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Anomalous two-day wave behavior during the 2006 austral summer

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[1] An anomalous behavior of the two-day wave is observed during the 2006 Austral Summer in the mesospheric temperature and line-of-sight wind, retrieved from the Microwave Limb Sounder (MLS) aboard NASA's Earth Observing System (EOS) Aura mission. During January 2006, the wave appears to exist in an unusually strong summer easterly jet, and its spectral signature spreads over a broader range of zonal wavenumber and frequency. In addition to the typical wavenumber 3 component, a wavenumber 2 disturbance with a near 2-day period is also evident, traveling westward at similar phase speed. The wavenumber 3 component exhibits the previously observed dual characteristics of both a normal and an instability mode, while the wavenumber 2 feature appears to be an instability mode, in agreement with recent theoretical calculations.
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1. Introduction

[2] The two-day wave is a recurring, westward propagating, planetary-scale disturbance found in the upper stratosphere up through the thermosphere. Readily observed after the solstice during the Austral and Boreal summers (around January and August, respectively), the wave amplitudes appear in close proximity to the summer easterly jet core, where vertical and meridional wind shears are pronounced [e.g., *Burks and Leovy*, 1986; *Norton and Thuburn*, 1996; *Garcia et al.*, 2005]. At low summer latitudes, the maximum meridional and zonal wind amplitudes in the mesosphere reach ~60 m/s and ~20 m/s, respectively [e.g., *Wu et al.*, 1993, 2008]. At middle summer latitudes, the mesospheric temperature wave amplitude exceeds 5 K [e.g., *Azeem et al.*, 2001; *Limpasuvan and Wu*, 2003].

[3] The observed two-day wave is generally dominated by a zonal wavenumber 3 (W3) component, particularly during the Austral summer in the Southern Hemisphere, with a corresponding 2.1-day period. The wave appearance has been explained as a global normal mode [e.g., *Salby*, 1981] or a manefestation of the easterly jet instability [*Plumb*, 1983; *Pfister*, 1985]. However, this W3 component generally exhibits dual characteristic of both a normal and an unstable mode [*Randel*, 1994; *Salby and Callaghan*, 2001]. The two-day wave's zonal wavenumber 4 (W4) component has also been reported with a corresponding period of ~1.8 days [e.g., *Burks and Leovy*, 1986; *Wu et al.*, 1996; *Limpasuvan et al.*, 2000a]. While weaker than the W3 component during the Austral summer, the W4 component tends to dominate the two-day wave disturbance during the Boreal summer. *Plumb* [1983] and *Pfister* [1985] demonstrated that the W4 component is consistent with an instability mode, a hypothesis further supported by a general circulation model simulation of *Norton and Thuburn* [1996].

[4] Interestingly, a few studies suggest that two-day wave may also have a zonal wavenumber 2 (W2) component. For the 1994 Boreal summer, *Riggin et al.* [2004] described a mesospheric two-day wave event that was dominated by a W2 component with a period between 1.4 to 4.0 days. In January of that same year, *Lieberman* [1999] observed the two-day wave as a mesospheric disturbance packet containing W2 component with a period of about 3.5 days, as well as W3 and W4 components mentioned above. *Nozawa et al.* [2003] suggested the predominace of W2 and W4 components over W3 in the higher northern latitudes between 76–88 km altitude. Recently, *Wu et al.* [2008] noted a strong W2 component of the two-day wave signature in the equatorial upper mesosphere during January 2006 with a period slightly shorter than 2 days. In general, unlike the W3 and W4 components, the observed period associated with the W2 component tends to vary considerably.

[5] To date, the presence of the W2 two-day wave component is unclear but may be also an instability outgrowth of the easterly jet. Instability calculations of *Pfister* [1985] initially indicated the possibility of W2 through W4 unstable modes of near 2-day period in the middle and high summer latitudes. For a Boreal summer background condition, *Rojas and Norton* [2007] recently found that one of the fastest growing mode is a westward propagating W2 component with a period of ~49 hours. They demonstrated that the W2 amplitude peaks near 60 degree summer latitude, with the meridional wind distubance peaking near the equator.

[6] In this paper, we present a new observational evidence of the W2 component of the two-day wave in mesospheric temperature and a special wind data product. In continuosly examing the two-day wave evolution in a two-year, global data set, we note the wave's anomalous behavior during the 2006 Austral Summer (relative to other summers) when the wave signature spreads out across a larger range of frequency and wavenumber. Such broadening of the wave signal results in a relative enhancement of the W2 component during 2006 January, a behavior not present at other times.

2. Data and Analysis

[7] As in work by *Limpasuvan et al.* [2005], we use the preliminary retrievals of mesospheric line-of-sight (LOS) wind from EOS MLS in the spacecraft's moving direction (see *Wu et al.* [2008] for more details about this data). For

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the polar-orbiting Aura satellite, the MLS LOS wind is dominated by the meridional wind component in the tropics, and therefore, winds derived from the northward (ascending) and southward (descending) tracks are directly out-of-phase. Only results from the ascending LOS wind profiles are presented in this study; descending LOS winds yeild very similar results. We also examine the EOS MLS temperature profiles from an offline research retrieval for the same time period. The data product spans nearly the entire globe with useful vertical range of 300-0.001 hPa and has a vertical resolution of ~4 km in the middle stratosphere (decreasing to ~10 km above 0.1 hPa). The time period of both data set is September 2004 through January 2007, which have been processed so far by the MLS research algorithm.

[8] The least-squared-fitting method of *Wu et al.* [1993, 1996] is applied to the data to extract the two-day wave. Based on an *a priori* assumption of the two-day wave recurring presence, the along-track profiles at each pressure levels are regressed onto a linear combination of cosine and sine functions of W3 at 0.48 cycles per day (cpd; ~2.1 day period) and W4 at 0.52 cpd (~1.8 day period) as done by *Limpasuvan et al.* [2005]. For W2, 0.49 cpd is used to be consistent with the recent instability calculation of *Rojas and Norton* [2007]. As discussed in the Introduction, the spectral peak associated with W2 can spread over a range of frequency. As such, the chosen 0.49 cpd fit is a first attempt to elucidate the wave structure. However, as shown later, the amplitude spectra of the data clearly show dominant peak near these chosen wavenumber-frequency pairs. This fitting method was successful in identifying the two-day wave in the preliminary EOS MLS data [*Wu et al.*, 2008].

3. Results

[9] Figure 1a shows the temperature amplitude evolution of the two-day wave for W2, W3, and W4 components at 91 km. Here, a 4-day sliding data window is used in the best fit method to compute the wave evolution. Such short data window allows for fine temporal details of transient events like the two-day wave (albeit noisier in amplitude). A larger sliding window makes the results smoother and diminishes the amplitude. However, the occurrence of the various two-day wave components and their relative strength are independent of the chosen length of data window.

[10] Relevant W2, W3, and W4 wave signatures in the summer hemisphere are highlighted by the black contours. The W3 signature is clearly most dominant, appearing between 10°S–70°S a few weeks after the winter solstices. Its Austral summer signature exceeds 5.5 K and is relatively more persistent during January 2006. The W4 feature appears mainly during the 2006 Boreal summer (4–9 August). The prevalence of W3 (W4) during the Austral (Boreal) summer concurs with the observations of *Wu et al.* [1996] and *Limpasuvan et al.* [2000a]. Modeling results *Limpasuvan et al*. [2000b] suggest that the climatologically weaker Northern Hemisphere summertime easterly jet preferentially excite the W4 unstable component. The corresponding two-day wave evolution in the LOS wind is illustrated in Figure 1b. The LOS wave amplitudes peak nearly the same time as the temperature disturbances. As shown by *Limpasuvan et al.* [2005] and *Wu et al.* [1993], the two-day wave meridional wind signature (which dominates the LOS data) extends across the equator toward the winter hemisphere.

[11] Unlike the typical two-day wave signatures observed in previous studies (mentioned in the Introduction) and those observed here during 2005 Austral Summer, the 2006 Austral Summer two-day wave exhibits an unusually large W2 component (Figures 1a and 1b). Around 21 January 2006, the temperature W2 component is quite pronounced in the summer latitude and the LOS wind W2 amplitude peaks strongly near the equator. For both temperature and LOS wind, the W2 component presence is in close spatial proximity to the dominant W3 component but trailing slightly in time. During other summer periods, the W2 signals are generally very weak.

[12] The enhanced W2 feature during January 2006 is further elucidated in the amplitude distribution over frequency and wavenumber (Figure 2). Here, the analyzed data length is approximately 30 days (corresponding to the dates noted on the plots) to capture a wide range of frequency. The least-squared-fitting method was done for each wavenumber and westward frequency in increments of 0.2 and 0.025 cpd, respectively, to obtain the amplitude spectra. During the 2005 Austral summer, the two-day wave amplitude is focused on W3 with a period of ~2.1 days (0.48 cpd), as shown in Figure 2 (left). This concentrated nature of the wave signature is typical for the Austral summer two-day wave, as reported in previous studies [e.g., *Limpasuvan et al.*, 2000a; *Limpasuvan and Wu*, 2003, and references therein]. During the 2006 Boreal summer (Figure 2, right), the wave amplitudes tend to focus more on W4, in agreement with the W4 dominance in the LOS wind and temperature evolution shown in Figures 1a and 1b.

[13] During 2006 Autral summer, the amplitude wavenumber-frequency distribution is clearly quite different. The signal is very strong but is very diffused, encompassing portions of W2 through W4 and larger frequency range. In particular, the W3 amplitude tends to be at frequency higher than 0.5 cpd, and the W2 amplitude (especially temperature) is located near 0.49 cpd (~2 days), similar to the W2 unstable mode identified recently by *Rojas and Norton* [2007]. The temperature spectral signature appears to split between W2 and W3. Because of the diffused/displaced nature of the two-day wave signature, the amplitude evolution of the W2 component (associated with 0.49 cpd, as shown in Figures 1a and 1b) reveals enhancement of the W2 during 2006 Austral Summer.

[14] Lines of constant phase speed are superimposed on the amplitude distribution shown in Figure 2. Note that the slope of these lines depends on phase speed and latitude. The line associated with faster phase speed or at higher latitude has steeper slope. Phase speeds of 40, 60, and 80 m/s are selected here to match the typical strength of the mesospheric summer easterly jet [e.g., *Garcia et al.*, 2005]. During the 2005 Austral Summer and 2006 Boreal Summer, the near 2-day period amplitude is generally confined around the center of the "rays" defined by the 40 and 80 m/s constant phase speed lines. However, the phase speeds of W2-4 are not exactly the same. During the 2006 Austral Summer, signatures near the 2-day period (0.5 cpd) are displaced off the rays center toward large phase speed. If the W2 and W3 components are associated with instability modes, Figure 2 (middle) suggests that the mesospheric

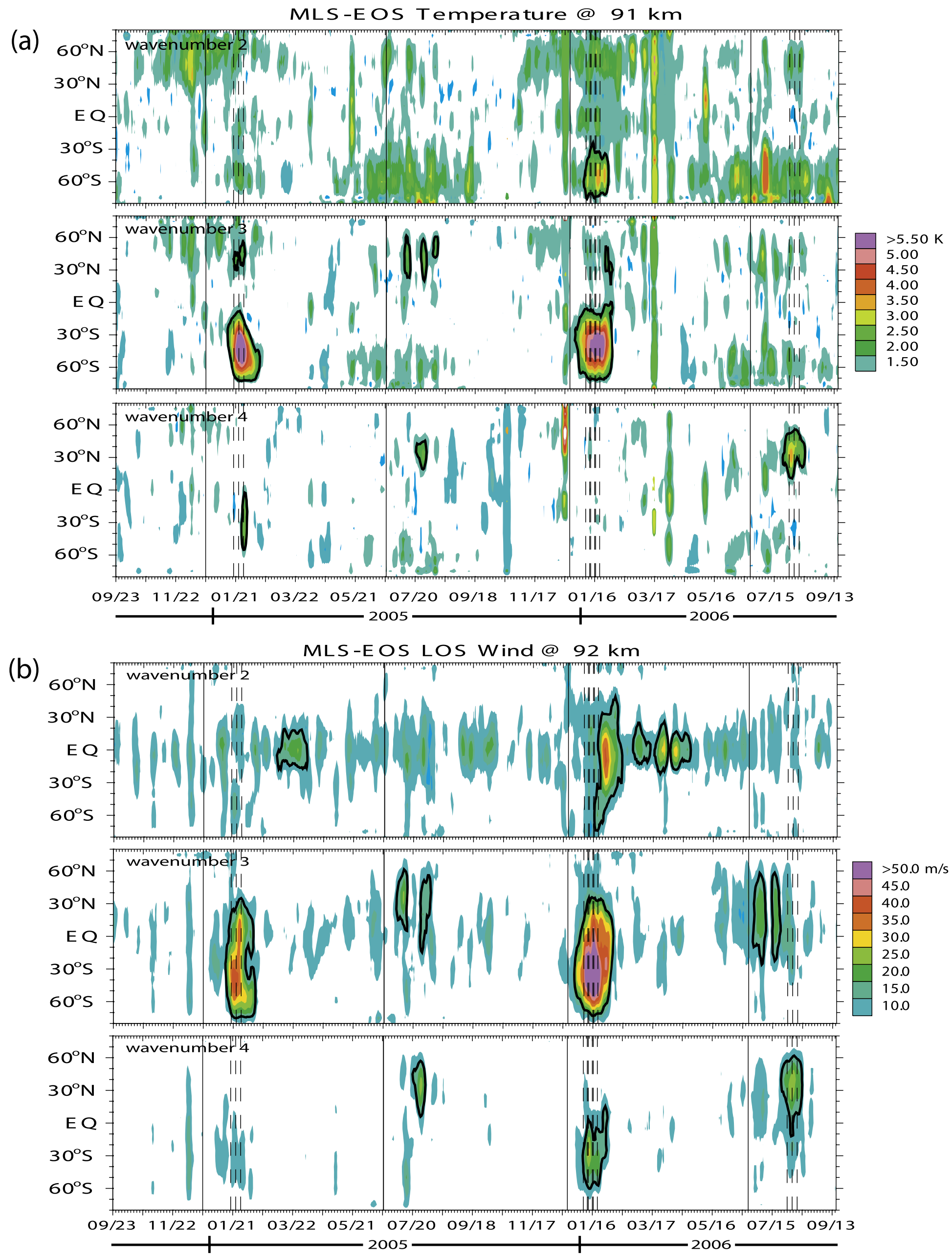

Figure 1. Latitude-time evolution of (a) the temperature wave amplitude at 91 km and (b) LOS wind data at 92 km. The along-track profiles at each pressure levels are regressed onto a linear combination of cosine and sine functions of zonal wavenumber 3 of 0.48 cycles per day (~2.1 day period) and zonal wavenumber 4 of 0.53 cycles per day (~1.9 day period). For zonal wavenumber 2, 0.49 cycles per day was used. The solid vertical lines mark the solstice. The 3 sets of dashed vertical lines indicate Jan. [19, 24, 29] of 2005, January [11, 16, 21] of 2006, and July 30, August [4, 9] of 2006.

easterly jet during the 2006 must be stronger than other summers.

[15] The W3 amplitude (at 0.48 cpd) cross sections are shown in Figure 3 (left) for early 2006. Only regions with coherence square (COH2) level above 95% are shown with respect to the largest amplitude peak. The method of *Blackman and Tukey* [1958] was used to evaluate the number of degrees of freedom (DOF) of the individual spectra at each latitude. Approximately, five DOF is attained, and the corresponding 95% confidence level for COH2 is about 0.55. During 14-18 January (when the W3 activity is strongest), the temperature amplitude exhibits the typical inverted wedge-like shape (as described by *Burks and Leovy* [1986]), ranging from 50 km to the upper observational limit. Below 80 km, the axis of maximum amplitude leans toward the summer pole as the amplitude's latitudinal extent grows with increasing altitude. The wave phase generally tilts westward with altitude (overlaid black contours predominantly increasing with elevation). A relatively weaker wave signature is evident in the winter (Northern) hemisphere near the stratopause and above 80 km. The associated winter disturbances tend to be out-of-phase with those found in the summer hemisphere.

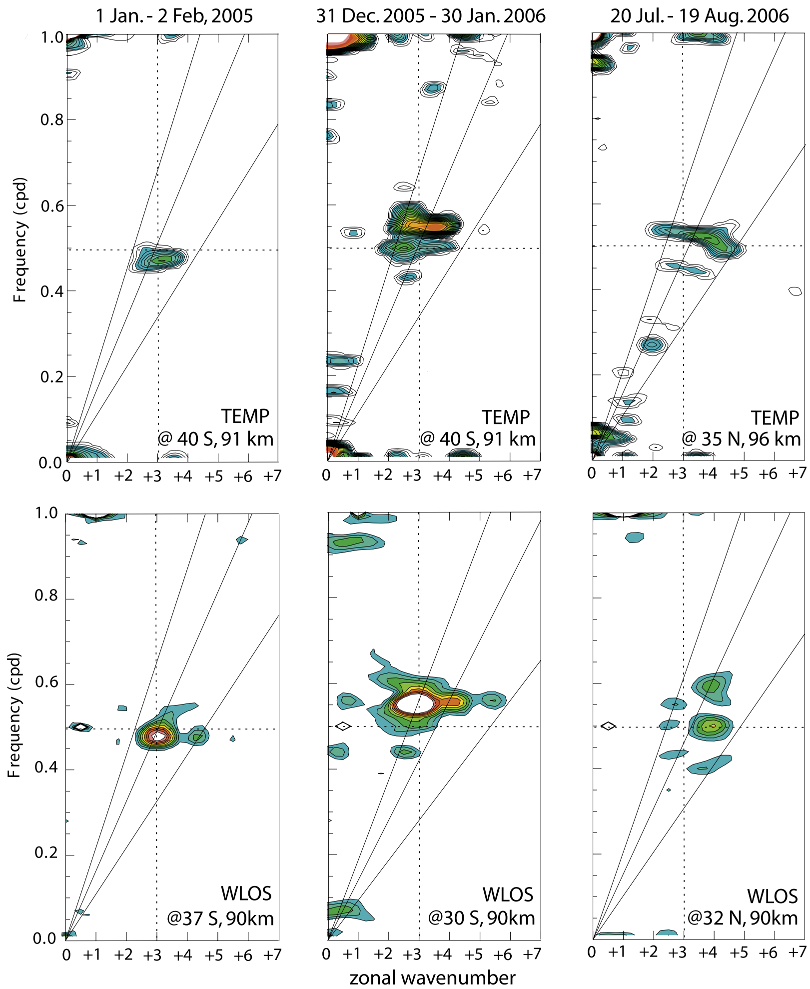

Figure 2. (top) EOS MLS temperature and (bottom) LOS wind amplitude as a function of frequency versus zonal wavenumber. Only westward propagating signals are shown as these regions (latitude and altitude) during the indicated the time range (over which these spectra are computed) are generally devoid of eastward propagating waves. For reference, the vertical (horizontal) dashed line indicates zonal wavenumber 3 (0.5 cycles per day, cpd). Slanted lines are lines of constant phase speed of 40, 60, and 80 m/s (in increasing order of steepness).

Overall, the described structure and magnitude bear strong resemblance to the temperature observations by previous studies [e.g., *Limpasuvan and Wu*, 2003; *Garcia et al.*, 2005] and are consistent with the characteristics of both a normal and unstable mode.

[16] The W3 LOS wind amplitude during 14–18 January 2006 reveals wind speed in excess of 45 m/s near 40°S at 90 km (Figure 3, bottom left). Like the temperature structure, the overall amplitude takes on an inverted wedge shape and the wave phase tilts westward with height. However, the structure is not evident at higher northern latitudes. As the two-day wave signature is larger in the meridional wind than in the zonal wind, the LOS wind is expected to exhibit significant disturbance. Indeed, the LOS wind amplitude structure and values are comparable to satellite observations of *Wu et al.* [1993].

[17] The strongest W2 signal (at 0.49 cpd) occurs during the 2006 Austral summer just slightly after the W3 component. The peak W2 temperature slightly precedes the W2 LOS wind (see Figures 1a and 1b). As shown in Figure 3 (right), the temperature structure during 19–22 January 2006 bears strong likeness to the W3 structure, with wedge-like structure in the summer hemisphere and relatively weaker amplitudes in the winter hemisphere. Although peaking closer to the equator, the LOS wind structure during 28 Jan. to 1 Feb. 2006 also looks very similar to its W3 counterpart. The W2 phase structure tilts generally westward with height in the summer latitudes.

[18] We emphasize that the W2 structure presented above is remarkably similar to the W2 fastest growing mode calculated by *Rojas and Norton* [2007] as discussed in the Introduction. Based on a linear instability analysis with a realistic easterly jet, these authors showed that the temperature structure maximizes around 60 degrees summer latitude and 80 km in altitude – similar to that shown in Figure 3. However, in the structure presented here, the W2 temperature amplitude has a relatively weak counterpart in the winter hemisphere. This difference is perhaps due to the smearing of the two-day wave signal over a greater range of wavenumbers/frequencies as shown in Figure 2 (middle), mixing the W3 normal mode chracteristics with the unstable W2 features. The meridional wind of the computed W2 unstable mode [see *Rojas and Norton*, 2007, Figure 4] exhibit

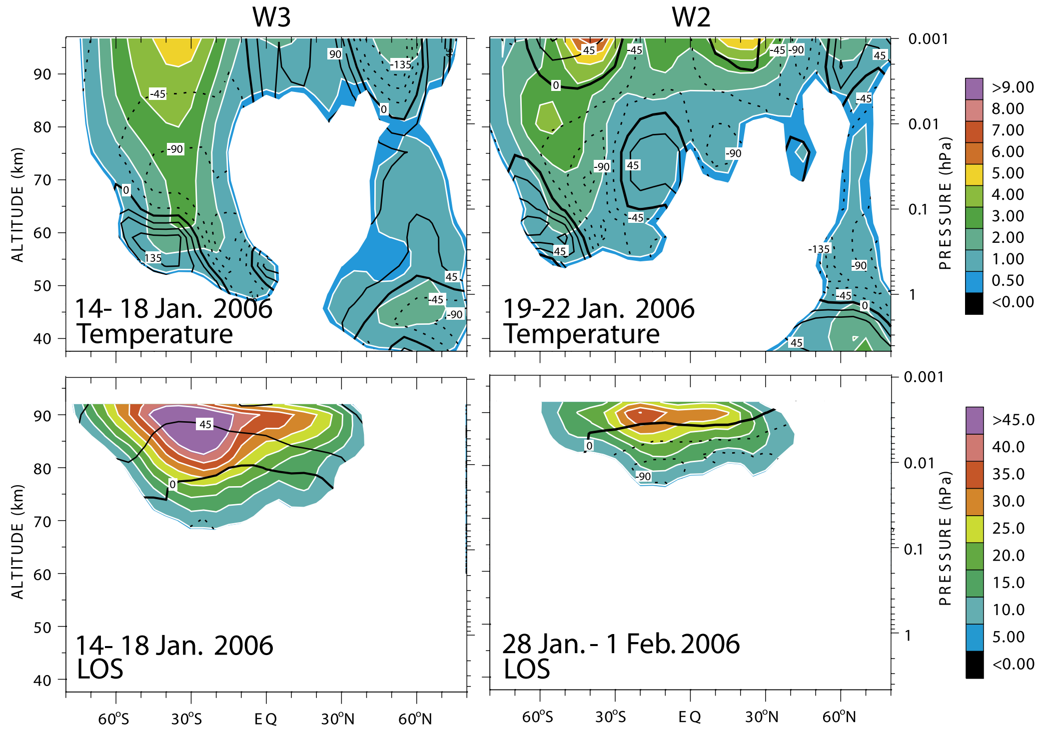

Figure 3. Meridional cross-section of wave amplitude (filled contours) during 2006 for (top) temperature and (bottom) LOS wind. Black contour lines indicate the wave phase in 45-degree intervals. Shown are the (left) W3 (at 0.48 cpd) and (right) W4 (0.49 cpd) amplitudes during the 2006 Austral summer.

an equatorial structure strikingly similar to that shown in Figure 3 (right).

4. Summary

[19] A recent, two-year observation of the global mesospheric temperature and line-of-sight wind derived from the EOS MLS indicates an unusual two-day wave behavior during the 2006 Austral summer. Unlike previous Austral summers noted in past studies and the 2005 Austral summer in the present data set, the temperature and wind disturbances are dominated by a W3 component, followed by a W2 component traveling westward (at similar phase speed) with nearly the same 2-day period. While typical two-day waves during the Austral summer tend to concentrate strongly on W3 (as shown in Figure 2, left), the spectral signature during 2006 Austral Summer wave is very diffused, covering a larger band of zonal wavenumber and period. The W3 power tends to be associated with a period slightly longer than 2 days and the W2 power (especially temperature) being instead closer to 2 days.

[20] Despite this unusual behavior, the meridional structure of the 2006 Austral summer W3 amplitude/phase is typical of the two-day wave. Its structure is similar to a normal mode with a relatively weak, nearly out-of-phase amplitude appearing concurrently in the winter hemisphere when the two-day wave was strongest. Yet, the overall W3 structure is also consistent with an instability mode of the summer easterly jet. In agreement with previous studies [e.g., *Fritts et al.*, 1999; *Lieberman*, 1999], the wave phase generally tilts westward with height indicating upward wave energy propagation based on the dispersion relationship of planetary-scale waves. This dual instability-normal mode existence of the W3 two-day wave is supported previously by models [e.g., *Salby and Callaghan*, 2001] and observations [e.g., *Randel*, 1994].

[21] In this study, we find that the meridional structure of the W2 wave is remarkably similar to W3 described above (Figure 3). The W2 amplitude and phase structures in the summer hemisphere appear consistent with the instability theory and in agreement with an instability mode recently calculated by *Rojas and Norton* [2007]. Given its period, the W2 does not appear to be consistent with a normal mode. The presence of the W2 signature in the winter hemisphere is most likely due to the leakage of the normal mode W3 characteristics onto W2, as possibly a result of the smeared nature of the amplitude spectra (Figure 2). If both W2 and W3 are instability modes, they should have similar phase speed nearly matching the background wind. If so, Figure 2 suggests that the 2006 Austral summer has an anomalously strong easterly jet.

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