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The 4-day wave in the Antarctic mesosphere

Bryan N. Lawrence

Rutherford Appleton Laboratory and The University of Oxford, Oxford, United Kingdom

Grahame J. Fraser

The University of Canterbury, Christchurch, New Zealand

Robert A. Vincent and Andre Phillips [1]

The University of Adelaide, Adelaide, Australia

Abstract. A zonal wave number one eastward propagating planetary wave observed in the high latitude winter stratosphere with a period near 4 days has been studied by a number of previous authors. Radar observations coupled with stratospheric analyses are here used to demonstrate that this wave, known as the 4-day wave, extends into the Antarctic upper mesosphere. Previous workers have asserted that the wave is a manifestation of the observation of warm pools rotating in the polar vortex, and that the pool seems to behave in a quasi-nondispersive manner. The observation of the 4-day wave in the upper mesosphere presented here appears to validate previous claims that the warm pools are being maintained by wavelike dynamics, rather than simple advection.

1. Introduction

The 4-day wave is a winter polar stratospheric phenomenon, first reported by Venne & Stanford (1979) and Venne & Stanford (1982) (hereinafter V&S). Using zonal space-time spectra computed from satellite radiances, they found power near a period of 4 days in both the northern and southern hemisphere winters, peaking in amplitude at about 70 degrees latitude. The wave was seen to travel eastward and have zonal wave number one. In the southern hemisphere the wave phase was observed to tilt eastward with decreasing (equatorward) latitude, leading V&S to conclude that the wave was transporting momentum from the polar region into the jet. By contrast, in the northern hemisphere the wave slope was westward and equatorward, suggesting momentum was being removed from the jet by the wave. Little phase tilt was observed with height in either hemisphere.

Subsequent investigations by Prata (1984) led to the observation that this wave was a manifestation of the spectral analysis of a warm pool orbiting the pole with a period of around 4 days. Further investigation of the spectral characteristics of this feature led to the discovery of a significant zonal wave two power with a period around 2 days and power at 1.2 days in the zonal wave three spectrum. Prata noted that the period taken to encircle the pole was not consistent with simple advection of a warm pool, and concluded that nonlinear dynamics were involved.

Lait & Stanford (1988) (hereinafter L&S) further analyzed SSU data using an asynoptic space-time Fourier transform technique. They were also able to identify a zonal wave four feature with a period of 0.8 days. Examination of the latitudinal structure revealed that wave one had two amplitude peaks in latitude, and the amplitude maxima for the other three components (waves two, three and four) moved poleward in latitude with decreasing wave number. Each of the components exhibited almost no phase tilt with height.

L&S were also able to produce twice daily synoptic maps, which revealed several warm pools rotating around the pole with periods between 3.5 and 4.0 days. These pools were observed through many cycles, with one lasting seven full revolutions: about a month. At times multiple pools were observed, and one example of the collision and coalescence of a pair of such pools was shown.

A number of theoretical investigations into the existence of such features have been completed. Venne (1980) utilizing the polar beta plane first introduced by Haurwitz (1940a) and Haurwitz (1940b) and subsequently investigated by Bridger & Stephens (1980), hypothesized that the 4-day wave exhibited the charac-

[1]Now at the British Antarctic Survey, Cambridge, United Kingdom.

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teristics of a Doppler shifted resonant free wave. However, his explanation did not explain the existence of the higher order modes.

Hartmann (1983) who examined the unstable modes of a linear nondivergent barotropic model of the stratosphere, was able to predict the existence of wave number two and three harmonics, and explain much of the structure of the wave. In the same paper, Hartmann also used a quasi-geostrophic model to examine the effect of divergence and baroclinicity on the unstable modes identified using the barotropic model. With this second model, Hartmann examined the vertical structure of the modes for a jet structure with vertical shear. He found that the amplitude of the maximum wave one occurred at around 75°S, and about one scale height above the level of maximum wind. In contrast to V&S (at least for the southern hemisphere) his investigation predicted the waves were transporting momentum away from the jet (poleward).

Manney et al. (1988) (hereinafter MNSa) extended Hartmann's barotropic analysis using a variety of mean state profiles including realistic summer and winter profiles. They found that decreasing the width of a jet caused the poleward modes to become more dispersive and unstable, eventually causing the most unstable poleward mode to shift from zonal wave number one to wave number two. In addition, increasing the strength of the jet was observed to cause the modes to grow faster, decreased the period, but had no appreciable effect on the dispersion. When the jet was closer to the equator, the poleward modes were observed to be more stable and more dispersive. When the jet was skewed toward the pole (i.e., the falloff in zonal wind speed was slower on the poleward side), the poleward modes grew faster.

As a consequence MNSa concluded that if what they called quasi-nondispersive features (QNDF) arose from barotropic instability, they would be expected to appear at times when the polar night jet was comparatively broad and peaked at high latitudes, and either symmetric or skewed poleward, causing a region of negative absolute vorticity gradient only on the poleward side of the jet. They also noted that such conditions might not necessarily be required for a long period of time, and might not be visible in the average statistics; the wind fields need only maintain barotropic instability (on a daily basis) through the growth period of the wave in order for it to be observed.

MNSa were not able to state clearly whether the observed QNDF were moving slower than the background state (in accordance with Prata (1984)), but stated that the features definitely traveled slower than the peak wind speed. They commented that this would imply the existence of a critical latitude (where the wave phase speed equals the zonal wind speed) between the jet maximum and the pole, which is in accordance with the barotropic instability explanation.

Manney et al. (1989) (hereinafter MNSb) extended their previous analysis of realistic stratospheric states by examining the stability of a basic state including a jet and a traveling wave. It had been hypothesized by Hartmann (1983) that such a basic state might favor the appearance, through a barotropic instability mechanism, of a disturbance that included higher zonal wave numbers, moving with the basic state wave. In the two cases examined by MNSb where the traveling waves were eastward moving wave one, higher wave number disturbances appeared that moved with the same speed as the basic state wave, although without enough amplitude to appear as localized as observed by L&S. In addition, these disturbances only appeared for a narrow range of basic state wave amplitudes. Examination of growth rates with other waves suggested that the presence of a strong quasi-stationary wave number one on the equatorward flank of the jet could preclude the growth of the QNDF. In all cases they concluded that growth times for modes which are caused by instability of the zonal jet may be changed dramatically by the presence of the (basic state) wave while their periods and spatial structure are relatively unaltered.

Manney (1991) examined 10 years of standard National Meteorological Center (NMC) data (the same data as used below) and showed that the 4-day wave was often prominent during July and August during that period. She further showed that the wave appeared to manifest two types of behavior: the first, consistent with barotropic instability of the stratospheric night jet, as suggested above, and the second due to barotropic instability of the double peaked mesospheric jet above. The latter cases were also examined by Randel & Lait (1991) who used the synoptic maps produced by L&S, coupled with base level geopotential data from the Climate Analysis Center of the NMC (CAC/NMC), to produce horizontal wind fields at levels near 1.5 hPa (53 km), 5 hPa (46 km) and 15 hPa (37 km). Using the wind fields they were able to demonstrate that in many cases the dynamics of the wave appeared to be very consistent with barotropic instability of the mesospheric double jet. These studies were extended by Manney & Randel (1993) who carried out a three-dimensional stability analysis of climatological wind fields near the polar stratopause. They found rapid growth rates for wave periods near 4 days and significantly, more rapid growth rates for the Southern Hemisphere - consistent with the more frequent observations of the wave there.

Fraser et al. (1993) used simultaneous wind data from the radar at Scott Base and the Fabry Perot instrument at South Pole to identify high frequency components in the winds in the mesosphere at very high latitudes. They asserted that these were manifestations of the 4-day wave discussed above. This conclusion is supported by the work described here, which uses more extensive data from Scott Base and data from other Southern Hemisphere locations capable of measuring mesospheric winds. Their analysis, completed after the work described here, and using data from almost a decade later, is evidence of the ubiquity of the 4-day wave not only in the upper stratosphere, but also in the upper mesosphere.

2. Data

The material presented in this paper is based on two main data sources: partial reflection radar winds, and the CAC/NMC stratospheric analyses available from the U.S. National Center for Atmospheric Research (NCAR).

2.1. Radar Winds

Wind measurements at mesospheric heights are gathered on a regular basis at four southern hemisphere radar stations: Adelaide (35°S, 138°E), Christchurch (43°S,172°E), Mawson Base (67°S, 63°E) and Scott Base (78°S, 167°E). The latter two stations are on the Antarctic continent and provide the only continuous climatological measurements of the mesosphere from the region south of New Zealand. The examination of data was limited to 1983 and 1984 from Scott Base, 1983-1985 from Christchurch, August 1984 and all of 1985 from Mawson Base, and 1984 from Adelaide.

The radar winds are obtained using the partial reflection technique first introduced by Fraser (1965) from heights between 60 and 105 km. Measurements are made every few minutes at vertical intervals of 1-3 km (depending on the installation). Details of the equipment used are given by MacLeod & Vincent (1985) and Fraser (1989), and the analysis method in Briggs (1984) and Hocking et al. (1989). Because of a lack of echoes, it was not always possible to have regular measurements, so hourly averages were used as the basic element of the time series; however, even at hourly intervals there were considerable periods during which no data were obtained.

In order to provide time series with enough resolution in time, but with infrequent missing data points, the hourly radar averages were first binned by averaging three adjacent heights and all measurements for 2 hours. The resulting series were then binned again in time to produce 6 hour averages at 80, 85, 90 and 95 km. This procedure is here referred to as "triple height and time smoothing." Any remaining missing points were filled using linear interpolation. The series was smoothed with a quarter-half-quarter filter, except for the examination of the harmonics (Figure 2), and the cross spectra (Figure 9). Because the vertical scale of the 4-day wave was expected to be large, the vertical averaging should not have affected the results in any significant way. Not all months and locations had sufficient data for time series analysis, but both July and August 1983 and 1984 at Christchurch and Scott Base had enough data. Each month was examined by producing spectra of the zonal and meridional winds separately at each height, using the 120-point series ob-

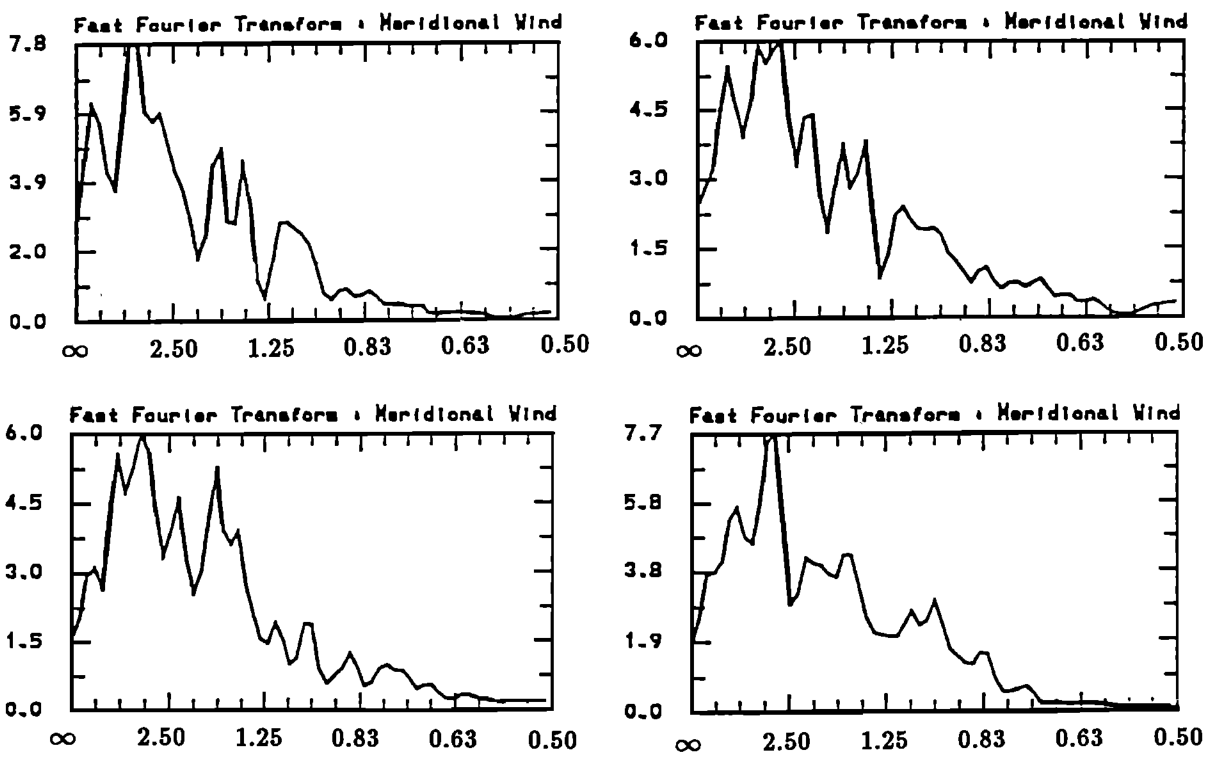

Figure 1. Smoothed amplitude spectra from (top) 80 and 85 km, and (bottom) 90 and 95 km. The vertical axis is periodogram amplitude in meters per second, the horizontal, period in days. A fast Fourier transform with extension by zeroes was used to produce the spectra.

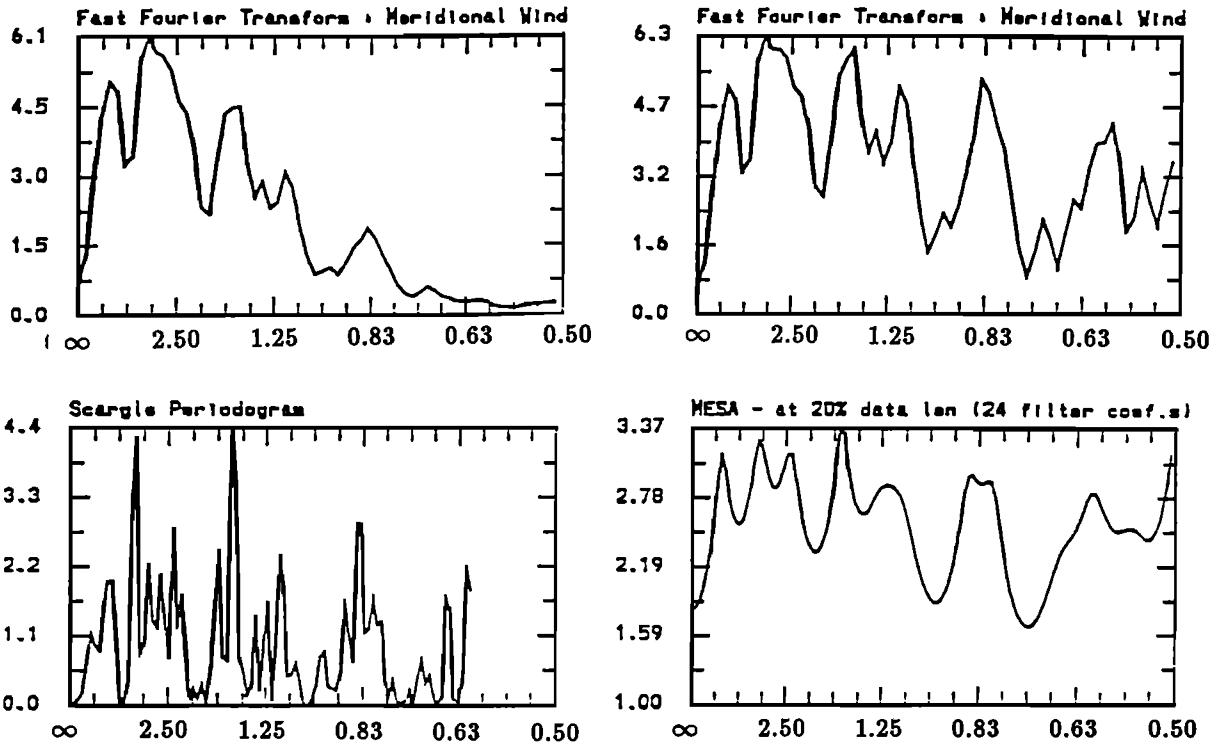

Figure 2. Evidence for the harmonics from 87 km: (Top left) fast Fourier transform (FFT) spectrum of the smoothed series, (top right) FFT spectrum of the unsmoothed series, (bottom left) amplitude spectrum produced by the Scargle method, and (bottom right) maximum entropy (MEM) spectrum. (For this and all plots to follow, Fourier spectra show amplitude in meters per second and the MEM spectra log spectral density, unless otherwise noted). The horizontal axis is period in days. The data series used was not the product of triple height and time smoothing, it was simply 6-hour binned data from 87 km.

tained from the 6 hour binned data. Examination of the individual time series was also used to choose subjectively periods of interest. Results are presented from two short periods here, from July 1983 when the wave was the most prominent above Scott Base, and August 1984 when data were available at both Scott Base and Mawson Base.

2.2. Stratospheric Analyses

Stratospheric analyses for 1983-1985 available from NCAR were used to look for the wave in the stratosphere. The analyses consisted of temperature and geopotential fields at each of 100, 70, 50, 30, 10, 5, 2, 1, and 0.4 hPa at 1200 UT. Each field consisted of 4225 points on a grid set down in polar stereographic coordinates. The grids were initially produced by the Climate Analysis Centre (CAC), Washington, by using satellite-retrieved layer mean temperatures in a successive correction scheme on top of the 100 hPa NMC analysis Randel & Stanford (1985). These data were used to provide the 1 hPa synoptic maps of temperature in Figure 6.

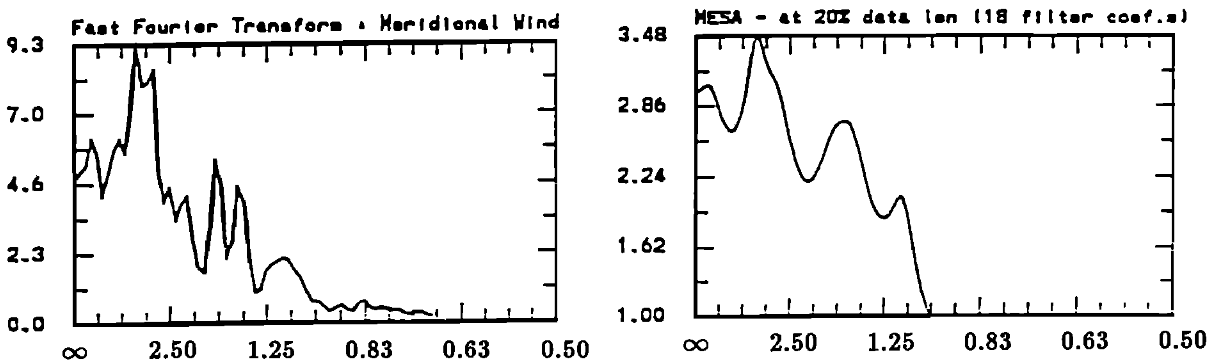

Figure 3. Comparison spectrum from 83 km with simple 8-hour means: evidence that the results are independant of the data averaging method. (Left) fast Fourier transform amplitude spectrum, and (right) maximum entropy log spectral density.

3. Analysis of Data

Since the observations detailed by V&S showed that the amplitude of the "4-day" wave appeared to increase into the upper stratosphere, an investigation of the radar winds was carried out to see if there was any evidence for dynamic effects reaching the upper mesosphere.

The only way such effects could manifest themselves in the radar winds would be via the observation of periodicities in the winds with periods of between 2.5 and 4.0 days and the concomitant harmonics. For this reason time series analysis was attempted.

Both Fourier transform periodograms (amplitude spectra) and maximum entropy based spectra were produced. For the periodograms, amplitude spectra (which are closer to the physical information of interest as opposed to the power spectra) smoothed with one pass of a Hanning filter are shown here. For the maximum entropy spectra, log spectral density is displayed, in order to deemphasize the spurious nature of some of the signal amplitude fluctuations. In addition, to confirm that missing data were not a problem, the Scargle method (Scargle, 1982; Press & Teukolsky, 1988), which only uses the available data, was also used to produce amplitude spectra. All procedures were repeated with different series length and different binning to ensure that the data treatment was not producing spurious peaks.

In general the winter spectra obtained were quite "noisy" at all locations and heights, a not unexpected result. Nonetheless, in general the zonal wind spectra were dominated by low frequency components (greater than 10 day periods) with the meridional wind spectra featuring considerably more spectral amplitude in the 1- to 10-day range.

3.1. The 4-day wave, 1983

Both spectral analysis (Figure 1) and examination of time series from Scott Base show a clear episode of an oscillation in the meridional wind which has a primary period near 4 days with a number of harmonics which are consistent with the observations above. The oscillation is discernable in both the time series and spectra from all heights, but the harmonics are not prominent at all heights, presumably due to interference from the general planetary wave noise expected at these heights (Lawrence, 1990). All spectra in this section are from a 30 day series starting on July 9th, 1983.

The amplitude appears to be around 6-10 m/s in the meridional component, with the harmonic amplitudes somewhat smaller as expected. This amplitude is almost certain to be an underestimate; first, because the wave was not apparent during all the entire period, and second because the spectra were produced by using a fast Fourier transform (FFT), which meant that the series was initially extended with zeroes. Not all harmonics are present at all heights, and none of them can be isolated as statistically significant in the plots, since the series lengths are too small to give significance to other than the strongest peak in the spectrum. In order to ensure that the analysis method was not contributing to the harmonic power, other methods of spectral analysis were also used (Figure 2). The repeated appearance at a number of heights, coupled with their appearance in series which are binned at both 6 and 8 hours (e.g., Figure 3), leads one to have confidence in the (a posteriori) reality of these features. Although the "4 day" components are not as obvious in the zonal wind spectra, which are generally dominated by a low-frequency (> 10 day) peak, the MEM spectrum (Figure 4, right) seems to indicate that the zonal wind has weak features at periods corresponding to the disturbance even though the higher frequency peaks in the periodogram (Figure 4, left) are far from signifcant.

To confirm whether these observations were contemporaneous with the appearance of the 4-day wave in the stratosphere below, two investigations were carried out. First, space time series analysis was used to investigate the data for the presence of eastward wave number one energy at the appropriate frequences, and second, daily synoptic maps of temperature on the 1 hPa surface were examined.

Space Time Spectral Analysis Since the NMC data is available only daily, the Nyquist period is 2 days. In order to have some spectral fidelity near 4 days and to minimise leakage from longer period phenomena it

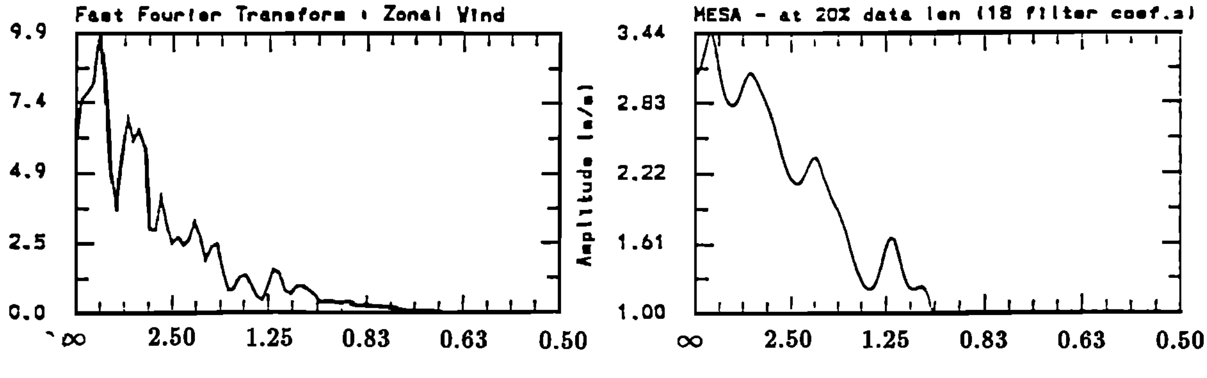

Figure 4. Zonal wind spectra from 80 km, 1983. (Left) fast Fourier transform amplitude spectrum, and (right) maximum entropy log spectral density.

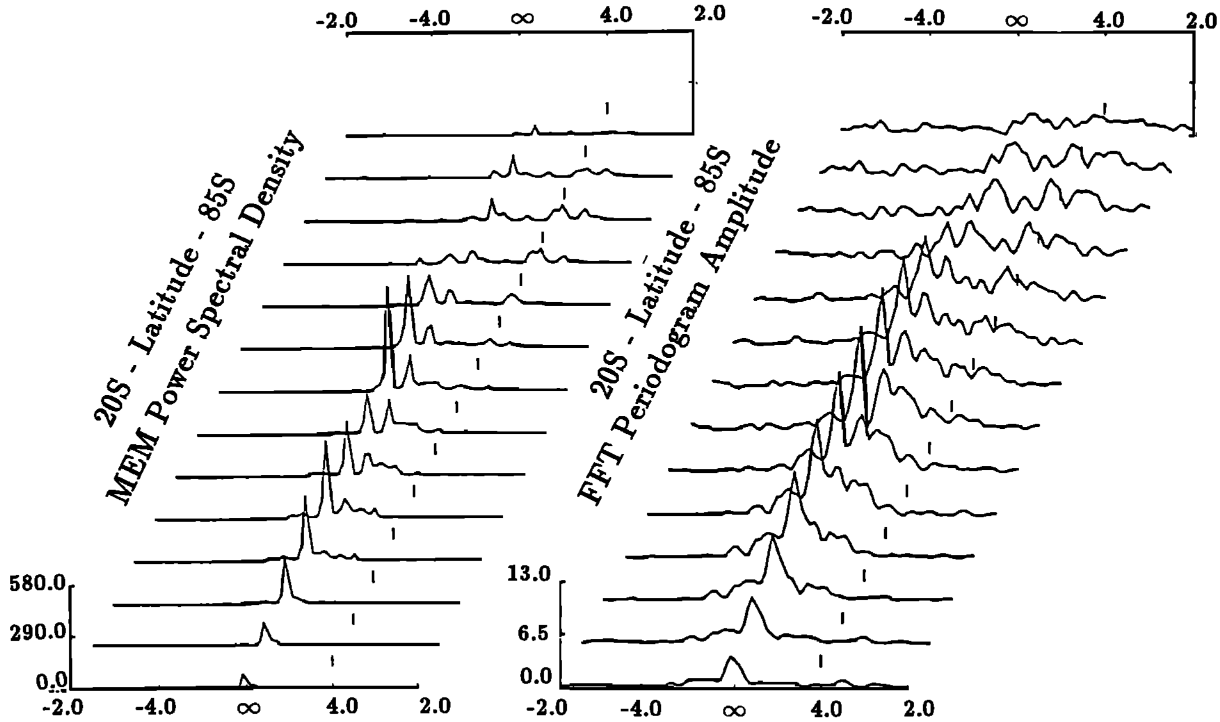

Figure 5. Space time spectral analysis for 10 hPa (July 1 for 90 days). (Left) spectral density as produced by maximum entropy, and (right) Fourier amplitude spectra. Westward power is at negative frequencies. The position of eastward moving 4.0 day power is marked on each spectrum with a vertical bar. Spectra are produced at 5 degrees of latitude intervals, with 20°S at the bottom and 85°S at the top. The increase in power near 4 days at high latitudes is obvious in both sets of spectra.

was found necessary to analyse time series of ninety days, which means that small peaks near 4 days in the spectra produced here are simply evidence that a weak 4-day component existed some time during winter 1983 (or possibly that a strong component existed for a short time). However, Figure 5 shows that a polar eastward moving wave number one temperature disturbance did exist at 1 hPa during winter 1983, and that its latitudinal structure was as expected. The identification of this disturbance with the expected 4-day wave is assisted by the observation of Venne (1985) that by far the largest contributions to the eastward moving wave one and two at high latitudes were from the 4-day wave. (Venne also showed a westward moving feature near 2.4 days in the wave two data and attributed it to aliasing of 4-day wave harmonics.)

In an effort to demonstrate the likely existence of the associated eastward moving disturbances of the wind components, space time series analysis was also carried out on the geopotential and derived wind components. Unfortunately, for 1983 these spectra showed little eastward moving power near 4 days. However, during 1984 there is some power at the appropriate frequencies. It is not clear whether the lack of power in 1983 was a consequence of the analysis scheme smoothing out the 4-day wave in the geopotential (and hence in the derived winds), or whether the wave had no manifestation in these fields.

Synoptic Maps. To further confirm that the eastward moving features observed in the space-time spectral analysis are a manifestation of the 4-day wave, synoptic maps are used to demonstrate that the peak in the spectra is associated with a warm pool of temperature rotating around the pole. An example of such a warm pool, similar to that reported above is shown from July 1983, a period during which the 4-day wave was identified in the radar data. One 4 day sequence is displayed (Figure 6), each map is a polar stereographic projection, with the 40°S latitude circle on the rim, the south pole at the centre, and the Greenwich Meridian on the left. The temperature maps clearly show the eastward movement of a region of warm temperatures - generally at least 10 degrees warmer than the surrounding air mass at these heights.

3.2. The 4-day wave, 1984

A similar picture can be seen in the spectra from 1984, although the wave is not as obvious in the time series of winds from Scott Base. In August 1984, data is available at all four radar stations, so time series analysis was carried out at all the locations.

No power was found at planetary wave frequencies for Adelaide for August 1984 as shown by the Scargle periodogram in Figure 7. As an aside, Figure 7 also demonstrates the dangers of applying linear interpola-

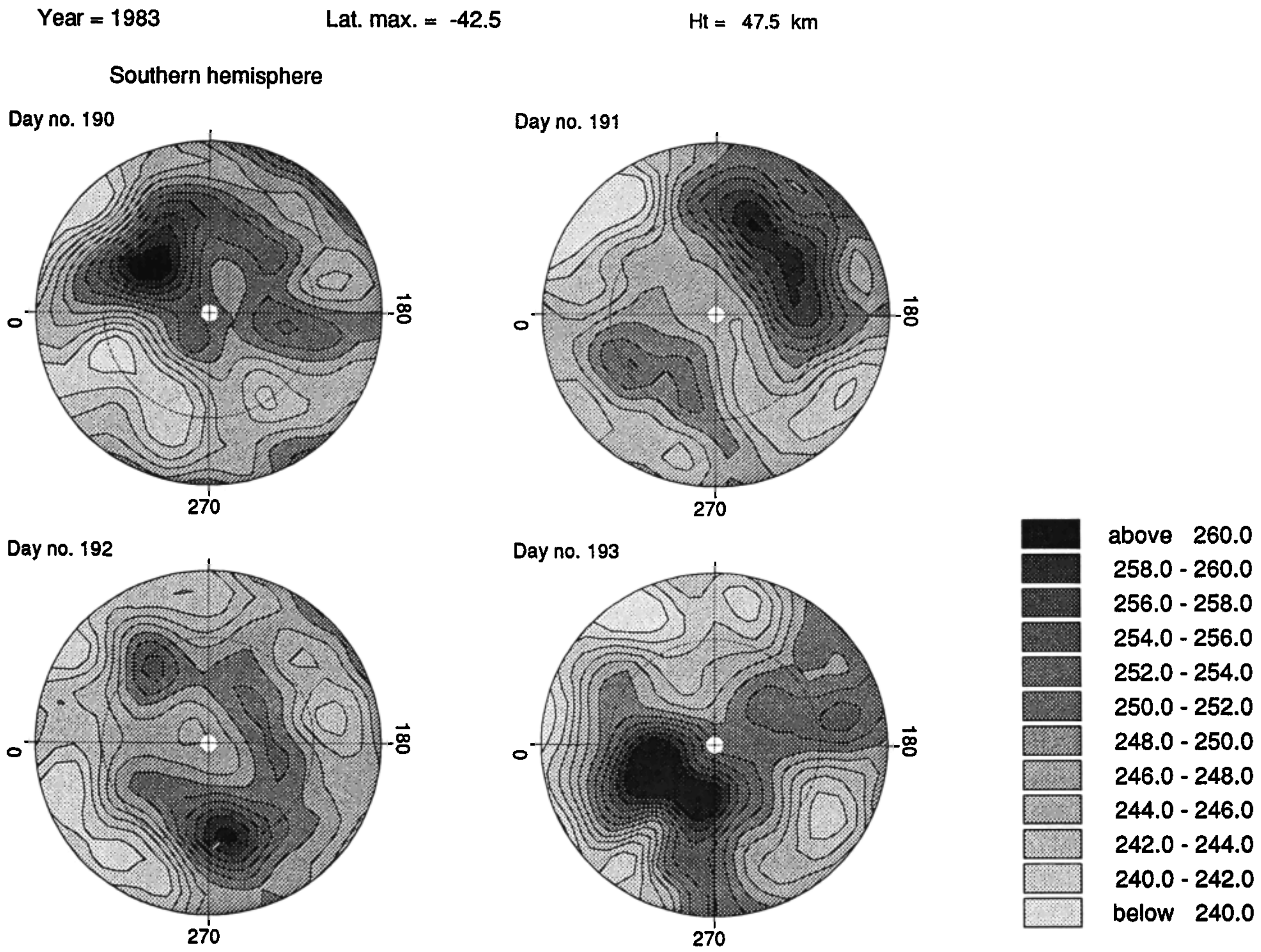

Figure 6. Synoptic maps of temperature at 1 hPa. The outer ring is at 40°S, the inner ring at 60°S with 0°E on the left. The warm pool can be seen centred near 65°S and 45°E on day 190 (of 1983) and clearly rotates eastward over the next three days.

tion and filtering to the data without prior knowledge of the spectral content of the data. The FFT periodogram shown in this figure was produced from the smoothed data series with 8% of the data (10 points) filled by linear interpolation. The amplitude response at lower frequencies is a completely spurious consequence of the interpolation coupled with the quarter-half-quarter smoothing. Removal of the smoothing increases the 1-day power so it is obviously dominant, and the Scargle method demonstrates that the low-frequency power is purely due to the interpolation.

Spectra from Christchurch (Figure 8, left) show that

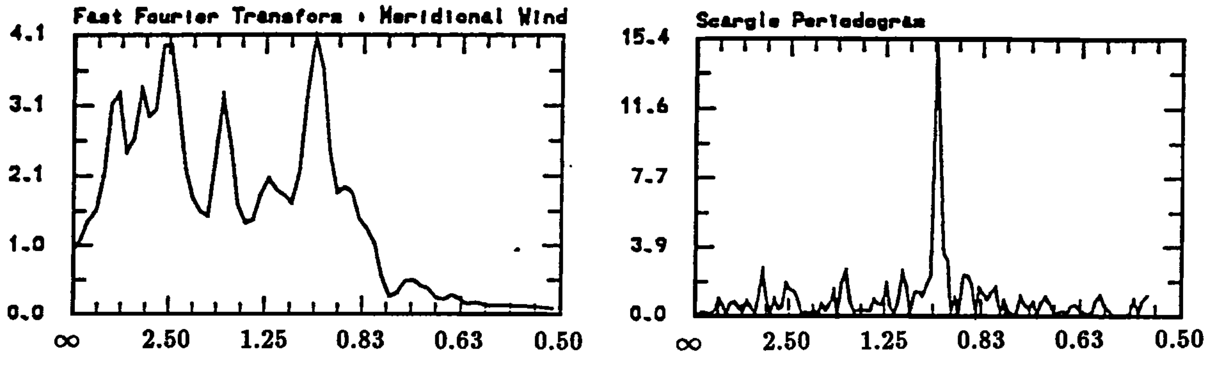

Figure 7. Meridional wind spectra from 90 km at Adelaide: evidence for caution in spectral analysis. (Left) fast Fourier transform periodogram of the standard smoothed triple height and time series. (Right) Scargle periodogram of the triple height and time series, with no replacement of missing data or final time smoothing.

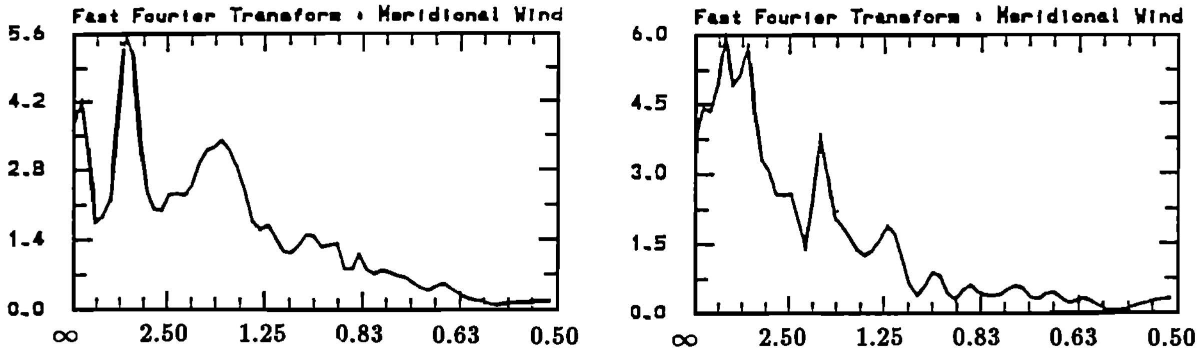

Figure 8. Meridional wind spectra from (left) Christchurch 80 km and (right) Mawson Base 85 km. Standard fast Fourier transform periodograms of smoothed triple height and time series.

the effect of the 4-day wave is also seen in the meridional winds there, although weakly. The wave is also visible in the winds from Mawson Base (Figure 8, right), and so cross spectral analysis between Mawson Base and Scott Base was carried out.

The cross spectral analysis was carried out using both FFT methods similar to those of Otnes & Enochson (1972), and using a Numerical Algorithms Group (NAG) package based on the Blackman-Tukey scheme. Both methods gave similar results, and the cross spectra for two heights are shown in Figure 9, with the phases for the various frequencies displayed in table 1.

The results of the cross spectral analysis are completely consistent with the hypothesis that the dominant spectral contribution is due to a zonal wave one "4-day" wave and its harmonics. The harmonics are seen to have scales which are consistent with the first harmonic being wave number two, the second, wave number three. The fourth harmonic is not distinguishable in 1984.

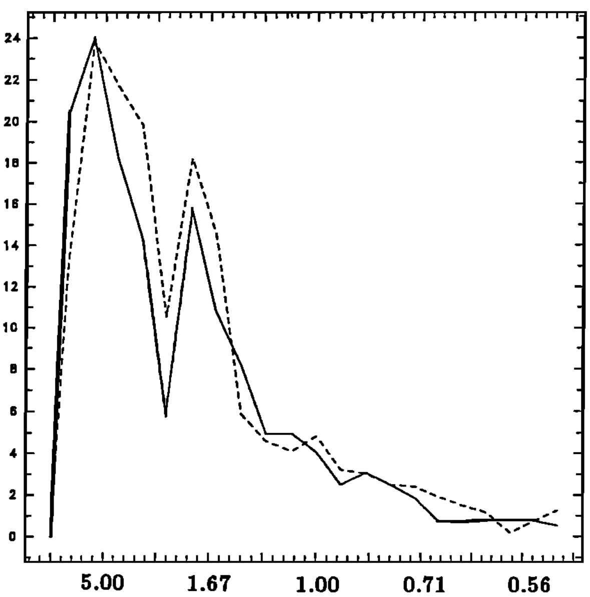

Figure 9. Cross spectral amplitude between Mawson Base and Scott Base for August 1984. Note that the bandwidth of the spectral estimate is such that the 6-day peak would include power down to 3.5 days. The vertical axis is cross spectral amplitude in meters per second, and the horizontal axis is period in days.

Cross spectral analysis between Christchurch and Scott Base showed appropriate amplitude behavior but the phase was not stable enough to provide any useful information.

4. Discussion

It is important to take care with the interpretation of spectral data alone. The period of primary interest is rather close to that of the normal mode 5-day wave reported many times in the literature. Without spatial information (in particular with respect to the direction of propagation), the separation of the 5-day wave mode from the 4-day mode is not really possible. Unfortunately, the situation is compounded by the probable coexistence of these modes (evidence for the coexistence is given by Figure 7 of Hirota & Hirooka (1984)) during transient buildup and decay.

Nonetheless, the presence of the harmonics suggests that the observed wave is definitely the eastward moving 4-day wave. This coupled with the existence of the wave in the NMC data at the same time gives confidence to the identification. The observations at upper mesospheric heights are new and must give some further observational constraints on the origin of the wave.

Table 1. Cross Spectral Phase Between Mawson Base and Scott Base for August 1984

Period (days)	85 km	90 km	Theory
6.0	96	118	104
1.9	124	174	208
1.1	-77	-74	-48

Note that the bandwidth of the spectral estimate is such that the 6 day peak would include power down to 3.5 days. The theoretical phase difference, assuming zonal waves one to three, is displayed in the fourth column. It can be seen that reasonable agreement is found.

Clearly there is no question of the atmosphere being in solid rotation with a period near 4 days at upper mesospheric heights, thus the mean wind must be unable to advect anything around a latitude circle in a period of 4 days, and so the observations must be of a propagating wave per se, as opposed to the mean flow advection of a warm pool. This conclusion had already been made (essentially the reasoning behind the QNDF description) and is entirely consistent with the energetic study of Randel & Lait (1991), but the wave period has not previously been unambiguously isolated from the mean flow rotation period.

It is not clear how the wave activity reaches the upper mesospheric heights. The large-scale barotropic nature of the southern hemisphere polar winter stratosphere is well known (Randel & Lait, 1991), but the observation of the harmonics at altitudes separated by 40 km suggests that the wave maintains its nondispersive nature much higher than expected. It has been demonstrated (Lawrence, 1990) that apart from normal mode activity and direct propagation, planetary wave activity in the upper mesosphere could be due to the modulation of gravity waves by stratospheric planetary waves. Such modulation can result in planetary scale disturbances in the mesosphere due to differential momentum deposition as the gravity waves break. However, given that the spectral analysis of the actual stratospheric winds was not able to detect the wave, it seems unlikely that gravity wave modulation has a part to play in the dynamics of the 4-day wave. It must be assumed that the same nonlinear characteristics which maintain the non-dispersive characteristic of the wave in the stratosphere, also contribute to its maintenance with altitude. Unfortunately, due to the vertical averaging applied to these data, the vertical structure of the wave at mesospheric heights cannot be unambiguously determined. It is hoped that the more sophisticated wind analysis software now installed at Scott Base might lead to data more amenable to this type of investigation.

MNSb noted that the QNDF might not be evident during times when the observed quasi-stationary zonal wave one is particularly strong. It is quite evident from the wave amplitudes presented by Lawrence (1990) that the stationary wave activity is not strong on the poleward side of the jet during July, which is consistent with the prominent wave noted in July 1983. However, during August 1984 the stratospheric wave one is quite strong around 60°S, yet the wave is still observed at Christchurch, Mawson Base, and Scott Base.

The observation of the 4-day wave together, with its harmonics, indicates the potential presence of QNDF in the upper mesosphere. Although they are not always present in the winter spectra taken from the radar winds, they do appear in each winter examined. This observation is consistent with the expectation that they appear whenever there is a region of negative potential vorticity gradient on the poleward side of the jet (all 3 years examined here). If the wave was ever detected in the radar data and not in contemporaneous satellite data, one would need to consider mechanisms not involving barotropic instability of the polar night jet. Any such detection would have to ensure that contributions to the spectrum from normal mode activity were carefully isolated.

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References

Bridger, A. & Stephens, D. Long atmospheric waves and the polar-plane approximation to the earth's spherical geometry. *J. Atmos. Sci.*, *37*, 534-544, 1980.

Briggs, B. The analysis of spaced sensor records by correlation techniques. pp 166-186, *Handbook for MAP, volume 13.* Edited by R. Vincent. International Council of Scientific Unions, Paris, 1984

Fraser, G. Monthly mean winds in the mesosphere at 44S and 78S. *Pure. Appl. Geophys.*, *130*, 291–301, 1989.

Fraser, G., Hernandez, G., & Smith, R. Eastward-moving 2-4 day waves in the winter antarctic mesosphere. *Geo. Res. L.*, *20*, 1547–1550, 1993.

Fraser, G. J. The measurement of atmospheric winds at altitudes of 64-120km using ground based radio equipment. *J. Atmos. Sci.*, *22*, 217-218, 1965.

Hartmann, D. L. Barotropic instability of the polar night jet stream. *J. Atmos. Sci.*, *40*, 817–835, 1983.

Haurwitz, B. The motion of atmospheric disturbances. *J. Mar. Res.*, *3*, 34, 1940a.

Haurwitz, B. The motion of atmospheric disturbances on the spherical earth. *J. Mar. Res.*, *3*, 254, 1940b.

Hirota, I., and T. Hirooka. Normal mode Rossby waves observed in the upper stratosphere. Part I: First symmetric modes of zonal wavenumbers 1 and 2. *J. Atmos. Sci.*, *41*, 1253–1267, 1984.

Hocking, W., P. May, and J. Röttger. Interpretation, reliability and accuracies of parameters deduced by the spaced antenna method in middle atmosphere applications. *Pure Appl. Geophys.*, *130*, 571-604, 1989.

Lait, L. R., and J. Stanford. Fast, long-lived features in the polar stratosphere. *J. Atmos. Sci.*, *45*, 3800–3809, 1988.

Lawrence, B. N. *The Southern Hemisphere Mid-*

dle Atmosphere: Climatology and Waves. Ph.D. thesis, Phys. Dep., University of Canterbury, Christchurch, New Zealand, 1990.

MacLeod, R., and R. Vincent. Observations in the antarctic summer mesosphere using the spaced antenna technique, 1985. *J. Atmos. Terr. Phys.*, *47*, 567–574.

Manney, G., and W. Randel. Instability at the winter stratop[uase: A mechanism for the 4-day wave. *J. Atmos. Sci.*, *50*, 3928–3938, 1993.

Manney, G. L. The stratospheric 4-day wave in NMC data. *J. Atmos. Sci.*, *48*, 1798–1811, 1991.

Manney, G. L., T. R. Nathan, and J.L. Stanford. Barotropic stability of realistic stratospheric jets. *J. Atmos. Sci.*, *45*, 2545–2555, 1988.

Manney, G. L., T. R. Nathan, and J.L. Stanford. Barotropic instability of basic states with a realistic jet and a wave. *J. Atmos. Sci.*, *46*, 1250–1273, 1989.

Otnes, R., and L. Enochson. *Digital Time Series Analysis.* John Wiley and Sons, New York, 1972.

Prata, A. The 4-day wave. *J. Atmos. Sci.*, *41*, 150–155, 1984.

Press, W. H., and S. A. Teukolsky. Search algorithm for weak periodic signals in unevenly spaced data. *Comp. Phys.*, *2*, 77–82, 1988.

Randel, W. J., and L. R. Lait. Dynamics of the 4-day wave in the southern hemisphere polar stratosphere. *J. Atmos. Sci.*, *48*, 2496–2508, 1991.

Randel, W. J., and J.L. Stanford. An observational study of medium-scale wave dynamics in the southern hemisphere summer. Part I. Wave structure and energetics. *J. Atmos. Sci.*, *42*, 1172–1188, 1985.

Scargle, J. D. Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data. *Astrophys. J.*, *263*, 835–853, 1982.

Venne, D. E. A 4-day winter polar stratosphere temperature wave: Observation and theory, in *Handbook for MAP, volume 2.* International Council of Scientific Unions, Paris, 1980.

Venne, D. E. The horizontal structure of travelling planetary waves in the upper stratosphere. *J. Geophys. Res.*, *90*, 3869–3879, 1985.

Venne, D. E., and J.L. Stanford. Observation of a 4-day temperature wave in the polar winter stratosphere. *J. Atmos. Sci.*, *36*, 2016–2019, 1979.

Venne, D. E., and J. L. Stanford. An observational study of high-latitude stratospheric planetary waves in winter. *J. Atmos. Sci.*, *39*, 1026–1034, 1982.

G.J. Fraser, Physics Department, University of Canterbury, Christchurch, New Zealand.

B.N. Lawrence, R25 Space Sciences Division, Rutherford Appleton Laboratory, OX11 0QX, United Kingdom.

A. Phillips and R.A. Vincent, Physics Department, University of Adelaide, Adelaide, South Australia.

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