) MAM, c) JJA and d) SON. The temporal evolution of SAM in DJF can be divided subjectively into two epochs (1979-1993 and 1994-2009) that have the largest contrast. For JJA, the entire period can be divided into 1979-1989 and 1990-2009. The
average of each epoch is denoted as red line in a and c. Note that the upward trend in DJF is significant at the 98% confidence level and the downward trend in JJA is marginally significant at the 95% confidence level by Mann-Kendall test (Kendall 1955) and trend to noise ratio test (Wilks 1995).

**Fig. 10** Epochal differences (1994-2009 minus 1979-1993) of DJF mean a) SH Z200 (contour interval 10m), c) tropical SST (contour interval 0.1 degree) and e) tropical OLR (shading interval 2W/m²) and 200hPa velocity potential (contour interval 2*10⁵ m²/s). Epochal differences (1990-2009 minus 1979-1989) of JJA mean b) SH Z200 (contour interval 10m), d) tropical SST (contour interval 0.1 degree) and f) tropical OLR (shading interval 2W/m²) and 200hPa velocity potential (contour interval 2*10⁵ m²/s).

**Fig. 11** Epochal differences (1984-2009 minus 1958-1983) of JJA mean a) SH Z200 (contour interval 10m), b) tropical SST (contour interval 0.1 degree) and c) 52-yr (1958-2009) normalized JJA seasonal mean Z200 anomalies averaged over the Amundsen Sea (black curve, 75ºS-57.5ºS, 210ºE-250ºE, denoted as box in a) and 31-yr (1979-2009) JJA seasonal mean SAM index (red curve, adopted from Fig. 9c, sign is reversed).

**Fig. 12** Principal modes of covarying tropical sea surface temperature and Southern Hemisphere circulation in austral summer (DJF). a) Spatial patterns of tropical SST (shading) and 200 hPa geopotential heights (Z200, contour interval 10 m) associated with mode 1 and b) mode 2. c) Time series of SST and Z200 for mode 1 and d) mode 2. Amplitudes in (a) and (b) are scaled by one standard deviation of the corresponding time series in (c) and (d). SCF (squared covariance fraction) and the temporal correlation coefficient (r) between the two expansion coefficient time series are indicated on the top.
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Fig. 13 Same as Fig. 12 but for austral winter (JJA). Note that the upward trends in both time series in mode 2 are significant at the 99% confidence level by the Mann-Kendall test and signal to noise ratio test. Figure from Ding et al., 2011 and reproduced with permission from *Nature Geoscience*.

**Fig. 14** Standard deviation of 31-yr (1979-2009) seasonal mean Rossby wave source (shading, unit: \(10^{-10}\) s\(^{-2}\)), together with isotachs of climatological seasonal mean 200 hPa zonal wind indicating the location of the jet stream (red contours, 10m/s contour interval, values >30 m/s only) for a) DJF, b) MAM, c) JJA and d) DJF.

**Fig. 15** EOF1 of 31-yr (1979-2009) pentad mean SH 200hPa height anomalies (contour interval 10 m) for a) the entire year, b) JJA only and c) SON only. EOF1 has been scaled by one standard deviation of the corresponding principal component. The variance explained by leading two EOFs are denoted on the top of each panel: the first two EOFs are well separated based on North et al. (1982).
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