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A representative time-series for the Southern Hemisphere zonal wave 1

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[1] Recent studies show that an ENSO component of west Antarctic climate variability is related to a persistent zonal pressure anomaly in the south Pacific, which in turn is related to the zonal wave 1 of the subpolar atmospheric circulation. In order to promote further investigation into its dynamics, a suite of time series are presented that describe the intensity and location of ZW1. These time series are shown to represent the SH zonally asymmetric circulation reasonably well. Analysis of the time series suggests that, consistent with previous research, there was a poleward and eastward shift in ZW1 over the late 20th Century. There was also an increase in amplitude variance over this period. Cross-correlation confirms a link with ENSO, and suggests a link between the subtropical and subpolar ZW1. Results also indicate a significant local interaction between south Pacific sea surface temperature and the intensity and location of ZW1. **Citation:** Hobbs, W. R., and M. N. Raphael (2007), A representative time-series for the Southern Hemisphere zonal wave 1, *Geophys. Res. Lett.*, *34*, L05702, doi:10.1029/2006GL028740.

1. Introduction

[2] Zonal wave 1 (ZW1), described as the first harmonic of the zonal geopotential height field, is the dominant quasi-stationary wave in the Southern Hemisphere, and has been shown to account for up to 90% of the SH circulation's spatial variance [*van Loon and Jenne*, 1972]. It is thought to be related to disturbances in the mean zonal flow (e.g., the SH split jet [*Trenberth*, 1980]) and has been linked to blocking events in the Pacific [*Renwick*, 2005]. Several studies [e.g., *Trenberth*, 1980; *Raphael*, 2003] have found significant links between ZW1 and the El Niño-Southern Oscillation (ENSO), with *Trenberth* [1980] noting an oscillatory variation in ZW1 amplitude at subtropical latitudes with a period of 3–4 years, approximately consistent with ENSO.

[3] Recent studies on SH sea-ice variability have shown that the high latitude climate system is affected by regional variations in the South Pacific circulation, particularly in the region of the Antarctic Peninsula. There are indications that shifts in the spatial location, as well as the intensity, of the zonally asymmetric circulation are responsible for climate variations in the southern Bellingshausen and western Ross Seas [*Yuan*, 2004; *Fogt and Bromwich*, 2006], although changes in this region have also been attributed to the meridional component of the Southern Annular Mode [*Lefebvre et al.*, 2004]. This same region west of the Antarctic Peninsula has one of the highest observed warming trends globally over the late 20th century [*Vaughan et al.*, 2003], and several researchers have suggested that there have been simultaneous changes in the strength and evolution of ZW1.

[4] Following the late 1970s, changes in the SH circulation became apparent [e.g., *Meehl et al.*, 1998; *Thompson et al.*, 2000; *Marshall*, 2003]. *Mo and Higgins* [1997] suggested an increase in the importance of ZW1 over time during this period. ZW1 closely follows the seasonal cycle of the zonal circulation, being strongest during the late austral winter and weakening during the austral fall. *Raphael* [2003] found that after 1975, ZW1 reached peak amplitude later (August for the later period, compared to the long-term mean of July) and persisted longer (from March to October, compared to March to September). The peak amplitude also tended to be higher after 1975. These studies indicate that ZW1 is a significant feature of the SH circulation, and an improved understanding of its dynamics could improve understanding of current trends in the high latitude SH climate.

[5] The Trans-Polar Index (TPI) has previously been proposed as an index of the SH ZW1, and is defined as the normalized difference in sea level pressure (SLP) between Hobart and Stanley [*Pittock*, 1980; *Carleton*, 1989]. A potential disadvantage of defining an index based on fixed locations is that information regarding spatial variations is lost. Additionally, as is evident from Figure 1, the defining locations for the TPI do not directly coincide with the areas of greatest ZW1 activity, which occur over the traditionally data-sparse Southern Ocean. It may be argued that a truly representative time series should include data from these regions of greatest ZW1 intensity. The advent of satellite observation and the availability of observation-based reanalysis data have since improved SH spatial data coverage, allowing the definition of a more representative index of ZW1.

[6] To facilitate further investigation into the dynamics and trends over the late 20th century, a set of descriptive time series for the SH ZW1 are proposed here, and subsequently analyzed with respect to significant changes. Most previous research has concentrated on the subpolar ZW1, which tends to be stronger in amplitude than the subtropical wave. By generating time series of the subtropical as well as the subpolar wave characteristics, analysis of the teleconnection between the latitude bands is made possible. Initial results presented below suggest that ocean-atmosphere interaction is important to the dynamics of ZW1 teleconnection between the tropics and the SH high latitude system.

2. Method

[7] Time series were derived from the NCEP/NCAR Reanalysis (NRA) monthly mean 500 hPa geopotential

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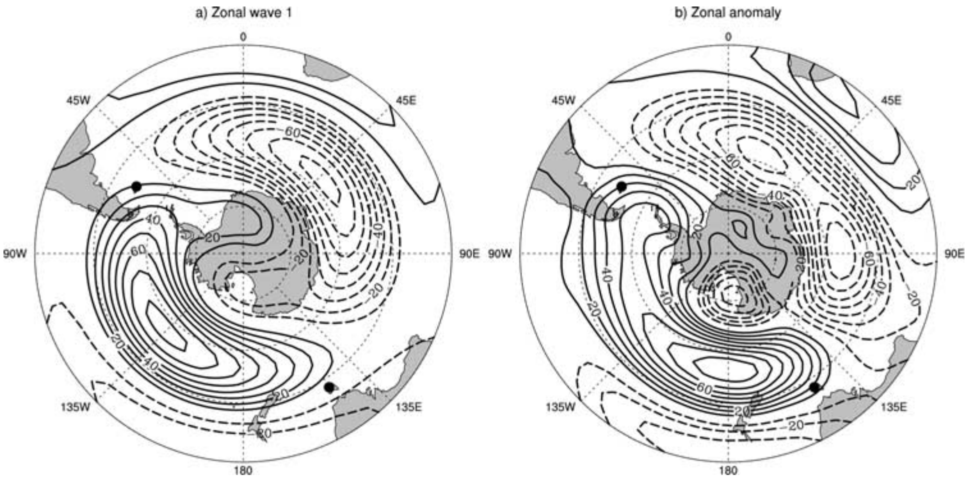

Figure 1. (a) First harmonic and (b) zonal anomaly of the 1960–2004 annual mean NRA 500 hPa geopotential height field. Dashed contours indicate negative values. Markers indicate the locations used to derive the TPI (i.e. Hobart and Stanley).

height [*Kalnay et al.*, 1996] for the period 1960–2004. The ZW1 signal was obtained by applying a Fast Fourier Transform (FFT) at each latitude coordinate (NRA latitudinal resolution is 2.5°), and for each month. By applying the FFT at each time interval, information about the temporal evolution at each spatial location is retained. The FFT can result in possibly spurious wave-like patterns, and the phase and amplitude from wavenumber analysis is sensitive to relatively small changes in the geopotential height field [*Trenberth*, 1980]. However, Figure 1 demonstrates clear signals of both ZW1 and ZW3 in the mean geopotential height zonal anomaly, with ZW1 being the most extensive.

[8] Time series were created of the ZW1 monthly mean amplitude (gpm), phase (degrees E) and ridge/trough latitude (degrees N) for the subpolar and subtropical waves (time plots are in Figure S1 of the auxiliary material[1]). To allow separation of the waveforms, the SH was divided into latitude bands of 0°–45°S (for the low latitude) and 45°S–75°S (for the high latitude). For each waveform and at each month, the amplitude was defined as the maximum wavenumber one intensity within the latitude band. The phase indicates the longitudinal location of the ZW1 wave maximum, and the peak latitude is defined here as the meridional location of the wave maximum. Between them, the phase and latitude time series define the location of the ZW1 ridge at each time-step.

[9] In order to verify that the time series indeed represent a significant component of variability of the SH circulation, the amplitude time series were cross-correlated with the untransformed NRA 500 hPa geopotential height field (Figure 2). For all correlations presented in this paper, the long-term monthly mean was first removed from each dataset to avoid spuriously high correlations due to seasonality. (Note that a weak seasonality was retained in the subpolar amplitude due to its trend in summer amplitude, discussed in section 3). To account for serial autocorrelation retained after this transformation, equivalent sample sizes were then estimated for the deseasoned ZW1 time series using the method of *Zwiers and von Storch* [1995], which were used to estimate significance levels. For both the subpolar and subtropical cases obvious ZW1 spatial patterns are indicated, with maximum correlation coefficients greater than 0.55. Both time series show maximum correlations in the Pacific Ocean basin.

[10] A commonly raised issue is the uncertain quality of reanalysis data for the SH, especially for the pre-satellite era before 1979 [e.g., *Kidson*, 1999]. Similar research using both the NRA and the European Centre for Medium Range Forecasting ERA40 pressure field data have shown that there is good agreement for the SH between these reanalyses [*Renwick*, 2005; *Fogt and Bromwich*, 2006]. To validate the physical significance of the time series, the subtropical amplitude time series was compared with station observations of SLP taken from the National Climatic Data Center World Monthly Surface Station Climatology dataset. For the vertical levels considered here ZW1 is approximately barotropic [*van Loon and Jenne*, 1972], hence due to the limited number of long upper-air station data in the regions of interest, SLP was chosen as a reasonable proxy for the mid-troposphere pressure field. (This assumption appears not to hold true over Australia/New Zealand, so stations from this region were excluded). Nine stations with at least ten years of continuous available data were found for the region of subtropical ZW1 influence, as indicated by the cross-correlation with the geopotential height field (Figure 2b). The density of station observations was approximately similar for the periods before and after 1979 (see Table S2). Five of the stations were correlated with the subtropical amplitude time series at the 0.1 significance level. The stations with no significant correlation were clustered on the coast of South Africa. Seasonal correlations with the NRA 500 hPa geopotential height field (not shown) indicated that there was no significant correlation between subtropical ZW1 amplitude and the 500 hPa geopotential height over eastern South Africa during February–April and August–December, which may explain the weak covariance in this region. Whilst the presence of a significant correlation with observed SLP

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl028740. Other auxiliary material files are in the HTML.

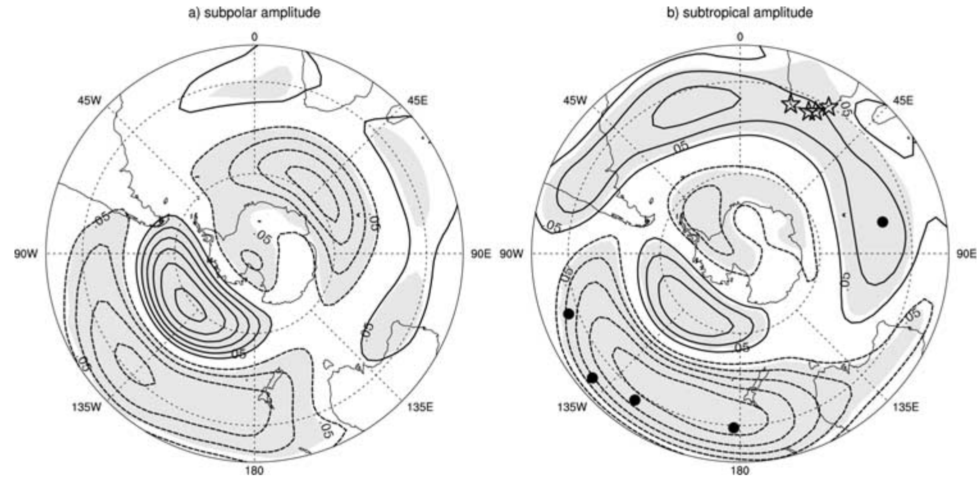

Figure 2. Correlation coefficients for 1960–2004 NRA 500 hPa geopotential height field for (a) subpolar amplitude and (b) subtropical amplitude time series. Contour interval is 0.1. Dashed contours indicate negative correlations and shading indicates statistically significant correlations at the 0.05 level. Significantly correlated surface stations are shown by filled circles, uncorrelated stations are shown by stars.

gives no information concerning uncertainty in the time series, it does at least serve to indicate that the time series represent an important component of the observed pressure field.

3. Time Series Analysis

[11] In this section, the ZW1 time series are analyzed with respect to both changes over time and interactions between wave strength and location. Linear regression indicated that the subpolar wave amplitude had no significant trend. However, there were trends in the location, significant at the 0.01 level, with a poleward shift of 2.5° and an eastward shift of 11.0° over the 45-year period. Recent research indicates that the strong observed trends in sea ice concentration in the western Ross and southern Bellingshausen Seas are linked to an ENSO-related poleward and eastward shift of the South Pacific SLP anomaly [*Fogt and Bromwich*, 2006]. It seems reasonable to suggest that the shift in the subpolar ZW1 represents the same phenomenon, and so the time series may prove useful in further analysis of the effect of south Pacific circulation on the west Antarctic region.

[12] The subpolar ZW1 amplitude and phase showed an increase in standard deviation over time, from 27 (1960–1969) to 29 gpm (1990–2004) for amplitude, and from 26 to 32°E for phase (see also Table S1). Furthermore, spectral analysis (not shown) indicated that the time series have significant oscillatory components of variability on interannual, annual and (for the subpolar wave) semi-annual timescales. Given the apparent change in variance and the importance of oscillatory behavior, wavelet analysis was applied to the time series (not shown). The subpolar ZW1 amplitude had a clear annual oscillation that showed a general increase in intensity over the period of study, suggesting that the increased variance was in part accounted for by an increasingly pronounced seasonal cycle. Regression analysis by months showed significant negative trends in subpolar amplitude only for November/December, months when the wave is relatively weak, possibly explaining the increased annual cycle. There was little evidence of a persistent oscillatory component in the phase. Although the latitude had no apparent change in variability, we note here a clear annual component in the time series, which may be evidence that its meridional location is an important factor in the seasonal evolution of ZW1.

[13] Analysis of the subtropical wave yielded similar results. Like the subpolar wave, the subtropical wave had a shift poleward (2.2°) and eastward (15.7°), but in this case there was also a slight strengthening in amplitude of 5.9 gpm, significant at the 0.1 level. There was a general increase in amplitude standard deviation (from 17 to 21 gpm), and as for the subpolar case this appears to be partly manifested as an increase in the intensity of the annual cycle. There were significant positive trends for both July (0.41 gpm/year) and January (0.17 gpm/year), so that unlike the subpolar wave the increased annual cycle appears to be due to an increase in the winter amplitude rather than a decrease in summer amplitude. There was no increased variance in the phase as shown by the subpolar wave.

[14] To explore the interactions amongst the wave amplitude and location, cross-correlations were calculated for the different time series, where correlations at the 0.05 level were considered significant. No significant correlation was found between the subpolar amplitude and phase, despite the apparent coincidence in their seasonal evolution and interannual variability, whereas a high correlation was found when the seasonal cycle was not removed from each series. The retention of a seasonal cycle can lead to spurious correlations, but the result may also indicate that covariance between the phase and amplitude only occurs at sub-annual timescales. A significant cross-correlation between phase and peak latitude at lag zero ($r = -0.53$) was found indicating a tendency towards a poleward location during eastward phases, consistent with the long-term trends.

[15] For the subtropical ZW1 a significant correlation was found between amplitude and latitude ($r = -0.40$), with a tendency toward stronger amplitude during poleward shifts, a relationship that was not found for the subpolar

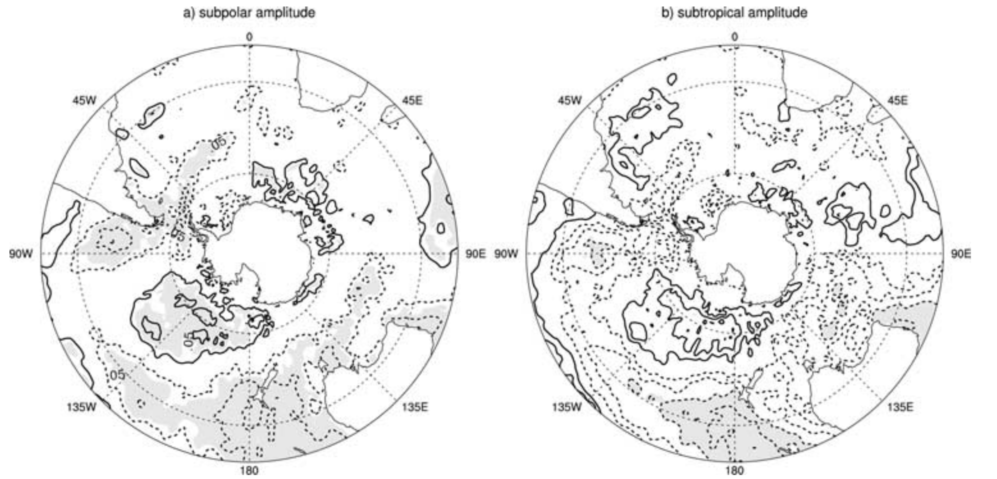

Figure 3. Correlation coefficients between the HadISST SST and (a) subpolar and (b) subtropical amplitude time series, for 1980–2004. Dashed contours indicate negative correlations and shading indicates statistically significant correlations at the 0.05 level. Contour interval is 0.1.

wave. Inspection of the phase and latitude periodograms (not shown) indicated that both had significant 24-month oscillations, which were removed from the time series in addition to the annual cycle. This yielded a still significant cross-correlation of $r = -0.21$, as opposed to $r = 0.97$ before removal of the biennial fluctuation. Hence, a biennial component of the subtropical wave location is indicated, along a northeast-southwest track.

[16] The relationship between the two waveforms was also explored. There was no strong cross-correlation between high and low latitude ZW1 peak latitude, but both phase and amplitude indicated significant relationships. The wave amplitudes were positively correlated ($r = 0.42$), as were the phases ($r = 0.21$).

[17] As stated above, previous investigators have found statistical links between ZW1 and ENSO [*Trenberth*, 1980; *Mo and Higgins*, 1997; *Renwick*, 2005]. The apparent ENSO cross-correlation between the time series and the revised Southern Oscillation Index (SOI) defined by *Trenberth* [1984] was calculated. A significant negative correlation between amplitude and SOI was found for both waves, confirming a tendency towards a strong ZW1 during El Niño events. The correlation coefficients were higher in magnitude for the subtropical wave ($r = -0.4$) than the subpolar wave ($r = -0.25$). The correlations were significant for the SOI both leading and lagging the ZW1, but maximum correlations occurred when SOI led by one month, and were significant for SOI leading ZW1 by up to 10 months. To compare the relationship between atmospheric and oceanic ENSO indices, the analysis was repeated for the NINO3.4 region SST time series. The results were similar in magnitude and temporal extent to those for the SOI index.

4. Relation With Sea Surface Temperature

[18] Several studies have suggested that the quasi-barotropic structure of ZW1 could indicate a thermal forcing; hence, ZW1 could represent an atmosphere-ocean coupled mode [e.g., *Milliff et al.*, 1999]. Here the ZW1 time series were used to make an initial exploration of ZW1 as a potential coupled high-latitude teleconnection, by calculating the cross-correlations with both the HadISST and NOAA OI v2 sea surface temperature (SST) datasets, for the period 1980–2004 [*Rayner et al.*, 2003; *Reynolds et al.*, 2002]. (Records prior to 1979 were omitted due to the previously discussed issue of data quality, and as before the annual cycle was removed from each dataset.) Results were approximately the same for both datasets, so only the HadISST results are shown here. Figure 3 shows that the amplitudes were negatively correlated with western Pacific SST, implying a tendency for a stronger ZW1 during El Niño events, and indicating an atmosphere-ocean interaction. Correlations were larger in magnitude and extent for the subpolar wave. A potentially important result is the obvious region of significant positive correlation between subpolar amplitude and SST in the approximate region of the subpolar ridge. A full analysis of this feature is outside the scope of this paper, but we note that this may represent a component of the ZW1 forcing mechanism.

[19] In section 3, a significant negative correlation was found between phase and latitude for both waves. The spatial patterns of correlation with the untransformed geopotential height field (not shown) were somewhat different for these two series, so their co-variance is rather curious. For both waves, it can be seen that phase was positively correlated with SST at approximately 130°W, 55°S, and negatively correlated with SST in the region of New Zealand (Figures 4a and 4b). These same regions also showed significant cross-correlations with latitude, but the polarities of the correlation coefficients were reversed compared to those of the phase (Figures 4c and 4d). Thus, warmer than normal SST in the mid-latitude south-east Pacific tends to coincide simultaneously with an eastward phase and with a poleward latitude. This suggests that not only are phase and latitude interrelated, but also that they are both linked with SST at these key locations. The statistical relationships between phase and latitude may be partly a result of their simultaneous long-term trends. However, given their corresponding patterns of SST correlation, and their simultaneous seasonal cycles (which were not included in the correlation), a physical response to SST

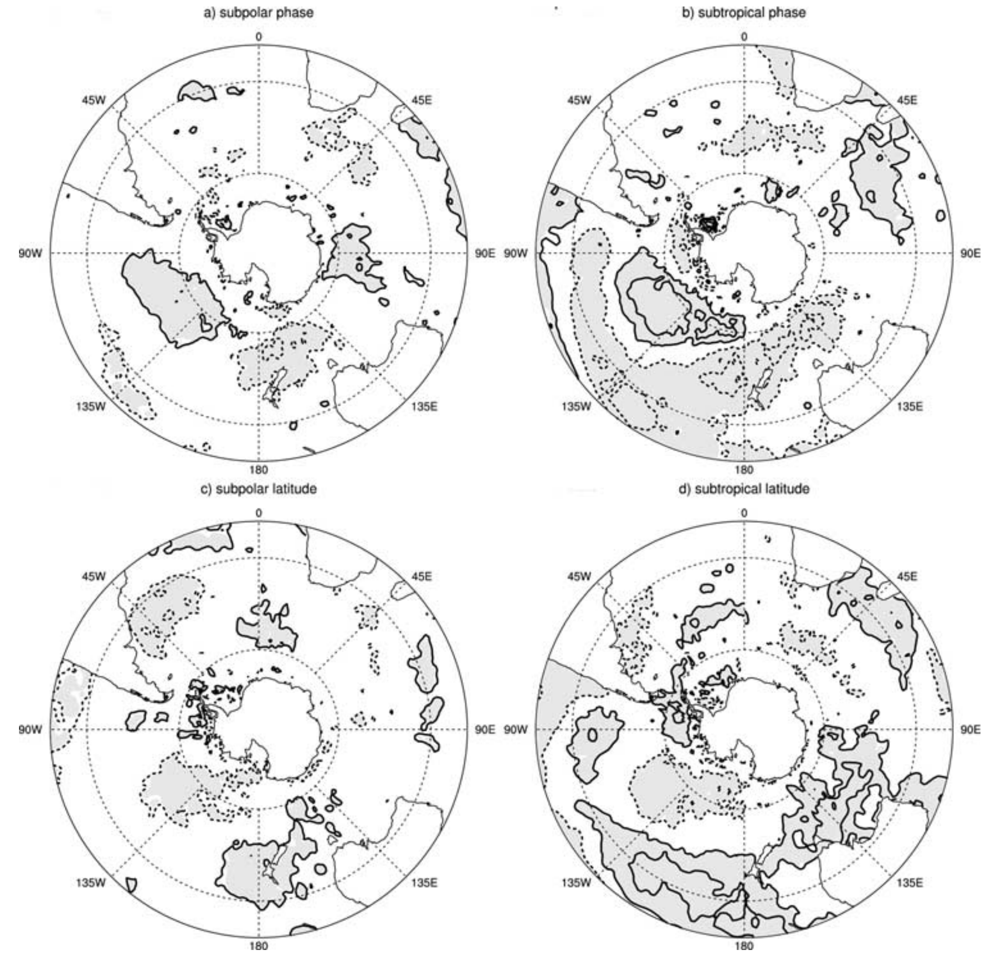

Figure 4. As in Figure 3, but for (a) subpolar phase, (b) subtropical phase, (c) subpolar latitude, and (d) subtropical latitude. Contour interval is 0.1.

anomalies in ZW1 meridional and zonal location cannot be discounted.

5. Conclusions

[20] ZW1 is a significant component of the SH mean circulation that may have an important influence on strong regional climate trends at high latitudes, but no index currently exists to fully describe the behavior over time of the wave. To facilitate further study, a set of time series describing the strength and spatial location of the SH subpolar and subtropical ZW1 time series are proposed.

[21] Correlations with the untransformed geopotential height field indicated that the time series represent the first harmonic of the zonally asymmetric circulation reasonably well. The correlations indicated that for both waveforms the ZW1 pattern is stronger in the Pacific Ocean basin compared to the Atlantic/Indian Ocean sector. In regions showing a strong ZW1 signal in the geopotential height field, good agreement was generally found between station records of SLP and the relevant amplitude time series. The trends and seasonality shown by the time series were consistent with previous studies of ZW1. Furthermore, the time series appear to represent aspects of the SH circulation that have been shown to influence regional changes in the west Antarctic. Therefore, we believe that these time series may facilitate further investigation of the effect of zonal anomalies on trends in Antarctic climate.

[22] Linear regression indicated a poleward and eastward shift in both waves over the period of analysis. The shift in the Pacific high pressure related to the subpolar ZW1 ridge has been implicated in the observed trends in temperature and sea ice concentration in the Ross and Bellingshausen Seas. There was also an increased variability in amplitude for both the subpolar and subtropical waves, with a simultaneous increase in the strength of the annual cycle. The two amplitude time series showed similar patterns of interannual variability.

[23] The results indicated that the subtropical and subpolar waves are clearly related. There were significant cross-correlations between them for both amplitude and phase. Additionally, they showed very similar relationships with SST. Pacific SST was found to have a significant link with the amplitude and location of the subpolar and subtropical waves, but correlations were slightly stronger and more persistent for the subtropical wave. Other than the subtropical amplitude (which was dominated by the tropical western Pacific), all the time series were significantly correlated with the SST at approximately 135°W, 60°S (the approximate location of the subpolar ZW1 ridge).

The reasons for this regional link with SST are not discussed in this paper, but future work is proposed that will analyze the possible mechanism of atmosphere-ocean interaction that this implied.

[24] We conclude that these results are evidence that the SH ZW1 represents a possibly important teleconnection between the tropics and the SH high latitudes, and in particular to Antarctic regions that have shown strong trends in the late 20th Century. Additionally, analysis of the relationship with SST indicates that both the intensity and spatial location of the wave represent an ocean-atmosphere coupled mode of climate variability.

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