Mesospheric planetary waves over Antarctica during 2002

P. J. Espy and R. E. Hibbins

British Antarctic Survey, Natural Environment Research Council, Cambridge, UK

D. M. Riggin and D. C. Fritts

Colorado Research Associates, NorthWest Research Associates, Boulder, Colorado, USA

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[1] Wind measurements from a series of atmospheric radars located around Antarctica have been used to characterize the mesospheric planetary-wave field during the winter of 2002. Combining winds from the medium-frequency (MF) radar at Rothera (68°S, 68°W) and the SuperDARN high-frequency meteor-wind radars at Halley (76°S, 27°W), Sanae (72°S, 3°W) and Syowa (69°S, 40°E) stations, we have been able to measure the period, wavenumber and propagation direction of the most prominent planetary waves. The results show that the planetary-wave field before the unusual stratospheric warming in 2002 was dominated by a very long-period ($\tau \approx 43$ days), westward and upward-propagating zonal planetary wavenumber 1. However, after the stratospheric warming events began in late winter, the character of the wave field changed and a shorter period ($\tau \approx 14$ days), westward, zonal wavenumber 1 became established. It would appear that the previously reported oscillations of the mesospheric hydroxyl airglow temperatures at Rothera and Halley, which were strongly anti-correlated to the meridional wind, were the result of these planetary waves.

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1. Introduction

[2] The unusual dynamical state of the southern hemisphere stratosphere during the winter of 2002 has been well documented by several recent works [*Baldwin et al.*, 2003; *Dowdy et al.*, 2004; *Siskind et al.*, 2005]. In addition, it has been recognized that these atypical conditions led to increased variability of winds and temperatures in the mesosphere over Antarctica [*Espy et al.*, 2003; *Hernandez*, 2003; *French et al.*, 2005], and have been linked to the high variability seen in the northern hemisphere [*Becker et al.*, 2004]. In particular, *Dowdy et al.* [2004] measured the period, direction and zonal wavenumber of a 14-day planetary wave present in mesospheric winds and temperatures coinciding with the onset of the minor stratospheric warming events and extending through the major warming. However, *Espy et al.* [2003] showed that mesospheric temperatures and winds, particularly the meridional winds, displayed synchronized, quasi-periodic variations throughout the winter season, well ahead of the stratospheric warming events in mid-August through late-September.

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[3] We present here observations of mesospheric meridional winds from a series of atmospheric radars separated by only 8° of latitude but by nearly 108° of longitude. These demonstrate that the coherent variations in temperature and wind observed by *Espy et al.* [2003] are primarily due to long-period, travelling and propagating planetary-scale waves throughout the winter season. In addition, the planetary wave observed by *Dowdy et al.* [2004] during the late winter represents a distinct change in the character of the planetary-wave field associated with the stratospheric warming events.

2. Instrumentation and Observations

[4] The radars used in this study have been described in detail elsewhere, and only the salient points will be mentioned here. The Rothera MF radar [*Jarvis et al.*, 1999] operates at 1.98 MHz, and the echoes received by spatially separated antennas are analysed using the full-correlation analysis technique [*Briggs*, 1984]. Estimates of the zonal and meridional components of the horizontal wind are derived typically between 70 and 100 km. Although the altitude resolution is 4 km, the data are sampled every 2 km with a temporal resolution of 2 min.

[5] The high-frequency radars at Syowa, Sanae and Halley stations are part of the global Super Dual Auroral Radar Network (SuperDARN, hereafter referred to as SD) operating at ~10 MHz in the northern and southern hemispheres [*Greenwald et al.*, 1985, 1995]. The "grainy, near-range echoes" from the radars have been shown to be due to meteor scattering between ~88 and 100 km, and the mesospheric wind has been derived from the motion of the meteor trails [*Hall et al.*, 1997; *Yukimatu and Tsutsumi*, 2002]. The data are integrated for 30 min, producing average zonal and meridional winds that have been validated against MF radar techniques and used to infer the dynamics and climatology of the mesopause region centred near 92 km [*Jenkins and Jarvis*, 1999; *Hussey et al.*, 2000].

[6] Although the SD radars all have a similar altitude range for the meteor echoes and subsequent wind determinations, it was necessary to average the altitude bins of the Rothera MF radar to match the SD altitude response. To determine this response, the winds from a digital ionospheric sounder, or dynasonde, that has operated as an Imaging Doppler Interferometer (IDI) at Halley [*Jones et al.*, 1997] were compared with the co-located Halley SD winds. Unfortunately due to a mast failure, the IDI winds were not available for 2002, and the mean meridional wind derived from each altitude bin of the IDI radar at Halley was correlated against the co-located SD winds during 2004.

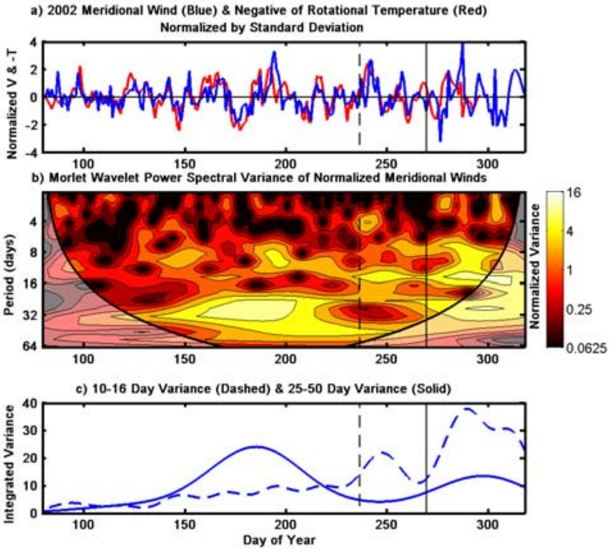

Figure 1. a) The meridional wind (blue) and hydroxyl temperature (red) over Rothera during 2002. The data have been de-trended (see text) and normalized by their respective standard deviations (8.8 $m \cdot s^{-1}$ and 8.0 K), and the location of the first minor and the major stratospheric warming are shown by the vertical dashed and solid lines, respectively. b) The local wavelet power spectrum of (a) using the Morlet wavelet. The normalized variance contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively, and the black areas represent normalized variances below 0.0625. The shaded areas below the cone-shaped solid lines are subject to end effects. c) The wavelet variance integrated over the 10–16 day band (dashed) and the 25–50 day band (solid).

The maximum correlation occurred for the range bin centred at 92.5 km, with a nominal half width of ~5 km. Thus, the Rothera MF radar altitude bins between 86 and 100 km were averaged to approximate the response of the IDI and SD systems. The individual observations of meridional wind from each of the aforementioned radars, averaged in altitude as described, were averaged over each 24-hour period, and the resulting daily mean winds between days 79 and 281 analysed. In order to examine the fluctuations of the wind from the seasonal average, the daily averaged model winds from the Horizontal Wind Model (HWM-93) [*Hedin et al.*, 1996] were subtracted from the data and the resulting time series were analysed as described below.

3. Analysis and Results

[7] *Espy et al.* [2003] and *French et al.* [2005] described large-amplitude, long-period oscillations in the nightly averaged mesopause temperature derived from hydroxyl airglow spectra. *Espy et al.* [2003] found these to be highly anti-correlated with similar fluctuations in the meridional wind that had been averaged over the same time period and the same altitude range of the hydroxyl airglow, 84 to 94 km over Rothera. These data, de-trended using the NRL-MSISE-00 model temperatures [*Hedin*, 1991] and HWM-93 winds, are shown in Figure 1a. It is clear from Figure 1a that the fluctuations are not constant in amplitude or period throughout the season. To assess this, a Morlet-wavelet transform [*Torrence and Compo*, 1998] was performed on each data set, and the results for the meridional wind, which are nearly identical to the transform of the temperatures, are shown in Figure 1b. Here large amplitudes in the 25–50 day range begin by day 120, peak near day 185, and continue through to the minor stratospheric warming events. The first of these three events, which peak on days 236, 244 and 256, and the major warming on day 269 [*Baldwin et al.*, 2003], are marked by the dashed and solid vertical lines, respectively, in Figure 1b. Leading up to the warming events, periods in the 10–16 day band grow and become the dominant modes before the peak of the first minor warming. To illustrate this, Figure 1c shows the time series of the spectral power integrated over the 25–50 and 10–16 day spectral bands. Here it appears that the shorter period oscillation grows as the longer period decays, and that the transition to the shorter periods dominating takes place just ahead of the stratospheric warming events.

[8] In order to assess whether these long, quasi-periodic oscillations had a longitudinal phase progression characteristic of planetary waves, we examined the meridional winds from the sequence of mesospheric wind radars around Antarctica. The time series of meridional winds from each station, smoothed with 7-day running means, are presented in Figure 2, where it is clear that the large wind excursions at Rothera are mirrored by similar variations at Halley, Sanae and Syowa. Following from the wavelet analysis, we examined the data from days 120 to 230 to assess the presence of long-period waves in the data sets. As the meteor wind data had occasional gaps, the Fourier technique of *Scargle* [1989] was used to assess the data for spectral content and phase. The power spectra indicated that each time series had its major peak, with a significance level greater than 90%, at periods between 38 and 46 days. Although the unapodized full-with-half-maximum of the resulting spectral line shape was ~15 days, the Fourier

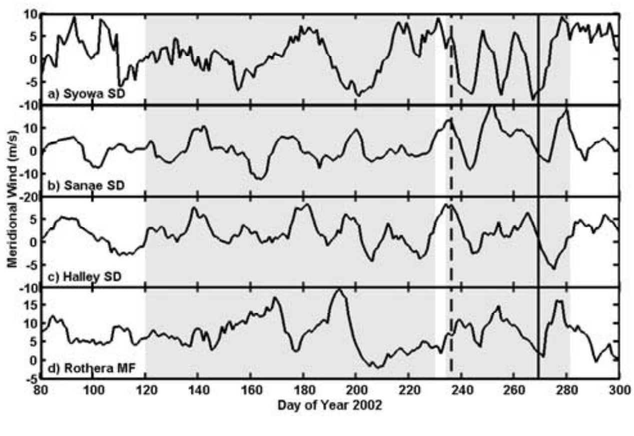

Figure 2. The meridional wind, smoothed by a running 7-day mean, from the longitudinally spaced radars: a) Syowa, SD. b) Sanae, SD. c) Halley, SD. d) Rothera, MF. The shaded areas represent the data used for the analysis of the 43-day (days 120–230) and 14-day (days 234–281) waves.

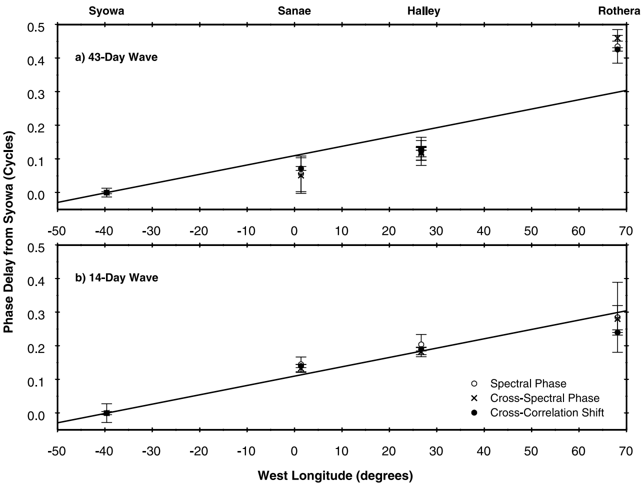

Figure 3. The phase delay with respect to west longitude of the a) 43-day wave derived for days 120 to 230, and the b) 14-day wave derived for days 234 to 284. The phase delay expected for zonal wavenumber 1 is shown by the solid line.

spectra were over-sampled to interpolate the peak positions. The average period for the four stations was 43.5 ± 3.2 days. The phase of the Fourier transforms showed a distinct progression from East to West, with the phase delay increasing from Syowa to Rothera.

[9] Utilizing the Fourier amplitudes, the cross-spectra and cross-correlations of each station relative to Syowa were constructed [*Scargle*, 1989]. Both the phase of the cross-spectra, and the shift of the cross-correlation functions, confirm the westward motion of the 43-day disturbance. Figure 3a shows the phase delay with respect to longitude from the three analyses. The phase delays are taken relative to Syowa, increasing westward, and the error bars represent the variation in the respective phases over the 43 ± 3 day peak. The phase slope of the spectral peaks, the cross-spectra and the cross−correlations are all consistent with the 43-day oscillation having a westward phase progression and a zonal wavenumber of 1. To illustrate this, the phase delay expected from a zonal wavenumber 1 wave is shown as the solid line in Figure 3a.

[10] The data between days 234 and 281, which the wavelet analysis shows to have been dominated by a shorter period oscillation, were analysed in the same manner as described above. Here, the major spectral peak was found to be 13.8 ± 0.7 days, in agreement with the work of *Dowdy et al.* [2004], who analysed the same time period using meridional winds from the MF radars at Davis, Syowa and Rothera. Figure 3b shows the phase delay, relative to Syowa, determined from the phase of the spectral peaks, the cross−spectra and the cross-correlations, with the error bars determined in the same manner as above. Here too, the phase slope of the 14-day oscillation is consistent with a westward phase progression and zonal wavenumber 1, as has been reported by *Dowdy et al.* [2004].

[11] Finally, in order to assess the propagation properties of these planetary-scale waves, we fitted sinusoids with 43 and 14-day periods, the average periods found in the above analyses, to daily running segments of the MF radar meridional wind. The individual segment lengths were set at three times the length of the sinusoid to be fit, and each 2 km altitude bin of the data was treated as a separate time series. The altitude progression of the phase delay of the 43-day period sinusoid, derived for days 120 through 230, is shown in Figure 4a, whilst the 14-day phase derived for days 234 through 281 is shown in Figure 4b. Both oscillations show a coherent phase structure with altitude, indicating the presence of waves at the two periods. The 43-day wave shows a phase advance with altitude, which would indicate an upward propagating planetary wave. Its phase slope yields a vertical wavelength of ~93 km, which indicates that this is the temporal signature of the wave observed in altitude and longitude by *Siskind et al.* [2005]. However, the phase of the 14-day period is constant with altitude to ~90 km, whereupon its phase also advances with increasing altitude. Thus, it has the characteristics of a travelling normal-mode oscillation that experiences virtually no damping in the wind fields weakened by the stratospheric warming. However, the wave begins to dissipate and transiently propagate in the vertical in the eastward wind regimes present above 90 km in the late winter season [*Salby*, 1981].

4. Summary

[12] Observations of mesospheric meridional winds from longitudinally spaced atmospheric radars have been used to measure the period, wavenumber, propagation direction and phase structure of the most prominent planetary waves present in the mesosphere during the 2002 Austral winter season. The results show that an upward propagating, 43-day planetary wave with zonal wavenumber 1 was present in the mesosphere from the start of the winter season. However, this wave weakened significantly just before the sequence of minor and major stratospheric warming events, after which a 14-day, westward travelling normal mode emerged and dominated the large-scale motion field.

[13] These results demonstrate that the coherent variations in temperature and wind observed by *Espy et al.* [2003], and the temperature extremes observed by *French et al.* [2005], are associated with the long-period planetary

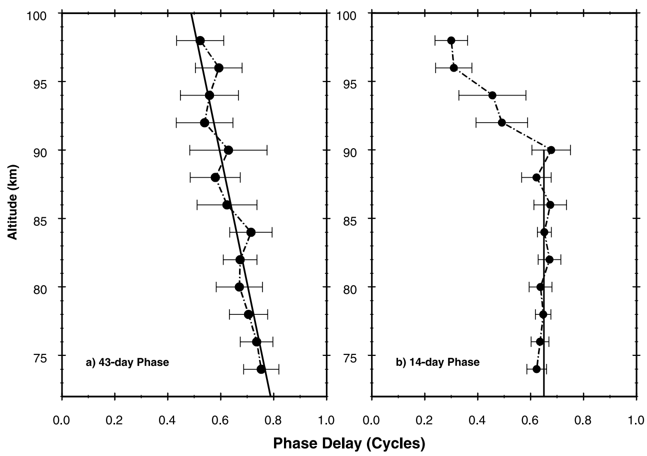

Figure 4. The phase delay with respect to altitude of the a) 43-day wave derived for days 120 to 230, and the b) 14-day wave derived for days 234 to 284. A decreasing phase delay represents a net phase advance with altitude.

wave that was present throughout the winter season. In addition, the planetary wave observed by *Dowdy et al.* [2004] during the late winter represents a distinct change in the character of the planetary-wave field associated with the stratospheric warming events. This is most likely due to changes in the filtering by the stratospheric winds brought about by the wind reversal.

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P. J. Espy and R. E. Hibbins, British Antarctic Survey, Physical Sciences Division, High Cross, Madingley Road, Cambridge, CB3 0ET, UK. (pje@bas.ac.uk)

D. C. Fritts and D. M. Riggin, Colorado Research Associates, NorthWest Research Associates, 3380 Mitchell Lane, Boulder, CO 80301, USA.