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UPPER MESOSPHERE DYNAMICAL BEHAVIOR NEAR SOUTH POLE

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Abstract: Recent ground-based measurements of the neutral winds and temperatures at mesospheric heights near the Earth's rotational pole, at Amundsen-Scott Station, show that the neutral atmosphere has a restricted zonal wavenumber behavior at very-high latitudes. This can be interpreted as the natural response of the atmosphere to the boundary conditions at the rotational pole(s). Experimentally, mostly planetary-scale waves have been observed during the austral winter.

1. Introduction

The experimental ground-based investigation of the neutral upper atmosphere near the rotational poles has shown that the boundary conditions at these locations allow only a few coherent oscillations to occur (HERNANDEZ *et al.*, 1992a, b, 1993, 1995; FRASER *et al.*, 1993). Although at low and midlatitudes the upper atmosphere supports a large variety of oscillations with varying periods and amplitudes, as the rotational poles are approached the atmosphere can no longer support all these oscillations. Only a few of them are left with enough amplitude to be observable. Also, those oscillations which are allowed to occur near the rotational pole have special properties.

Here we review the results near Amundsen-Scott Station (South Pole) derived from ground-based optical measurements of the motions and kinetic temperature of the neutral upper mesosphere, as well as the questions that these new findings have raised.

2. Experimental

The measurements of the Doppler shift and width of the $P_1(2)$ line of the (6–2) band of natural airglow emission by OH at 840 nm have been used (HERNANDEZ *et al.*, 1992a, b, 1993, 1995, 1996; FRASER *et al.*, 1993) as a tracer of the atmospheric behavior at the height of emission of this tracer species, which is near 88 km (WITT *et al.*, 1979).

The actual measurements are made with a high-luminosity, self-aligned Fabry-Perot spectrometer (HERNANDEZ and MILLS, 1973) operated at a resolving power of about 300,000. This resolving power is an operational compromise permitting the simultaneous study of the [OI] 630 nm emission from the upper thermosphere with the mesospheric studies. The inherent instrumental stability is near 1–2 m/s over the long term, making it possible to obtain long-term series of measurements of known reliability. The observations are made at 30° elevation above the horizon in order to determine the line-of-sight Doppler shift and the width of the emissions of interest; this places the measured regions about 150 km equatorward from South Pole. All observations are made at eight equally spaced azimuth directions and the zenith. Arbitrarily, we have defined the direction towards the Geomagnetic Pole (at 120° E) as the reckoning point for the azimuth scans. Although the measurement is light-limited, the duration of a typical measurement in any of the directions is typically about 5–10 min. The determinations made from measurements spanning this time range give uncertainties of velocity and temperature measurements of about 5 m/s and 8 K, respectively.

3. Results

Part of the observations obtained during August 1991, given in Fig. 1, show a strong wind oscillation of about 10–12 hours period, superimposed on longer period oscillations. The winds are presented as zonal (u_m) and meridional (v_m) direction winds in geomagnetic coordinates, where the South direction is at 120° E.

Examination of these data with modified power spectrum, or periodogram, techniques is illustrated in Fig. 2. The figure shows that only a few (statistically significant) oscillations are present in the wind, mostly at 10.1-hr and near 2-day periodicity, while the temperature shows just a few long period oscillations. However, the temperature periodicities are not the same as the periodicities found for the winds. This is clearly illustrated in Fig. 2.

The frequency region near 0.1/hr (periodicity of 10 hrs) is illustrated for both

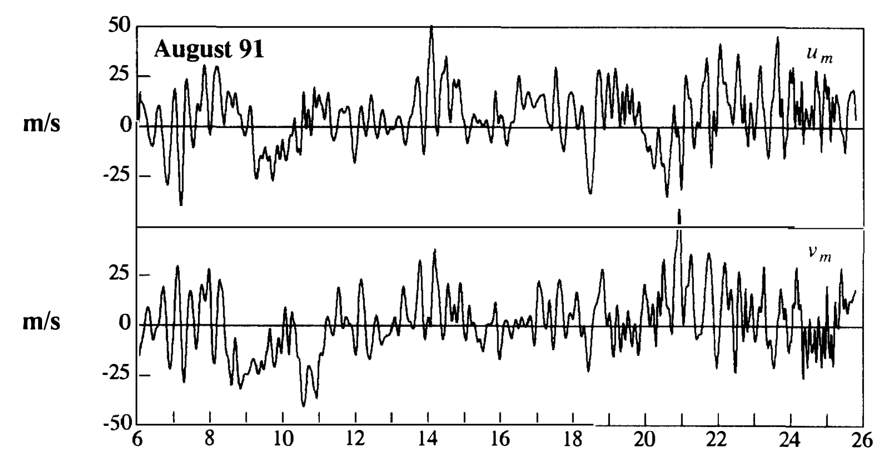

Fig. 1. Measurement of the zonal and meridional winds for 6 August 1991 to 26 August 1991 near South Pole. Note the short-term oscillations riding on the longer period oscillations. Geomagnetic coordinates are used for the directions of the motions.

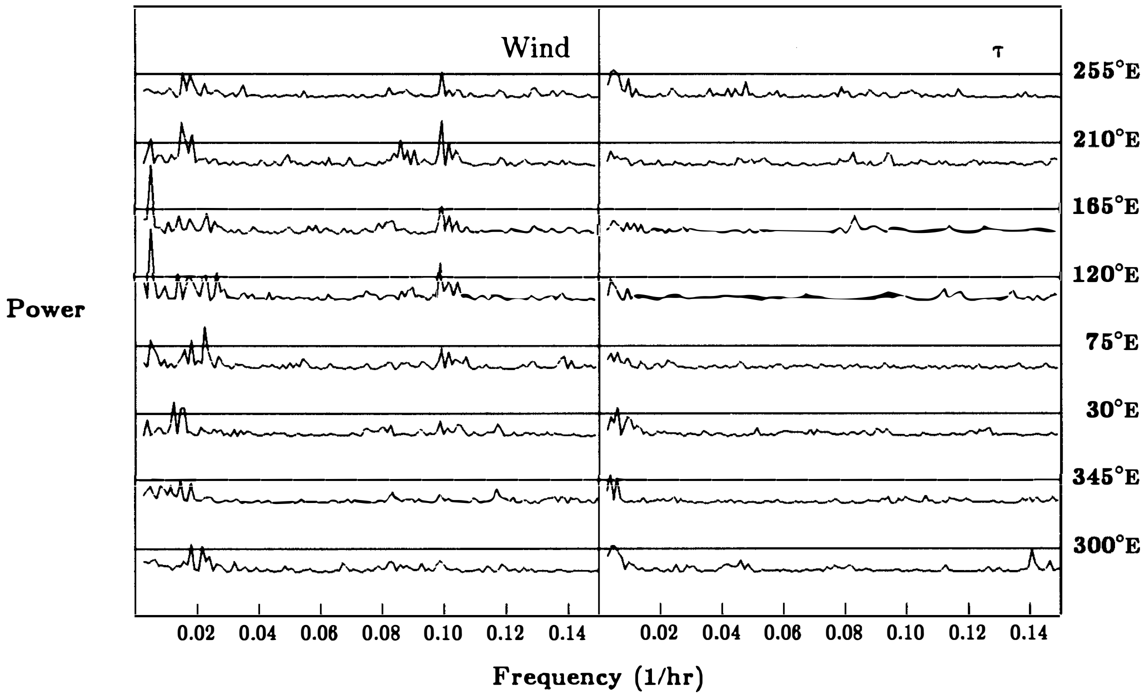

Fig. 2. Periodogram, relative to the 95% statistical confidence level for the 1–25 August 1995 mesospheric data from South Pole. The longitudes of measurement are indicated on the right of the figure.

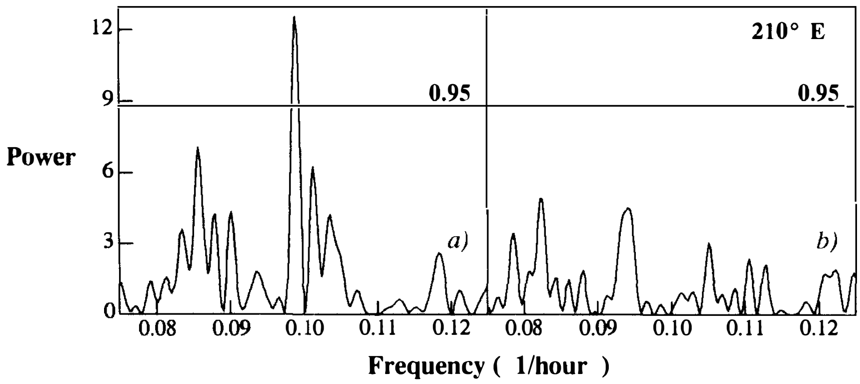

Fig. 3. Periodograms for the a) wind and b) kinetic temperature measurements at South Pole from August 1, 1991 to August 25, 1991. Measurements made in the 210°E direction. The 95% significance level is indicated; note the absence of significant temperature oscillations at the same frequency as the wind.

the wind and temperature in Fig. 3 and Fig. 4 for August 1991 and for August 1992, respectively. These figures show the 10.1-hr oscillation is present both years at the 95% statistical significance level, while in the August 1992 data of Fig. 4, a 12.2-hr oscillation is also found to be statistically significant. In both figures, the temperature measurements displayed on the right show no statistically significant oscillations.

Since our measurements are made at 8 equally-spaced azimuths, at the rotational pole it is possible to follow the motion of these oscillations with longitude (or

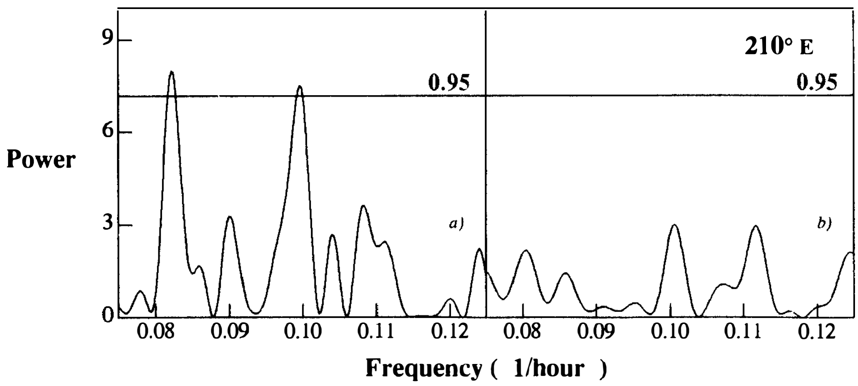

Fig. 4. Same as Fig. 3, except for measurements from August 1, 1992 to August 13, 1992. The appearance of a statistically significant oscillation near 0.08/hr (or near 12-hr periodicity) in the wind, is the highlight of this figure.

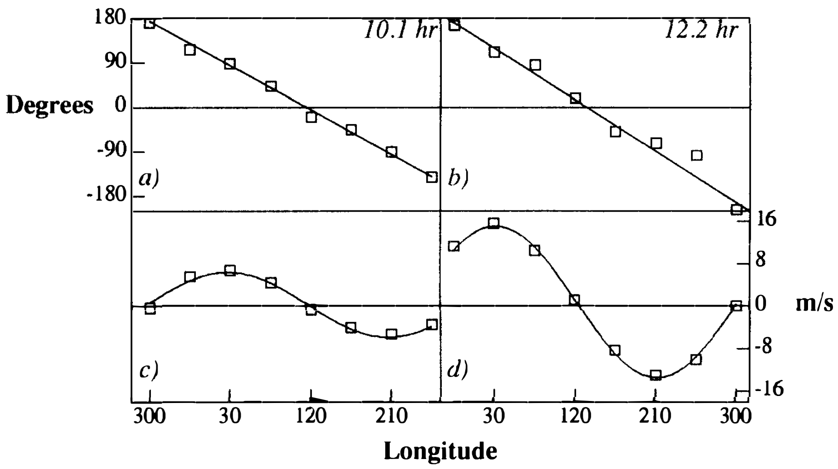

Fig. 5. Determination of the phase progression, (a, b), and the mean wind amplitude (c, d) associated with the 10.1-hr and 12.2-hr oscillations, respectively. The phase progression determination shows that a westward traveling zonal wavenumber one is observed for both oscillations. Left panels for August 1991 and right panels for August 1992.

local time). Plotting the time (expressed in the figure as degrees) at which the oscillation reaches a maximum at a given azimuthal direction as a function of the longitude for the azimuths, will give a phase progression diagram. The upper panels of Fig. 5 show the results obtained for the phase progression for both the 10.1-hr and the 12-hr oscillations previously shown in Figs. 3 and 4. In both cases, the phase progression is westward and of zonal wavenumber character one; that is, the oscillation shows only one maximum along the circumference of the Earth at the latitude of observation (88.7°S). It is useful to note here that at 88.7°S the circumference at the latitude circle is about 950 km. The significance of this small circumference will be discussed later.

The lower panels of Fig. 5 show the determination of the mean wind observed, obtained by plotting the value of the mean (or zero frequency) wind as a function of longitude. The results in the figure show that the mean wind for the month of

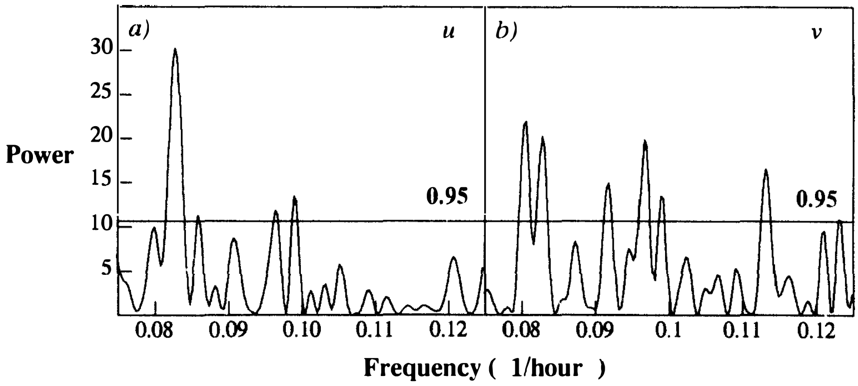

Fig. 6. Periodograms for the zonal (u) and meridional direction (v) measurements from Scott Base, for the same time period the measurements shown in Fig. 3 were made during August 1991. Note the existence of a common 10.1-hr oscillation with South Pole, as well as other oscillations.

August maximizes towards 20° E longitude, albeit with rather varying amplitude for the two years of observation. The mean wind for August 1992, given on the right bottom panel, is nearly twice as strong as the August 1991 mean wind on left bottom panel of the figure.

The medium-frequency (MF) radar at Scott Base (78° S) was operating during August 1991 and, as Fig. 6 illustrates, it showed oscillations at nearly the same frequency as that observed at South Pole. The South Pole measurements given in Fig. 3 are in the direction of Scott Base. Figure 6 shows, for both zonal (u) and meridional (v) directions, the presence of the near 10-hr periodicity oscillation observed at South Pole, as well as other oscillations at other frequencies. To further identify the simultaneous presence of the 10-hr oscillation, the data from both stations were analyzed with a sliding periodogram, as a function of time of measurements. Results are shown in Fig. 7, where the appearance of the near 10-hr oscillation is seen to occur during the same intervals at both stations. This is particularly clear for the time of observation near 100–150 hours for the Scott Base meridional winds. This frequency and temporal simultaneity indicate that both stations were observing the same phenomenon.

Since the Scott Base radar profiles the near-overhead upper mesosphere, it was then possible to obtain a vertical wavelength of propagation for this oscillation of nearly 100 km. Based on the zonal wavenumber character one and vertical wavelength of propagation, it was possible (HERNANDEZ *et al.*, 1992b) to identify this oscillation as a Lamb wave.

During August 1991, oscillations with 2.3-day and a 2.6-day periodicity were also observed at South Pole and Scott Base (FRASER *et al.*, 1993). The results from their study are shown in Fig. 8, where the South Pole measurements in the direction of Scott Base and the zonal and meridional winds from Scott Base are given. Again, note the richness of the spectrum at the lower latitude of Scott Base (78° S), when compared with that at South Pole. In particular, note the absence at South Pole of the very strong 4-day periodicity oscillation seen in the Scott Base record. The

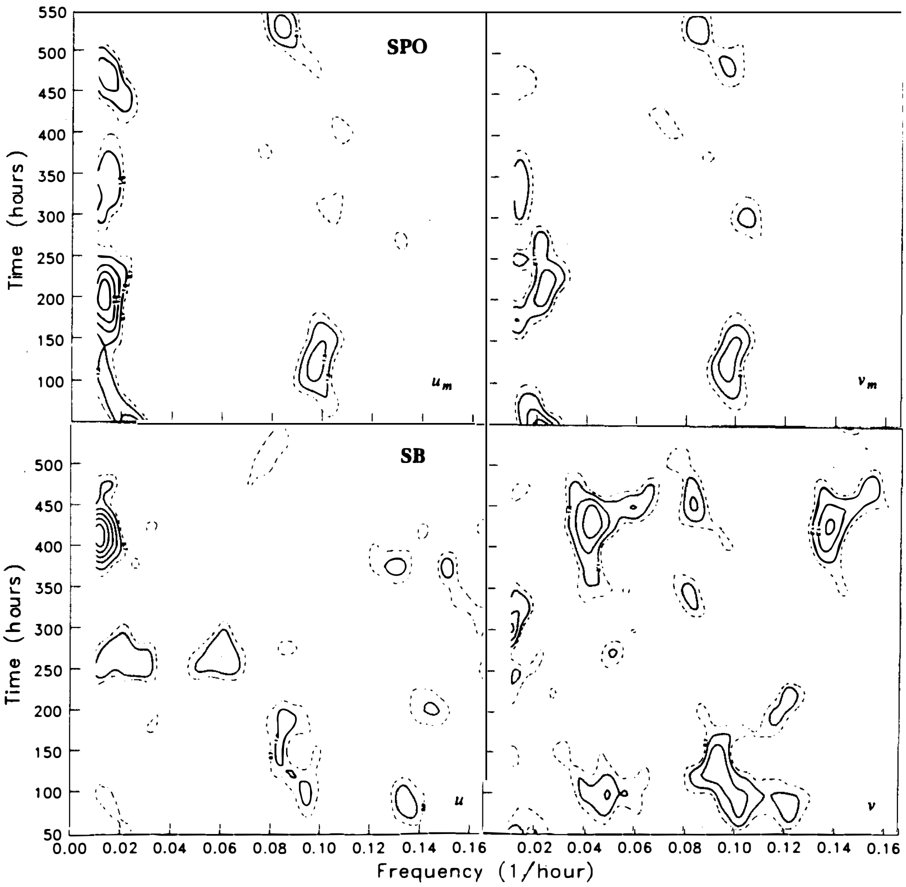

Fig. 7. Sliding periodogram for South Pole (SPO) and Scott Base (SB) during the period 1–25 August 1991. The results are shown as contours of statistical significance, relative to the 95% confidence limit. Note the similarities near the 0.1/hr frequency region for SPO and the meridional direction at Scott Base.

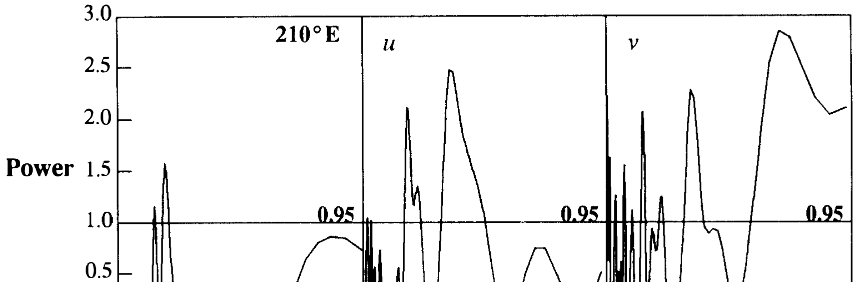

Fig. 8. Periodograms for South Pole wind (a) observations at 210° E, and the Scott Base zonal (b) and meridional (c) wind measurements during August 1991. The two stations show a common 2.3-day and 2.6-day period oscillations. Note the absence of the 4-day oscillation at South Pole and its strength at Scott Base, indicating the possibility of a high zonal wavenumber character for this oscillation.

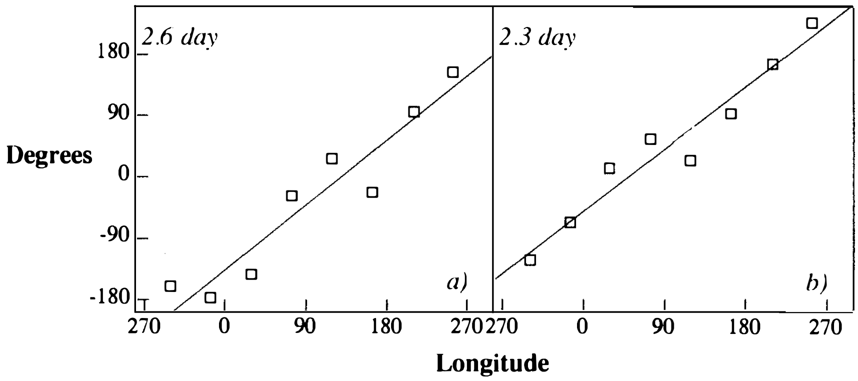

Fig. 9. Determination of the phase progression associated with the 2.3-day and 2.6-day oscillations, respectively. The phase progression determination shows that an eastward traveling zonal wavenumber one is observed for both oscillations.

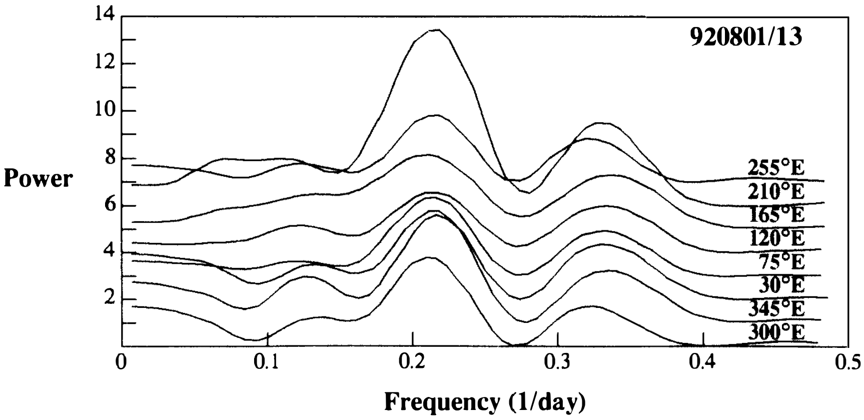

Fig. 10. Periodogram of the emission rate measurements of the OH molecule near South Pole, during August 1992. The longitude of observation are indicated in the figure. The periodograms are shifted upwards by one unit starting at 345° E.

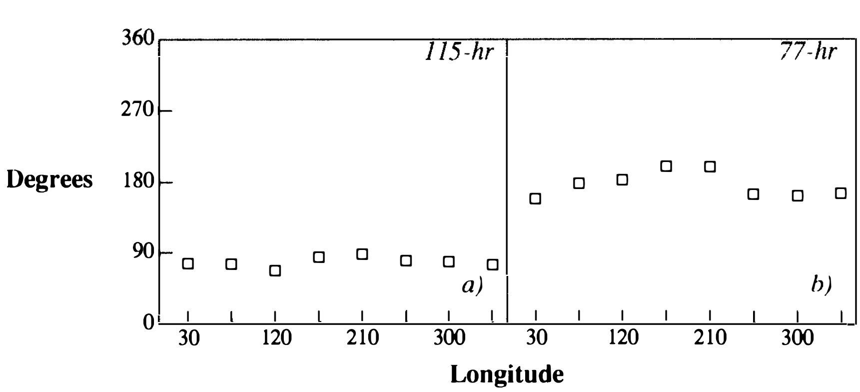

Fig. 11. Phase progression determination for the oscillations in the emission rate of Fig. 10. The near unvarying phase indicates a zonal wavenumber zero oscillation.

phase progressions of these two waves, determined from the South Pole measurements, are illustrated in Fig. 9. These results show that these oscillations are also of zonal wavenumber one character, although their phase progression is eastwards.

The emission rate of the OH tracer being measured also showed significant

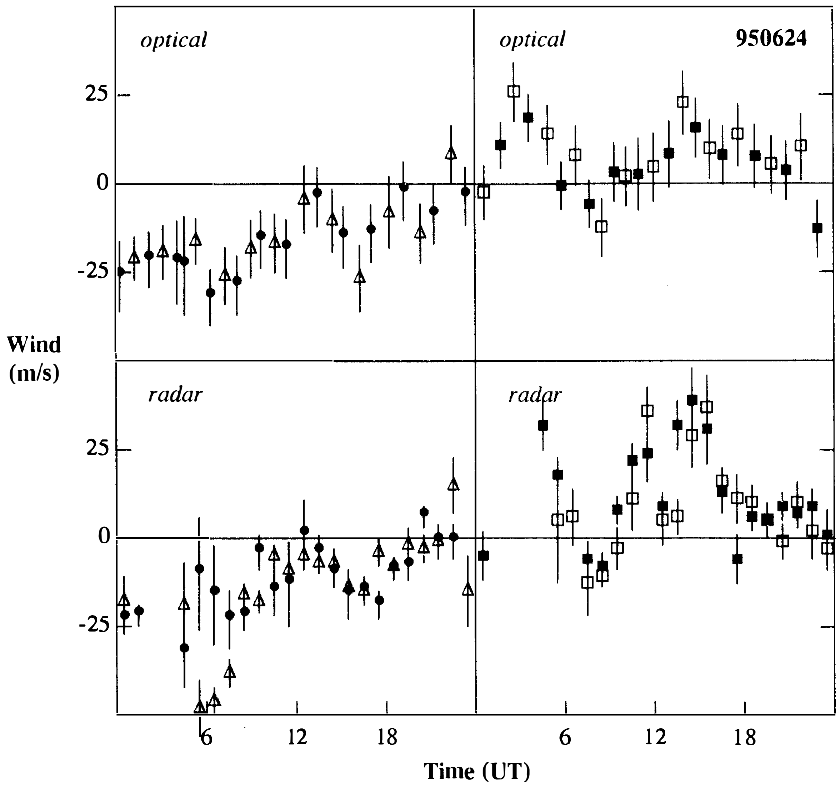

Fig. 12. Direct comparison between both South Pole optical and meteor radar measurements for 24 June 1995 UT. The eight-direction optical measurements have been interpolated to the same four directions observed by the meteor radar. The symbols used are □ for 0° longitude observations, △ for 90° longitude observations, ■ for 180° longitude observations, and ● for 270° longitude observations. Note that the directions at 180° and 270° have been reversed in order to show the flow of the wind. As shown, the convention for the motion is positive equatorwards for the 0° and 90° longitude winds. The uncertainties of determination are indicated.

oscillations during August 1992, as seen in Fig. 10. These emission rate oscillations, with 77-hr and 115-hr periodicity, show a nearly unvarying phase progression, illustrated in Fig. 11. This unvarying phase progression is indicative of a zero zonal wavenumber character, that is, the oscillations are simultaneous in all directions within the observing volume of our measurements.

A meteor radar was co-located with the optical experiment during the austral winter at South Pole (FORBES *et al.*, 1995; HERNANDEZ *et al.*, 1996). This meteor radar observations occur at near 95 km height (FORBES *et al.*, 1995). During the clear weather period of June 19 to June 30, 1995, an investigation of the measurements obtained by the two methods was made. Figure 12 shows the measurements for 24 June 1995 UT, indicating that the two experiments measure nearly the same motions. Note, in particular, the slow change in the wind motion in the 0°E–180°E longitude directions.

Periodogram analyses of the observations at the two stations show that both methods measure the same frequencies of oscillation, as given in Fig. 13. The phase progression analysis of the two data sets shows the existence of only statistically

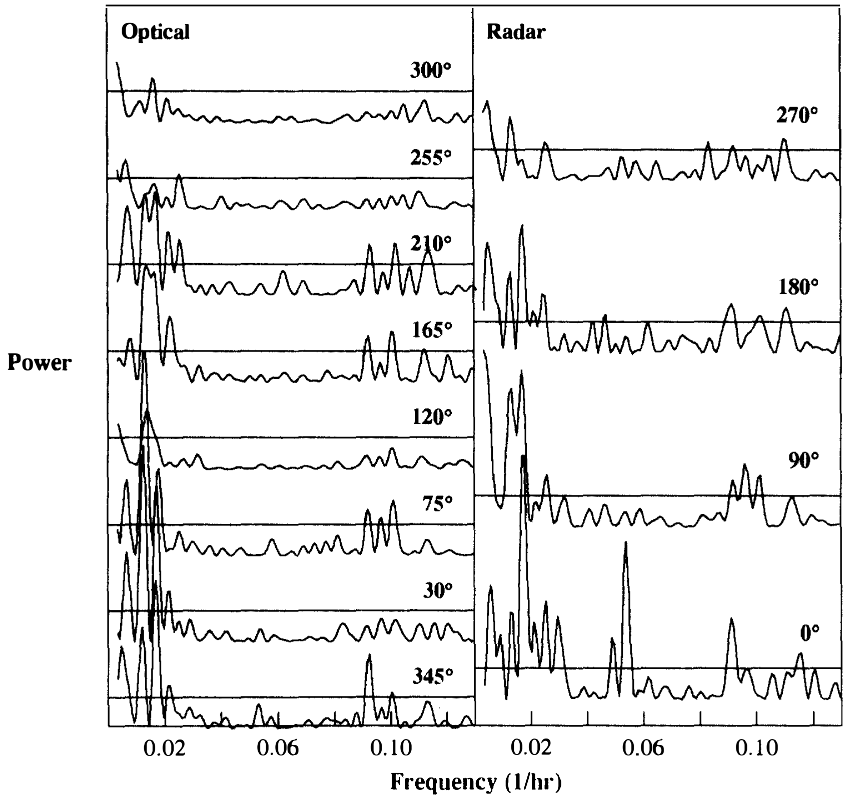

Fig. 13. Periodogram (normalized to the 95% confidence level) for the optical and meteor radar observations during the period 950619 UT–950630 UT inclusive. Note the similarities in behavior for the frequencies near 0.1/hr (10-hr periodicity) and 0.014/hr (72-hr periodicity). The separation between the normalized lines is 3 and 6 units for the optical and radar data, respectively.

significant zonal wavenumber one motions in the wind, and the presence of a phase lag in the phase progression of the waves, which is more noticeable in the long-periods waves. This is illustrated in Figs. 14 and 15. The figures also show that there is a phase lag in the phase progression determinations from the two stations. This is more obvious for the longer periodicity waves shown in Fig. 15. Figure 14 also illustrates the determination of the mean wind for both experiments, with quite similar results in amplitude and phase. Note that the direction of the mean wind is different during the June 1995 period than it has been during the earlier observations in August 1991 and 1992, shown in Fig. 5.

Since the optical and meteor radar experiments observe at slightly different heights in the upper atmosphere, 88 km for the OH emission (WITT *et al.*, 1979) and 95 km for the radar (FORBES *et al.*, 1995), it is possible to estimate the vertical wavelength(s) of propagation of the observed oscillations from the horizontal winds (KATO, 1980). This can be done, if it is presumed that the phase propagation lag, such as those shown in Figs. 14 and 15, represents a phase change due to the different altitudes of measurement by the two methods. The results obtained give a 65 km vertical wavelength of propagation or the 2.45-day and 3.2-day waves and greater than 100 km for the 10.9-hr oscillation. These, *in situ*, determinations are in

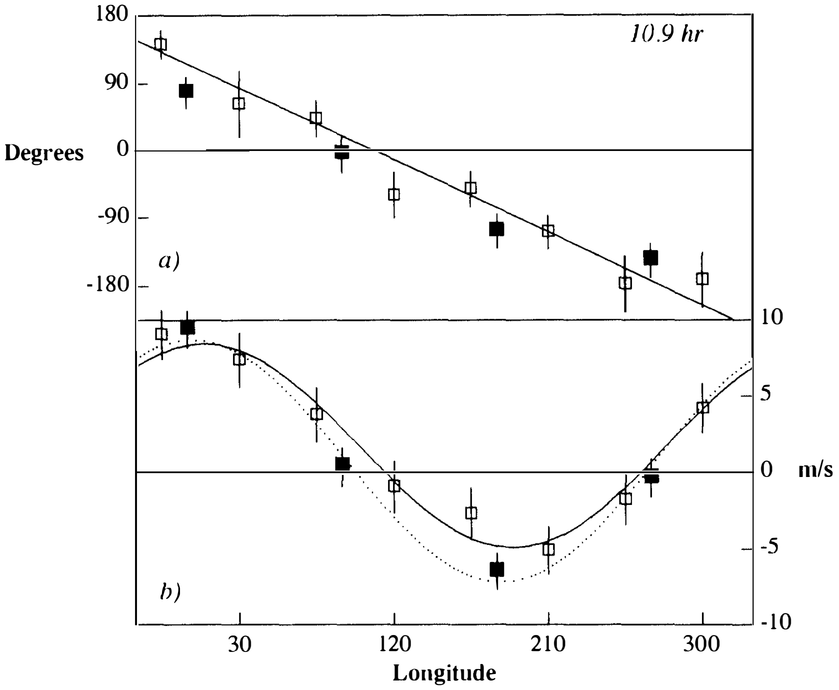

Fig. 14. Phase progression (a) of the 10.9-hr period oscillation for the optical (open symbols) and meteor radar (dark symbols). The figure shows this oscillation to be a westward phase traveling wave with zonal wavenumber one character. Determination of the mean wind (b) showing similar amplitude and direction of motion for the two methods. Derived from the June 19–30, 1995 measurements. The uncertainties of determination are indicated. See text for details.

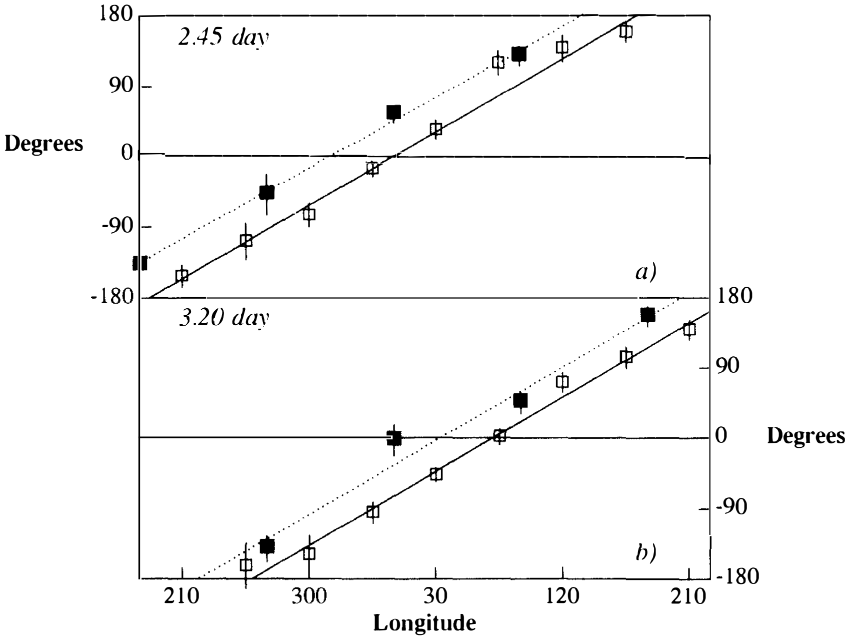

Fig. 15. Phase progression for the 2.45-day (a) and 3.2-day (b) periodicity oscillations. In both cases, the oscillations are eastward phase traveling zonal wavenumber one waves. The lag between the optical and meteor radar phase progressions is statistically significant to the 95% confidence level, indicating the existence of a height difference between the observations and a downwards phase propagation of the wave.

agreement with the vertical wavelengths of propagation determined for waves of similar period measured in 1991 at Scott Base (HERNANDEZ *et al.*, 1992b; FRASER *et al.*, 1993).

These co-located measurements have been very useful in that they confirm the earlier optical measurements and also provide the ability to make local determination of the vertical wavelengths of propagation.

4. Discussion

The results from the ground-based measurements of wind, kinetic temperature, and emission rate of the optical tracer of the upper mesosphere near the South Pole show a consistent pattern. The statistically significant motions typically have small amplitudes, below 20 m/s, while the oscillations show zonal wavenumber character one with both eastward and westward propagation, and long vertical wavelengths of propagation. The statistically significant temperature and emission brightness of the OH tracer have oscillations with zonal wavenumber zero character. The absence of higher wavenumber modes of oscillation is notable over the five years of observation near the South Pole.

Investigation of the behavior of waves near the rotational poles was done by HERNANDEZ *et al.* (1992b) by expanding the variables in a power series of sin Θ, where Θ is the colatitude, and substituting into the linearized equations for the equations of motion; the leading terms show the behavior close to the poles. If s is the zonal wavenumber, then the pressure and temperature vary as $(\sin \Theta)^s$ and only for zonal wavenumber zero can they be large; physically they cannot vary with longitude without being discontinuous at the poles. Similarly, horizontal winds vary as $(\sin \Theta)^{|s-1|}$, and zonal wavenumber one oscillations will be observed at the poles. A wind that is continuous and blows across the poles resolves into a wavenumber one component. Tidal winds, for which the predominant modes have $s=2$, would have negligible amplitude at the poles, and would increase with distance away from them.

The agreement of this simplified deduction with the observations is excellent and provides a theoretical explanation for the observations. However, the deduction does not say where the energy for the oscillations originates; it simply says that if oscillations exist, the atmosphere will support them. FORBES *et al.* (1995) have addressed this topic and propose that the interaction between wind waves of zonal wavenumber one (such as a mean wind) and zonal wavenumber two will give rise to a zonal wavenumber one (and zonal wavenumber three) waves, however with the periodicity of the zonal wavenumber two oscillation.

As mentioned in the Section 3, the circumference of the Earth at the latitude (88.7°S) of the mesospheric observations from South Pole is about 950 km. At this latitude, a zonal wavenumber one wind oscillation with a nominal 10-hr periodicity will have a phase velocity of 26 m/s. Longer periodicity waves will have a lower phase velocity, which is near the speed of the mean flow. Under these conditions of nearly equal speed for the wave and the mean flow, interactions between the two are likely (ANDREWS *et al.*, 1987), leading to the transfer of energy from one to the other. Therefore, it is easy to visualize a scenario where a random disturbance would excite one of the permitted zonal wavenumber modes which would, if it had the appropriate phase velocity, in turn would grow by interaction with the mean wind. This mechanism provides an alternate to the mechanism proposed by FORBES *et al.* (1995) to furnish the necessary energy to give rise to the observed oscillations.

Acknowledgements

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