A Novel Approach to Diagnosing Southern Hemisphere Planetary Wave Activity and Its Influence on Regional Climate Variability

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ABSTRACT

Southern Hemisphere mid- to upper-tropospheric planetary wave activity is characterized by the superposition of two zonally oriented, quasi-stationary waveforms: zonal wavenumber 1 (ZW1) and zonal wavenumber 3 (ZW3). Previous studies have tended to consider these waveforms in isolation and with the exception of those studies relating to sea ice, little is known about their impact on regional climate variability. A novel approach is taken to quantifying the combined influence of ZW1 and ZW3, using the strength of the hemispheric meridional flow as a proxy for zonal wave activity. The methodology adapts the wave envelope construct routinely used in the identification of synoptic-scale Rossby wave packets and improves on existing approaches by allowing for variations in both wave phase and amplitude. While ZW1 and ZW3 are both prominent features of the climatological circulation, the defining feature of highly meridional hemispheric states is an enhancement of the ZW3 component. Composites of the mean surface conditions during these highly meridional, ZW3-like anomalous states (i.e., months of strong planetary wave activity) reveal large sea ice anomalies over the Amundsen and Bellingshausen Seas during autumn and along much of the East Antarctic coastline throughout the year. Large precipitation anomalies in regions of significant topography (e.g., New Zealand, Patagonia, and coastal Antarctica) and anomalously warm temperatures over much of the Antarctic continent were also associated with strong planetary wave activity. The latter has potentially important implications for the interpretation of recent warming over West Antarctica and the Antarctic Peninsula.

1. Introduction

The relationship between mid- to upper-tropospheric planetary wave activity and regional climate variability in the Northern Hemisphere (NH) has received a great deal of attention in recent times, as researchers try to better understand the links between the Arctic amplification and midlatitude weather (e.g., Cohen et al. 2014; Screen and Simmonds 2014). While the meridional temperature gradient has not undergone such dramatic changes in the Southern Hemisphere (SH), this flurry of research activity has highlighted the deficits in our understanding of SH planetary wave activity and its link to surface conditions.

In both hemispheres large-scale topography and continent–ocean heating contrasts provide strong forcing for longitudinally asymmetric planetary-scale time-mean motions. Such motions, usually referred to as stationary or planetary waves, are especially strong during winter and tend to have an equivalent barotropic structure, meaning the wave amplitude increases with height but phase lines tend to be vertical (Holton and Hakim 2013). In the context of weather and climate variability at the surface, these waves are important because they produce local regions of enhanced and diminished time-mean westerly winds, which strongly influence the development and propagation of transient weather disturbances. Persistent (or blocked) weather patterns, for instance, are typically associated with high-amplitude waves in the upper troposphere (e.g., Trenberth and Mo 1985; Renwick 2005). The meridional transport of heat and moisture associated with these waves also influences surface conditions.
It was van Loon and Jenne (1972) who first characterized SH planetary wave activity as the superposition of two zonally oriented, quasi-stationary waveforms of zonal wavenumber 1 (ZW1) and wavenumber 3 (ZW3). Based on Fourier decompositions of the mid- to upper-tropospheric circulation, they concluded that the net effect of the other wavenumbers was simply to modulate ZW1 and ZW3. Since that landmark study, the ZW1 and ZW3 patterns have been identified as dominant features of the midlatitude circulation on daily (e.g., Kidson 1988), seasonal (e.g., Mo and White 1985), and interannual (e.g., Karoly 1989) time scales. Corresponding metrics and climatologies have been developed (Raphael 2004; Hobbs and Raphael 2007) and their relationship with circulation features, including the Amundsen Sea low (Turner et al. 2013) and two prominent quasi-stationary anticyclones in the sub-Antarctic Western Hemisphere (Hobbs and Raphael 2010), have been investigated.

While these climatologies and investigations reveal many of the basic characteristics of the ZW1 and ZW3 patterns (e.g., their variability and spatial pattern), with the exception of the ZW3 sea ice analyses of Raphael (2007) and Yuan and Li (2008) and the ZW1 sea surface temperature results of Hobbs and Raphael (2007), subsequent studies have not yet extended these climatologies to look at their influence on key variables such as surface temperature and precipitation. Related studies on topics such as Australian (Frederiksen et al. 2014) and Patagonian (Garreaud et al. 2013) precipitation variability sometimes mention a ZW3-like pattern in passing, but the literature lacks a broad, hemispheric perspective on the link between planetary wave activity and regional climate variability. One reason for this might be that the ZW1 and ZW3 patterns never really occur in isolation, which makes analyses of just one or the other somewhat problematic (Hobbs and Raphael 2010).

In this study we take a new approach to the analysis of quasi-stationary, monthly timescale (30-day running mean) zonal wave activity. Rather than focus on a specific wavenumber or stationary pattern, we use a signal processing technique based on the Hilbert transform to identify all data times of strong meridional hemispheric flow. The vast majority of these times are associated with a mixed ZW1–ZW3 pattern, and thus strong meridional flow is used as a proxy for planetary wave activity that does not suffer many of the shortcomings of existing approaches. We apply this proxy in considering 1) the climatological characteristics of SH planetary wave activity; 2) its impact on surface temperature, precipitation, and sea ice; and 3) the implications of this new approach for interpreting existing analyses of SH planetary wave activity. This investigation is particularly timely given that the middle-to-high southern latitudes have exhibited significant circulation (and consequent temperature, precipitation, and sea ice) changes over recent decades (e.g., Bromwich et al. 2013; Burgener et al. 2013; Simmonds 2015).

2. Data

a. Overview

The series of reliable, spatially complete atmospheric data available for the middle-to-high southern latitudes is relatively short. The reanalysis projects have produced sequences of surface and upper air fields that in some cases date back to the 1950s (Kistler et al. 2001; Uppala et al. 2005; Kobayashi et al. 2015); however, it is generally accepted that these have limited value prior to 1979 at high southern latitudes because of a lack of satellite sounder data for use in the assimilation process (Hines et al. 2000).

The latest-generation reanalysis datasets (which all date back to at least 1979) are the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim; Dee et al. 2011), Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011), Climate Forecast System Reanalysis (CFSR; Saha et al. 2010), and Japanese 55-year Reanalysis Project (JRA-55; Kobayashi et al. 2015). While assessments of the validity of these datasets in the middle-to-high southern latitudes have only just begun to emerge, the available evidence suggests that ERA-Interim may be the superior product. In comparison to its peers, ERA-Interim best reproduces the vertical temperature structure (Screen and Simmonds 2012), precipitation variability (Bromwich et al. 2011; Nicolas and Bromwich 2011), and mean sea level pressure and 500-hPa geopotential height at station locations (Bracegirdle and Marshall 2012) around Antarctica. As such, daily time scale ERA-Interim data for the 36-yr period 1 January 1979–31 December 2014 was used in this study.

While ERA-Interim may be considered the superior reanalysis product, it should be said that all reanalysis datasets need to be treated with caution in the middle-to-high southern latitudes because of the sparsity of observational data. There are also well-known difficulties with the representation of low-frequency variability and trends in reanalysis data. Spurious shifts and other artifacts can be present as a result of changes in the observing system, transitions between multiple production streams, or various other errors that can occur in a complex reanalysis production (Dee et al. 2014). Given these issues, it is probably not surprising that surface temperature trends over Antarctica, for instance, vary greatly among the latest reanalysis datasets.
(Nicolas and Bromwich 2014). These issues are less critical in our study because the primary focus is seasonal and interannual variability (as opposed to long-term trends or low-frequency variability), but they are still important to keep in mind.

b. ERA-Interim data

Reanalysis projects typically provide both analysis and forecast fields for download. The analysis fields are the output of the data assimilation cycle at each time interval, which for ERA-Interim is every 6h. They represent arguably the most accurate possible depiction of the atmospheric state for several dozen variables that are all coherent on the calculation grid. These analysis fields are then used to initialize weather forecasts for the coming hours/days. ERA-Interim forecasts are initialized twice daily at 0000 and 1200 UTC, and forecast fields are available for 3, 6, 9 and 12h after initialization.

In this study we analyze the daily average 500-hPa meridional wind (\(v\)), 500-hPa geopotential height (\(Z\)), surface air temperature, sea ice fraction, sea surface temperature, and mean sea level pressure, calculated as the mean of the 6-hourly analysis fields from ERA-Interim. For precipitation, the “total precipitation” forecast fields were used (i.e., the sum of the convective and large-scale precipitation, which is also provided separately). Each forecast field represents the accumulated precipitation since initialization, so the daily rainfall total was calculated as the sum of the two 12-h post initialization accumulation fields for each day. The horizontal resolution of the ERA-Interim data used here is 0.75° latitude × 0.75° longitude.

3. Computation procedures

The results in this paper were obtained using a number of different software packages. A collection of command line utilities known as the NetCDF Operators (NCO) and Climate Data Operators (CDO) were used to edit the attributes of netCDF files and to perform routine calculations on those files (e.g., the calculation of anomalies and climatologies), respectively. For more complex analysis and visualization, a Python distribution called Anaconda was used. In addition to the Numerical Python (NumPy; Van Der Walt et al. 2011) and Scientific Python (SciPy) libraries that come installed by default with Anaconda, a Python library called xray was used for reading and writing netCDF files and data analysis. Similarly, in addition to Matplotlib (the default Python plotting library; Hunter 2007), Iris and Cartopy were used to generate many of the figures.

To facilitate the reproducibility of the results presented, an accompanying Figshare repository has been created to document the computational methodology (Irving 2015). In addition to a more detailed account (i.e., version numbers, release dates, and web addresses) of the software packages discussed above, the Figshare repository contains a supplementary file for each figure in the paper, outlining the computational steps performed from initial download of the ERA-Interim data through to the final generation of the plot. (A version-controlled repository of the code referred to in those supplementary files can be found at https://github.com/DamienIrving/climate-analysis.)

4. Methods for quantifying planetary wave activity

a. Overview of existing methods

In analyzing SH planetary wave activity (i.e., the ZW1 and/or ZW3 patterns), previous studies have tended to define metrics based on either a stationary pattern or Fourier decomposition. With respect to the former, Raphael (2004) defines a ZW3 index that is essentially the average 500-hPa geopotential height zonal anomaly across three key points (the annual average location of the ridges of the ZW3 pattern in the 500-hPa geopotential height field), while Yuan and Li (2008) use the principal component of the leading empirical orthogonal function (EOF) mode of the surface monthly meridional wind. The stationary nature of these approaches means they cannot fully capture the subtle (approximately 15° of longitude on average) seasonal migration in the phase of the ZW3 (van Loon and Rogers 1984: Mo and White 1985) or the occurrence of patterns whose phase does not approximately coincide with the location of the three analysis points or leading EOF mode.

A number of studies have analyzed the zonal waves by using a Fourier transform to express the upper tropospheric geopotential height in the frequency domain as opposed to the spatial domain (Hobbs and Raphael 2007, 2010; Turner et al. 2013). The output of a Fourier transform can be expressed in terms of a magnitude and phase for each wavenumber (or frequency/harmonic; the terminology differs in the literature), so these studies simply analyzed the magnitude and phase information corresponding to the ZW1 and/or ZW3 pattern. While this might be considered an improvement on a grid point or EOF method in the sense that the phase is allowed to vary, a shortcoming is that the result is a constant amplitude wave over the entire longitudinal domain. The two major anticyclones associated with the ZW3 pattern (located over the western and eastern South Pacific, respectively) are known to be positively covariant with respect to their location (indicating a coordinated wave pattern) but not amplitude (Hobbs and Raphael 2010),
while in many cases ZW1- and/or ZW3-like variability is only prevalent over part of the hemisphere. As discussed in the seminal work of van Loon and Jenne (1972), it is clear that the other Fourier components (i.e., the non-wavenumber 1 or 3 coefficients) are required to modulate the amplitude of the ZW1 and ZW3 variability, and potentially vital information can be lost if those extra components are not incorporated when defining a metric of planetary wave activity.

None of the aforementioned studies attempted to combine their ZW1 and ZW3 metrics to get a measure of total planetary wave activity, so for an example of this we must turn to the NH. In analyzing the relationship between planetary wave activity and regional weather extremes, Screen and Simmonds (2014) calculated the 500-hPa geopotential height Fourier amplitudes for a range of wavenumbers of interest and then simply counted the number of positive and negative magnitude anomalies. While this may be an appropriate approach for the NH, it too fails to account for the fact that some of the waveforms in a Fourier transform simply exist to modulate others [something that was noted by Screen and Simmonds (2014)] and thus may not be appropriate to count all magnitude anomalies.

b. Wave envelope

A possible way of addressing the shortcomings of the previous approaches borrows from recent advances in the automated identification of Rossby wave packets. In particular, Zimin et al. (2003) pioneered a method of identifying the envelope of atmospheric waveforms based on the Hilbert transform, which is a well-known technique in digital signal processing but had been scarcely applied in the atmospheric sciences. In defining their algorithm, Zimin et al. (2003) consider the real function \( v(x) \) on an equally spaced grid along a latitude circle, which is parameterized by \( x \), with \( 0 < x \leq 2\pi \). The grid points are located at \( x = 2\pi l/N \), where \( l = 1, 2, \ldots, N \) and \( N \) is an even integer. The first step of the algorithm is to compute the Fourier transform of \( v(x) \):

\[
\hat{v}_k = \frac{1}{N} \sum_{l=1}^{N} v\left(\frac{2\pi l}{N}\right) e^{-2\pi ikl/N}, \quad k = -N/2 + 1, \ldots, N/2. \tag{1}
\]

The inverse Fourier transform is then applied to a selected band \((0 < k_{\text{min}} \leq k \leq k_{\text{max}})\) of the positive wavenumber half of the Fourier spectrum (this is the part of the process that was inspired by the Hilbert transform):

\[
w\left(\frac{2\pi l}{N}\right) = 2 \sum_{k=k_{\text{min}}}^{k_{\text{max}}} \hat{v}_k e^{2\pi ikl/N}. \tag{2}
\]

The (complex number) amplitude of the resulting waveform \( w \) represents the wave envelope \( E \):

\[
E(2\pi l/N) = |w(2\pi l/N)|. \tag{3}
\]

The various components of this process are illustrated in Fig. 1 for the case where \( v(x) \) is the meridional wind along the 54.75°S latitude circle.

Subsequent studies have gone on to apply the Zimin et al. (2003) algorithm in the context of identifying and tracking Rossby wave packets in daily time scale data.
however, its utility in identifying waveforms on longer temporal and larger spatial scales has not previously been investigated. In these studies, a spatial map of the wave envelope is constructed for each data time \[E(t, \lambda, \phi)\], where \(t\), \(\lambda\), and \(\phi\) represent time, latitude, and longitude, respectively. The utility of these maps is evident when considering the two maps (Fig. 2) that correspond to the single-latitude examples shown in Fig. 1. For (the diurnal averages of) both 22 May 1986 and 29 July 2006, it is clear that the wavenumber 3 component of the Fourier transform is dominant at 54.75°S (and at the other nearby latitudes not shown in Fig. 1). An analysis based on single wavenumbers could lead one to believe that both data times are associated with a pronounced hemispheric ZW3 pattern, despite the fact that this is clearly only true for 29 July (Fig. 2). On 22 May the spatial scale of the anomalous flow from 200° to 260°E approximately matches wavenumber 3, but elsewhere the flow is strongly zonal. The other components of the Fourier transform serve to modulate the wavenumber 3 component accordingly, and by using the wave envelope as opposed to a single wavenumber approach, this useful information is retained.

INDEX OF PLANETARY WAVE ACTIVITY

To define and calculate an appropriate metric of planetary wave activity, \(E(t, \lambda, \phi)\) was calculated from the 500-hPa meridional wind. The latitudinal dimension of \(E(t, \lambda, \phi)\) was eliminated by calculating the meridional maximum over the range 40°–70°S, and then the zonal median was taken to eliminate the longitudinal dimension and arrive at a single planetary wave index (PWI) value for each data time. Since wavenumbers 1–9 were retained during the process (i.e., essentially all wavenumbers), the PWI represents an integrated measure of the “waviness” of the hemispheric circulation.

The meridional wind was used in calculating the PWI because it fundamentally reflects the presence of waves in the zonal flow. If the flow is purely zonal there are no waves and \(v = 0\), while the magnitude of \(v\) reflects the activity of the waves. The meridional wind is also directly involved with meridional transports of heat and moisture, which directly impacts surface temperature, precipitation, and sea ice. In fact, many studies have shown that \(v\) (either filtered or unfiltered) contains much more dynamic information about synoptic processes than alternatives like the geopotential height or streamfunction (e.g., Berbery and Vera 1996; Hoskins and Hodges 2005; Petoukhov et al. 2013), neither of which has a direct involvement with meridional exchanges.

While better suited to the purposes of our study, the selection of \(v\) has important implications for the Fourier analyses we present. From the geostrophic relation we know that \(\nu \propto dZ/dx\), which means that \(Z\) tends to be dominated by longer wavelengths (or smaller wavenumbers) than \(v\). In particular, since \(Z\) is a sinusoidal function of \(x\) in Fourier space, it follows that \(\nu_k \propto kZ_k\) for any given wavenumber \(k\), meaning more of the variance...
in \( \nu \) is explained by the synoptic (and shorter) waves than it is for \( Z \). This is an important distinction that is discussed further in section 5. Besides the selection of the meridional wind, a number of other factors were taken into consideration in devising this methodology:

- The results show little sensitivity to the choice of atmospheric level because planetary waves are equivalent barotropic, and 500 hPa was selected as it represents a mid- to upper-tropospheric level that is below the tropopause in all seasons and at all latitudes of interest.
- The wave envelope is slightly smoother if wavenumbers greater than 9 are left out of the Hilbert transform, but otherwise the result is not appreciably different from when all wavenumbers are retained.
- The meridional maximum (over 40°–70°S) was taken to allow for slight north/south variations in the mean latitude of planetary wave activity and also for the fact that the waveform is not perfectly zonally oriented.
- The zonal median (as opposed to the mean or integral) was taken to guard against large values in one part of the hemisphere overly influencing the end result.

To be consistent with much of the existing literature, the majority of the analysis focuses on the monthly time scale. Monthly mean data were obtained by applying a 30-day running mean to the daily (i.e., diurnally averaged) ERA-Interim data, so as to maximize the monthly information available from the dataset. As noted by previous authors (e.g., Kidson 1988), potentially useful information may be lost if only 12 (i.e., calendar month) samples are taken every year. Dates are labeled as the sixteenth day of the 30-day period (e.g., the labeled date 16 January 1979 spans the period 1–30 January 1979).

\section*{c. Data analysis techniques}

\subsection*{1) Anomalies}

All anomaly data discussed in the paper represent the daily anomaly. For instance, in preparing the 30-day running mean surface air temperature anomaly data series, a 30-day running mean was first applied to the daily surface air temperature data. The mean value for each day in this 30-day running mean data series was then calculated to produce a daily climatology (i.e., the multiyear daily mean). The corresponding daily mean value was then subtracted at each data time to obtain the anomaly.

\subsection*{2) Composites}

Annual and seasonal mean composites are presented throughout the paper for key variables. To produce these composites, a mean spatial map was calculated across all data times that 1) fell within the season of interest and 2) exceeded a specified threshold value. To determine the statistical significance of the composite mean at each grid point, two-sided, independent sample \( t \) tests were used to calculate the probability \( p \) that the composite mean value was not significantly different from the climatological (i.e., all data times) mean for that season.

\subsection*{3) Periodograms}

The characteristics of data series that have been Fourier-transformed are often summarized using a plot known as a periodogram or Fourier line spectrum (Wilks 2011). These plots are also referred to as a power or density spectrum and most commonly display the squared amplitudes \( C_k^2 \) of the Fourier transform coefficients as a function of their corresponding frequencies \( \omega_k \). As an alternative to the squared amplitude, we have chosen to rescale the vertical axis and instead use the \( R^2 \) statistic commonly computed in regression analysis. The \( R^2 \) for the \( k \)th harmonic is

\begin{equation}
R_k^2 = \frac{(n/2)C_k^2}{(n-1)s_y^2},
\end{equation}

where \( s_y^2 \) is the sample variance and \( n \) is the length of the data series. This rescaling is particularly useful as it shows the proportion of variance in the original data series accounted for by each harmonic (Wilks 2011).

\subsection*{4) Climate Indices}

Two of the major modes of SH climate variability are the southern annular mode (SAM) and El Niño–Southern Oscillation (ENSO). To assess their relationship with the PWI, the Antarctic Oscillation index (AOI; Gong and Wang 1999) and Niño-3.4 index (Trenberth and Stepaniak 2001) were calculated from 30-day running mean data (i.e., the same time scale that was used to calculate the PWI). The former represents the normalized difference of zonal mean sea level pressure between 40° and 65°S, while the latter is the sea surface temperature anomaly for the region in the central tropical Pacific Ocean bounded by 5°S–5°N and 190°–240°E.

\section*{5. Results}

The results begin with a summary of the spatial and temporal characteristics of SH planetary wave activity, before considering its relationship with both the major modes of SH climate variability (SAM and ENSO) and surface conditions.
a. Spatial characteristics

Visual inspection of the SH circulation revealed that days (with 30-day running mean applied) of PWI greater than the 90th percentile overwhelmingly exhibit a mixed ZW1–ZW3 hemispheric planetary wave pattern (Fig. 3). Days of PWI less than the 90th percentile become increasingly unlikely to exhibit a coordinated hemispheric wave pattern, so the 90th percentile was taken as a threshold value for planetary wave activity.

Elements of the mixed ZW1–ZW3 pattern shown in Fig. 3 are not unique to days where the PWI is greater than its 90th percentile. As demonstrated in Fig. 4a, the ZW1 component of the flow is relatively insensitive to changes in the strength of the meridional flow. Instead, it appears that the main difference between days of very strong (PWI > 90th percentile) and very weak (PWI < 10th percentile) meridional flow is the prominence of the ZW3 component. While influential at all times, the ZW3 component is far more prominent when the meridional flow is strong and therefore dominates the streamfunction anomaly patterns (and thus surface impacts) discussed in section 5d.

Given the dominance of the ZW3, it is not surprising that the ZW3 index of Raphael (2004) shows a reasonably high level of agreement with the PWI (Fig. 5). Having said that, it is important to note that the shading of the dots in Fig. 5—which represent the phase of the wavenumber 3 component of the Fourier transform—are not randomly distributed. Whenever the phase of the wavenumber 3 component of the flow does not match up with the location of the three grid points used to calculate the ZW3 index (indicated by the dark gray or near-white shading), a low value is recorded for the ZW3 index. The outlying dots in the bottom right-hand quadrant are particularly noteworthy, as in these cases the PWI (and hence in most cases the amplitude of the wavenumber 3 component of the flow) is actually quite large. The failure of the ZW3 index to capture these out-of-phase patterns means that composite analyses based on that index may overstate the stationarity (and hence the time-mean impacts) of the ZW3 component of the flow.

b. Temporal characteristics

Consistent with previous studies (e.g., van Loon and Rogers 1984; Mo and White 1985), the composite mean 500-hPa streamfunction zonal anomaly pattern for days (with 30-day running mean applied) where the PWI exceeds its 90th percentile (Fig. 3) migrates zonally by approximately 15° from its most easterly location during summer to its most westerly during winter (notwithstanding the fact that the pattern breaks down from around 240°–330°E during summer). It has a slightly larger amplitude during the winter months, and the frequency of strong planetary wave activity was also far more pronounced at that time of the year (Fig. 6a). The seasonal counts of the number of days exceeding the PWI 90th percentile (Fig. 6b) show that 1980 was associated with a particularly high frequency of planetary wave activity; however, there were no statistically significant linear trends in these counts for time series including or excluding (i.e., 1981–2014) the year 1980.

While our focus is on the monthly (30-day running mean) time scale, it is interesting to consider whether similar behavior is observed at other time scales. It can be seen from Fig. 4b that wavenumber 3 dominates the average periodogram when the running mean applied to the daily 500-hPa meridional wind is greater than 10 days, with wavenumber 1 becoming progressively more influential as the smoothing increases. When the same process is repeated using the 500-hPa geopotential height (not shown), the results are very different. The ZW1 dominates at all time scales, and except for a slight upswing from wavenumber 2 to 3, the variance explained monotonically decreases for subsequent wavenumbers. This is an important result because van Loon and Jenne (1972) analyzed geopotential height data and concluded that ZW1 explains (by an appreciable margin) the largest fraction of the spatial variance in the 500-hPa SH circulation (a finding that has been quoted in many subsequent papers). In light of the results presented here and the previous discussion about the fact that \( \omega_k \propto kZ_k \) in Fourier space and that the meridional wind may be a more appropriate quantity to analyze in this context, it is clear that ZW3 plays a greater role than previously thought, particularly when there is a strong meridional component to the hemispheric flow.

c. SAM and ENSO

Composite analysis was also used to assess the relationship between the PWI and the major modes of SH climate variability. SAM events were defined according to the 75th and 25th percentiles of the AOI, while positive (El Niño) and negative (La Niña) ENSO events were defined as a Niño-3.4 above 0.5°C and below −0.5°C, respectively. Composites for each phase of SAM and ENSO were then calculated by taking the average across all data times for which the PWI exceeded its 90th percentile and the AOI or Niño-3.4 was greater or less than the relevant threshold.

The SAM composites show that the phase of the planetary wave pattern moves east during positive SAM events and west during negative events (Fig. 7). Planetary wave activity was also more common when the SAM was negative: of the 1312 data times where the PWI exceeded...
its 90th percentile, 510 (39%) had an AOI that was less than the 25th percentile as compared to only 166 (13%) with an AOI greater than the 75th percentile. Consistent with this finding, the aforementioned outlying year for planetary wave activity (1980; see Fig. 6b) was associated with a large negative SAM. The association between ENSO and planetary wave activity was far less pronounced. Besides a subtle east
(La Niña)/west (El Niño) movement of the anticyclone over the southeastern Pacific, no appreciable changes were seen in the phase of the planetary wave pattern (not shown), and planetary wave activity was only slightly more common during El Niño conditions (282 data times to 176).

d. Surface conditions

To assess the influence of planetary wave activity on regional climate variability, composite means of variables of interest (the surface air temperature anomaly, precipitation anomaly, and sea ice concentration anomaly) were calculated for all data times where the PWI exceeded its 90th percentile. In other words, we asked the question: what is the average temperature (or precipitation or sea ice concentration) anomaly when there is strong planetary wave activity? The anomalous flow associated with these composites (indicated by the 500-hPa streamfunction anomaly as opposed to the streamfunction zonal anomaly shown earlier) has a very strong ZW3 signature. This is consistent with the spatial characteristics presented earlier, which indicate that the distinguishing feature of days of strong meridional flow is the enhanced ZW3 component (as opposed to ZW1).

1) Surface air temperature

Planetary wave activity was found to be associated with large and widespread surface air temperature anomalies over and/or around much of West Antarctica during all seasons (Fig. 8). The most pronounced anomalies were seen during autumn and winter, with warmer-than-average conditions over the interior of West Antarctica (associated with an anomalous northerly flow) and correspondingly colder-than-average conditions over the Weddell Sea (associated with an anomalous southerly flow). Because of the aforementioned seasonal migration (and breakdown during

![Fig. 4. Temporal average (1979–2014) periodograms for the 500-hPa meridional wind at 54.75°S. (a) Three different subsets of the 30-day running mean data (all data times, PWI greater than its 90th percentile, PWI less than its 10th percentile); (b) all data times but with varied running mean (in days) applied to the data prior to the Fourier transform. The labels on the vertical axis correspond to Eq. (4).]

![Fig. 5. PWI vs the ZW3 index of Raphael (2004). Both were calculated using 500-hPa, 30-day running mean data (the PWI was calculated from the meridional wind and the ZW3 index from the geopotential height zonal anomaly). The gray shading represents the phase of the wavenumber 3 component of the Fourier transform of the meridional wind (expressed as the location, in degrees east longitude, of the first local maxima), while the black line is a linear least squares line of best fit. Both indices have been normalized to aid visual comparison (for each index this involved subtracting the mean of the index series and then dividing by the standard deviation).]
summer) of the mean planetary wave pattern, warm anomalies were confined to the Antarctica Peninsula during spring, while summer was associated with the smallest anomalies of any season.

With respect to other sectors of the high southern latitudes, anomalously warm temperatures were widespread over East Antarctica during all seasons except summer. The largest anomalies were seen over Wilkes Land during autumn and winter, in association with an anomalous northerly flow in that region. Other features of note included anomalously cool temperatures over the Ross Sea and mainland Australia during spring.

2) Precipitation

The largest composite mean precipitation anomalies were associated with either enhanced or suppressed flow over significant topography (Fig. 9). For instance, the same anomalous onshore flow that was associated with high temperatures over both West Antarctica and Wilkes Land was also associated with large positive coastal precipitation anomalies, with the precise location of those anomalies moving with seasonal variations in the location of the mean planetary wave pattern. In contrast, weakened westerly flow over the southern Andes during autumn, winter, and spring (but not summer because of the breakdown of the wave pattern in that region) was associated with large negative precipitation anomalies over Chilean Patagonia. A similar mechanism explains the large negative anomalies over New Zealand during winter and spring, when the mean planetary wave pattern is located far enough to the west to exert an appreciable influence on the westerly flow over the South Island. Enhanced orographic precipitation due to anomalous onshore flow might also play a role in the large positive precipitation anomalies seen over eastern Australia during spring; however, the anomalies extend far beyond the Great Dividing Range,
FIG. 8. Composite mean surface air temperature anomaly for days (with 30-day running mean applied) where the PWI was greater than its 90th percentile. Black contours show the corresponding composite mean 500-hPa streamfunction anomaly (dashed contours indicate negative values and the contour interval is $2.5 \times 10^6 \text{m}^2\text{s}^{-1}$), while the hatching shows regions where the difference between the composite mean and the climatological mean is significant at the $p < 0.01$ level.
Fig. 9. As in Fig. 8, but for precipitation anomaly.
suggesting that enhanced moisture transport from the Tasman Sea might be the dominant mechanism.

3) SEA ICE

The sea ice composites (Fig. 10) were highly consistent with the temperature composites. For instance, in autumn and winter anomalous onshore flow and warmth over the interior of West Antarctica was in accord with the reduced sea ice concentration over the Amundsen Sea, and anomalous offshore flow and cold over the Weddell Sea during autumn was consistent with the increased sea ice concentration. In spring, the anomalously warm over the western aspect of the Antarctic Peninsula concurred with the reduced sea ice concentration in the Bellingshausen Sea, while the anomalously cold temperatures over the Ross Sea coincided with an anomalously high sea ice concentration. The anomalous onshore winds and warmth over Wilkes Land were consistent with the reduced sea ice seen immediately to the north of George V Land, Adélie Land, and the Sabrina Coast of East Antarctica in all seasons except summer (when there is very little ice there anyway). One regional feature that does not appear to fit with this overall consistency was the anomalously high sea ice concentration to the west of the Antarctic Peninsula during autumn, which was not reflected in the corresponding temperature composite.

6. Discussion and conclusions

A novel method for identifying quasi-stationary planetary wave activity has been developed and applied to the problem of characterizing the SH zonal waves and their influence on regional climate variability. The method adapts the wave envelope construct traditionally used in the identification of synoptic-scale Rossby wave packets and improves on existing methods by allowing for variations in both wave phase and amplitude. The zonal wave analysis reveals that while both ZW1 and ZW3 are prominent features of the climatological SH circulation, the defining feature of highly meridional hemispheric states is an enhancement of the ZW3 component. These enhanced ZW3 states are associated with large sea ice anomalies over the Amundsen and Bellingshausen Seas and along much of the East Antarctic coastline, large precipitation anomalies in regions of significant topography and anomalously warm temperatures over much of the Antarctic continent.

In interpreting the results of our zonal wave analysis, it is important to clearly define what is meant by the phrase “quasi-stationary planetary wave activity” in the context of this study. It was evident from our analysis of the monthly time scale (30-day running mean) meridional wind that the ZW1 and ZW3 patterns are prominent features of the SH circulation even when the hemispheric meridional flow is weak (Fig. 4a). As the meridional flow gets stronger, the ZW3 component becomes increasingly prominent, while the ZW1 component remains relatively unchanged. This means the average anomalous flow associated with a highly meridional hemispheric state clearly resembles a ZW3 pattern (Figs. 8–10). It is this highly meridional and anomalous ZW3 circulation that is captured by high values of our PWI and thus we refer to as planetary wave activity, as opposed to the mixed ZW1–ZW3 pattern that is essentially present at all times.

Our climatology of planetary wave activity confirms previous results regarding the seasonality of the zonal waves (peak activity in winter, seasonal migration of the zonal location/phase) and also identifies a large sector of the Western Hemisphere (120°–30°W) where the mean wave activity breaks down during summer. In contrast to the results presented here, previous studies have suggested a link between planetary wave activity and ENSO (e.g., Trenberth 1980; Raphael 2003; Hobbs and Raphael 2007). Given the hemispheric nature of the PWI (i.e., it responds most strongly to coordinated, hemispheric patterns of meridional flow), it is perhaps not surprising that we found no strong link with ENSO, given that teleconnections between ENSO and the high southern latitudes tend to be localized around the southeastern Pacific (Simmonds and Jacka 1995; Turner 2004). While this result is not good news for the predictability of planetary wave activity, its increased frequency during negative SAM events offers some hope. The identified east–west migration of the mean planetary wave pattern with positive/negative phases of the SAM possibly ties in with the zonally asymmetric properties of the SAM (e.g., Kidston 1988; Kidston et al. 2009); however, a detailed analysis of this relationship was beyond the scope of this study.

With respect to the link between planetary wave activity and regional climate variability, most relevant investigations have focused on sea ice. The recent study of Raphael and Hobbs (2014) takes a new approach to assessing the influence of the atmospheric circulation, focusing on the ice advance (approximately March–August) and retreat (September–February) seasons for five distinct regions of sea ice variability around Antarctica. Their examination of the spatial pattern of correlation between sea ice extent and 500-hPa geopotential height for each season/region suggests that the ZW3 pattern is the primary driver of sea ice variability in the Weddell and Amundsen/Bellingshausen Seas during the advance season. Our results tend to support this
Fig. 10. As in Fig. 8, but for sea ice concentration anomaly.
finding, particularly during the early part [March–May (MAM)] of the advance season. In contrast, the strong association identified between the PWI and sea ice coverage just to the north of George V Land, Adélie Land, and the Sabrina Coast in East Antarctica does not seem to be in agreement with the results of Raphael and Hobbs (2014), who found the SAM to be the major driver in that region for both the advance and retreat seasons.

For the King Haakon VII Sea (10°W–70°E), Raphael and Hobbs (2014) were unable to identify an obvious atmospheric driver. Our results suggest that planetary wave activity may play an important role there, since the correlation patterns identified by Raphael and Hobbs (2014) bear some resemblance to the mean planetary wave patterns identified in this study. The reason the resemblance is not stronger may be because the association between the PWI and sea ice coverage appears to be unidirectional in that region. In MAM, June–August (JJA), and September–November (SON), PWI values greater than the 90th percentile are associated with anomalously low sea ice concentrations, while values less than the 10th percentile are associated with near-average (as opposed to anomalously high) concentrations (not shown). Of course, any discussion of the atmospheric drivers of sea ice variability is complicated by the relationships between those drivers. For instance, the SAM and ENSO show many similarities in their influence on sea ice. It is unclear whether this is because they operate together in their response mechanism, or if the similarity is due to a preferred hemispheric planetary wave response (e.g., Pezza et al. 2012).

In contrast to the sea ice literature, planetary wave activity is scarcely mentioned in relation to SH precipitation variability, even in the regions of significant topography so clearly identified in this study. Instead, analyses of precipitation variability over New Zealand, Patagonia, and eastern Australia tend to focus on the SAM and ENSO, with the former generally becoming increasingly influential at higher latitudes (e.g., Ummenhofer and England 2007; Aravena and Luckman 2009; Kidston et al. 2009; Risbey et al. 2009; Garreaud et al. 2013; Jiang et al. 2013). Such analyses may inadvertently capture some of the zonal wave influence due to its similarity with the zonally asymmetric features of the SAM; however, Garreaud et al. (2013) do note that winter precipitation anomalies over Patagonia are dominated by a wavenumber 3 mode rather than a more zonally symmetric SAM pattern.

Planetary wave activity also receives scant attention in overviews and analyses of Antarctic temperature variability (e.g., Russell and McGregor 2010; Schneider et al. 2012; Yu et al. 2012). In the main, we find that the enhanced meridional flow associated with planetary wave activity brings warm air poleward, and thus, large positive temperature anomalies are seen throughout most of Antarctica, particularly during autumn and winter. The link between planetary wave activity and West Antarctica temperature variability is particularly interesting, given the large positive temperature trends observed in that region over recent decades (e.g., Bromwich et al. 2013). The winter trends over the interior of West Antarctica (Ding et al. 2011) and the spring trends over the western aspect of the Antarctic Peninsula (Ding and Steig 2013) have been linked to the Pacific–South American (PSA) pattern, which is the most prominent nonzonal planetary wave pattern in the Southern Hemisphere (e.g., Mo and Paegle 2001). Temperature variability in these seasons/regions was shown here to be strongly associated with the PWI, so future work will attempt to disentangle the influence of the PSA and zonal wave patterns in the region, so as to better understand the role of both in recent trends.

In characterizing the PSA pattern, this future work will further exploit the utility of the wave envelope construct by considering a more restricted wavenumber range and situations where the mean meridional flow is nonzero. In fact, the demonstrated utility and flexibility of the wave envelope suggests that it might also be a useful tool in similar NH investigations. The debate on the link between the Arctic amplification and planetary wave activity is far from settled, so the application of the wave envelope has the potential to yield important new insights.

REFERENCES


