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The 16-day planetary wave in the mesosphere and lower thermosphere

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Abstract. A meteor radar located at Sheffield in the UK has been used to measure wind oscillations with periods in the range 10–28 days in the mesosphere/lower-thermosphere region at 53.5°N, 3.9°W from January 1990 to August 1994. The data reveal a motion field in which wave activity occurs over a range of frequencies and in episodes generally lasting for less than two months. A seasonal cycle is apparent in which the largest observed amplitudes are as high as 14 ms^{-1} and are observed from January to mid-April. A minimum in activity occurs in late June to early July. A second, smaller, maximum follows in late summer/autumn where amplitudes reach up to 7–10 ms^{-1}. Considerable interannual variability is apparent but wave activity is observed in the summers of all the years examined, albeit at very small amplitudes near mid summer. This behaviour suggests that the equatorial winds in the mesopause region do not completely prevent inter-hemispheric ducting of the wave from the winter hemisphere, or that it is generated *in situ*.

Key words. Meteorology and atmospheric dynamics (middle atmosphere dynamics; thermospheric dynamics; waves and tides)

1 Introduction

The motion field of the mesosphere/lower-thermosphere (MLT) region is now known to be dominated by atmospheric tidal, planetary and gravity waves of large amplitude. Large-scale oscillations of long period have been observed at these heights since the first ground-based studies of Muller (1972). Subsequent theoretical work suggests that these motions correspond to planetary-wave normal-mode solutions for oscillations in an isothermal atmosphere (e.g. Salby, 1981a, b, 1984). Such theory predicts free or resonant atmospheric response at periods near 2, 5, 10 and 16 days. There is now a substantial body of observational evidence reporting the existence of waves near these periods in the troposphere and throughout the middle atmosphere (e.g. Muller, 1972; Kingsley *et al.*, 1978; Madden, 1978, 1979; Salby and Roper, 1980; Hirooka and Hirota, 1984; Salby, 1984; Williams and Avery, 1992; Jacobi *et al.*, 1998a, b). The first observational evidence of waves in the MLT region with periods near 16 days appears to have been provided by the study of meteor radar data performed by Kingsley *et al.* (1978).

Planetary waves play an important and subtle role in the dynamics of the MLT region and its coupling to regions above and below. Recent studies have revealed that planetary waves at these heights are capable of non-linear interaction with tides in a process which generates a family of secondary waves, some of which have frequencies equal to the sum and difference of the primary tidal and planetary-wave frequencies and which then beat with the tide to cause significant modulation of the tidal amplitude at the period of the planetary wave (Teitelbaum and Vial, 1991; Mitchell *et al.*, 1996; Beard *et al.*, 1997; Beard *et al.*, 1999).

Observations of ionospheric parameters, such as the F-region critical plasma frequency, *f*oF2, have also revealed regular fluctuations at periods associated with planetary waves (e.g. Pancheva and Lysenko, 1988; Lastovicka, 1997; Forbes *et al.*, 1997). Planetary waves themselves are not believed to penetrate to ionospheric heights, so an indirect mechanism must be responsible. Suggestions for this mechanism have included: (1) planetary-wave influence on the dynamo generation of electric fields via the modulation of tidal fluxes as described; (2) a similar influence arising from planetary waves excited *in situ* at E-region heights by the deposition of momentum from a flux of gravity waves which is itself modulated at planetary-wave frequencies fol-

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lowing interaction with planetary waves at lower heights; and (3) planetary-wave modulation of the F-region [O]/[N_2] ratio (Pancheva and Lysenko, 1988; Forbes *et al.*, 1995).

The solar cycle may also exert an influence on planetary-wave propagation in the middle atmosphere. The modelling study of Arnold and Robinson (1998) has suggested that the longer radiative relaxation times of the lower thermosphere in the winter hemisphere allow an amplification of middle-atmosphere planetary-wave activity which would occur in phase with the solar cycle.

The majority of MLT-region planetary-wave studies appear to have addressed the quasi 2-day wave because its very large amplitude and comparatively short period make it an attractive subject for investigation by ground-based techniques (e.g. Muller, 1972; Tsuda *et al.*, 1988). In contrast, there have been relatively few studies of the planetary waves with periods near 16 days, probably because such studies require data sets of long duration and higher velocity resolution in order to reveal the relatively small amplitudes of the longer-period oscillations.

Of those studies which have been performed at MLT heights, Williams and Avery (1992) examined nearly one year of MST-radar data from Poker Flat (65°N) and measured oscillations with periods of 12–19 days. These workers also measured the 16-day wave at tropospheric heights. Forbes *et al.* (1995) used data obtained during January to March of 1979 from an MF radar at Saskatoon (52°N) and a meteor radar at Obninsk (54°N) to identify an oscillation of period near 16 days. Both of these studies identified the observed waves as the second symmetric, westward propagating, Rossby mode with a zonal wave number 1, corresponding to the (1, 3) Hough structure. Although referred to as the "16-day" or "quasi 16-day" wave, this feature is predicted from theoretical considerations to display periods between 11.1–20 days (Salby, 1981a). Similar oscillations have also been reported in the airglow measurements made by Espy and Witt (1996) in the summer of 1992 and Espy *et al.* (1997) over four successive summers from 1992 to 1995 at Stockholm (60°N). Jacobi *et al.* (1998a, b) examined oscillations with periods of up to 25 days in mesopause-region winds derived by the LF D1 radio technique from 1983–1995 over Collm (52°N). Episodes of wave activity at a period near 15 days observed over Kyoto (35°N) by meteor radar were also reported by Tsuda *et al.* (1988) in a study which otherwise concentrated on the quasi-two-day wave.

A particularly interesting feature of the observations of Williams and Avery (1992), Espy and Witt (1996), Espy *et al.* (1997) and Jacobi *et al.* (1998a, b) is the presence of a significant oscillation with a period near 16 days in the summer mesopause region. This is in contrast to the predictions of simple theory which would suggest that such long-period planetary waves are incapable of penetrating to mesopause heights from their lower-atmosphere source regions through the westward winds of the summer stratosphere and mesosphere (Charney and Drazin, 1961). Explanations advanced to account for the observed presence in summer of oscillations near 16-day period include inter-hemispheric ducting of the wave across the equator from the winter hemisphere or in situ generation by the momentum deposited by modulated gravity waves, where the modulation is applied by the summer-time 16-day oscillation in the troposphere and lower stratosphere (Williams and Avery, 1992; Forbes *et al.*, 1995; Espy *et al.*, 1997).

A further aspect of this behaviour was suggested by the observations of Espy *et al.* (1997) who reported that the wave was observed in the summers of 1992 and 1994, but not in the summers of 1993 or 1995. Espy *et al.* (1997) attributed this observation to the blocking of the wave's propagation from the winter hemisphere during the westward phase of the equatorial quasi-biennial oscillation (QBO) in the upper stratosphere.

Here we present observations of oscillations with periods between 10–28 days made by a meteor radar located at Sheffield (53.5°N, 3.9°W). The main advantage offered by meteor radars for such investigations is that they are able to provide data sets that are effectively continuous over several years duration. Also, whilst there are diurnal variations in meteor count rates, these do not affect data quality to such an extent that errors are introduced through the presence of unresolved tidal components in the data. Such radars are, however, limited in height coverage and often of poor height resolution.

2 Method and data analysis

In this study a meteor radar located near Sheffield has been used to determine horizontal velocities in the MLT-region over the period January 1990 to August 1994. The radar is a pulsed Doppler system operating at a frequency of 36.3 MHz. Two transmitted beams are directed NW and SW at elevations of 30°. The transmitting aerials are eight-element Yagis with half-power beamwidths of 12°. The receiving aerials are three-element Yagis of half-power beamwidth 30°, again directed at elevations of 30° to the horizontal. The beams intersect the meteor region at slant ranges of >200 km, and so each beam has a broad "footprint" on the meteor region and detects meteor echoes from a collecting volume of some several hundred kilometres in horizontal extent. No height finding was employed on the system during the times considered in this work. However, it is believed that $>80\%$ of meteor echoes come from heights between about 87–97 km (Mitchell, 1991) and so the vertical range from which the large majority of echoes are believed to come is significantly smaller than the vertical wavelengths of planetary waves and tides at these heights. The radar has now been relocated to a new site within the UK and it is planned that in the future it will operate in an interferometric mode with a height resolution of ≤ 3 km.

The recorded meteor count rates exhibit a diurnal variation because of astronomical and beam geometry

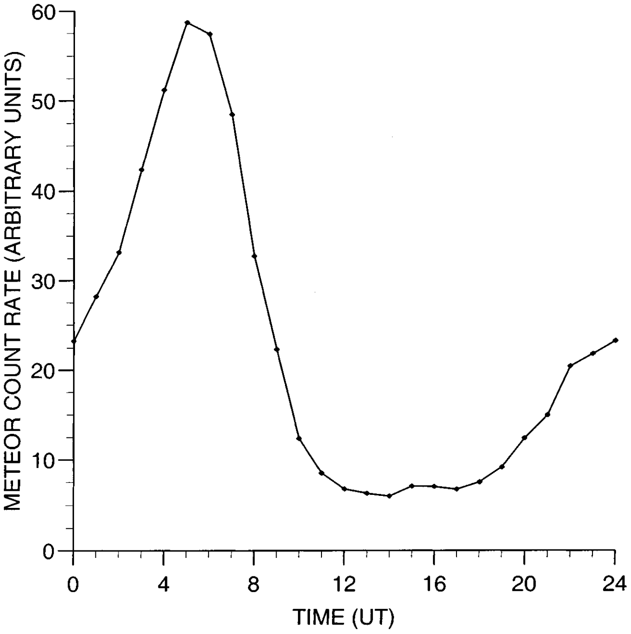

Fig. 1. The diurnal cycle in meteor count rates based on all meteors recorded in 1992. Data from both aerial directions are summed

factors. Figure 1 presents, as an example, the meteor counts in arbitrary units recorded as a function of time of day using all the meteors recorded during 1992. Meteor counts from both aerial directions are summed. The diurnal cycle in count rates is clearly evident, although it should be noted that the count rate never falls to zero.

The local wind patterns within each collecting volume may vary considerably because of turbulence and gravity-wave motions with horizontal or vertical scales comparable with that of the collecting volume. The low-frequency components of the wind field were therefore determined by temporal and spatial smoothing. For each beam, meteor echoes at ranges ≤100 km and ≥500 km were rejected. Also rejected were those meteor echoes with a measured velocity that lay more than three standard deviations from a detrended hourly mean. A two-hour mean, incremented in one-hour steps was then used to generate a time series of horizontal velocity for each beam. A Hamming window was used in the averaging process to reduce side-lobe effects. The time values corresponding to the individual velocity values in the time series cannot be assumed to be in the centre of the two-hour window because of the strong diurnal cycle in the count rate of meteor echoes in addition to stochastic fluctuations. Because of this, the time values were also averaged in a similar manner to the velocity values, and a representative time for each velocity value calculated. The resultant velocity values are therefore not spaced at exactly equal intervals, and so interpolation was used to generate a time series with a regular one-hour spacing.

The averaged, interpolated, hourly time series for the NW and SW beams were then converted into zonal and meridional velocities by a vector addition. This latter process introduces a degree of spatial smoothing because the centres of the meteor count distribution for each beam are separated by about 300 km. Also, as a result of this geometry, the winds measured by the system are representative of a position midway between the two collecting volumes, in this case 53.5°N, 3.9°W.

3 Results

3.1 Spectral analysis

The time series representing the zonal and meridional winds for each of the years in the period 1990–94 were first analysed to reveal the gross characteristics of any oscillations with periods near 16 days. To investigate the spectral composition of the low-frequency part of the motion field, a Lomb-Scargle periodogram was applied to a 48-day window within each time series and the window was then advanced through the data in one-day increments. The Lomb-Scargle periodogram is a technique able to estimate amplitude or power spectra of time series in which the data are unevenly spaced in time (e.g. Press *et al.*, 1996). In this case, the Lomb-Scarge periodogram was used in preference to a Fourier transform or maximum-entropy method because of the presence of intermittent gaps in the time series caused by radar down time, interference or episodes of very low meteor count rates. An over-sampling factor of four was used in calculating each periodogram and the results were only considered if data were actually recorded for more than 70% of the hourly intervals within the 48-day window. The 48-day window length was selected after trials as the best compromise between spectral resolution (favouring a longer window) and response to changes in the composition of the field of low-frequency motions (favouring a shorter window). Some caution must also be used in interpreting the spectral analysis. As noted by Jacobi *et al.* (1998a), the transitions between summer and winter circulations, and fluctuations in the strength of the mean flow may introduce additional energy into the derived spectra which is unconnected with the particular planetary waves of interest.

Figure 2a–j presents spectrograms for the zonal and meridional wind components calculated by this method for each of the years 1990–94. The figures cover the frequency range 0.1–0.035 cycles/day, corresponding to wave periods between 10–29 days (a frequency of 0.0625 cycles/day corresponds to a period of 16 days). The interruptions in the coverage in 1990 and 1991 arise because for these periods the radar was inoperative.

Confidence levels were calculated for each of the individual 48-day periodograms used to produce Fig. 2a–j. No frequency selection should be made in calculating such confidence levels, so oscillations of all frequencies present in the data contributed to the calculated confidence-level, including tides and higher frequency planetary waves. The confidence levels were found to vary slightly throughout each of the years, but the annual means of the 95% confidence-level amplitudes (i.e., 5% significance levels) were 4.6 $\mathrm{ms^{-1}}$ in 1990, 4.3 $\mathrm{ms^{-1}}$ in 1991, 3.7 $\mathrm{ms^{-1}}$ in 1992, 3.6 $\mathrm{ms^{-1}}$ in 1993 and

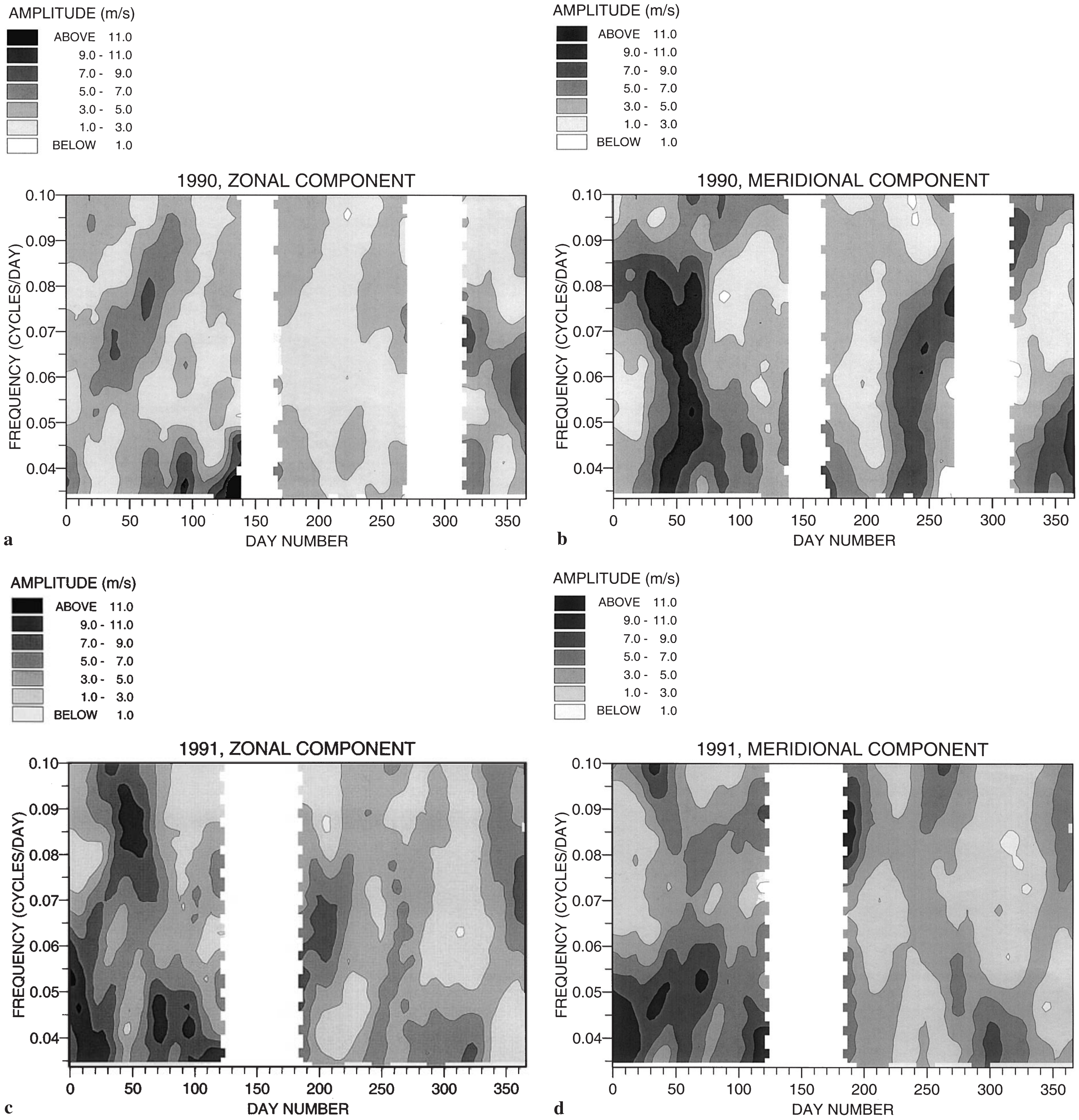

Fig. 2a–j. Spectrograms of zonal and meridional wind amplitudes as a function of frequency and time for 1990: **a, b**; 1991: **c, d**; 1992: **e, f**; 1993: **g, h**; 1994: **i, j**

3.5 ms^{-1} in 1994. However, as discussed by Beard *et al.* (1999), confidence levels determined for data containing deterministic signals of large amplitude may be overly pessimistic. Oscillations of large amplitude associated with the semi-diurnal tide and the quasi-2-day planetary wave present in the data considered here (although outside the scope of this study) may well therefore result in the 95% confidence-level amplitudes quoted being too cautious.

The figures reveal a rather variable pattern for this frequency range, in which "bursts" of wave activity occur which last generally no more than about 60 days and in which the behaviour of the oscillation in the zonal and meridional components can be quite dissimilar. Wave activity seems to occur most strongly in the winter months (i.e., December to mid-April; day numbers ~335 to 110) where there are typically two or three bursts of activity per year with amplitudes as high as

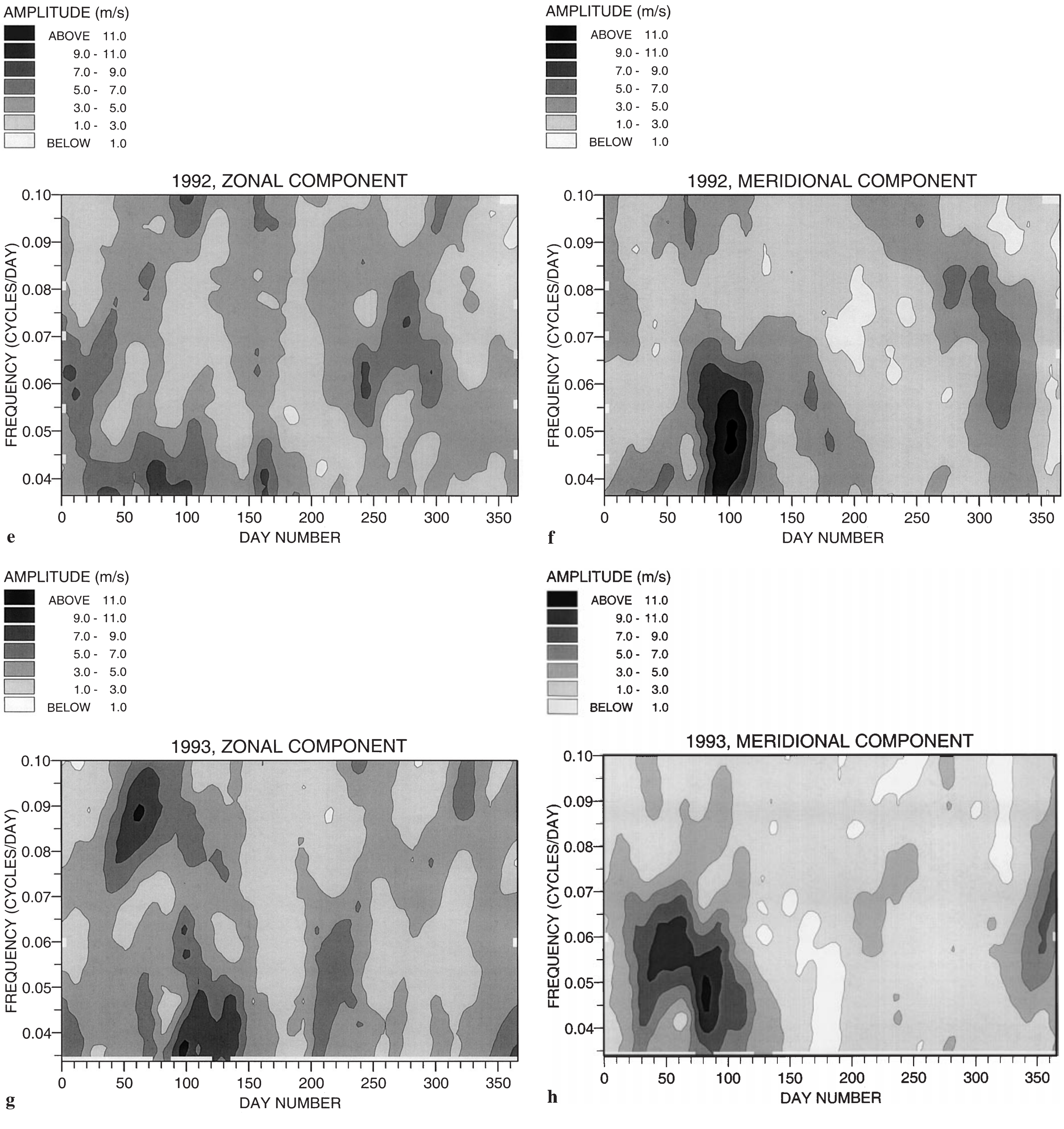

Fig. 2e–h.

12 ms^{-1}. A second episode of wave activity appears in late summer or autumn, generally occurring between day numbers 200–320 (late July–mid-November). In this case there appear to be only one or two bursts of wave activity of rather lower amplitude, typically of up to 6 ms^{-1}.

The frequencies of oscillation at which the bursts of activity occur are quite varied, with oscillations of above 7 ms^{-1} amplitude in the winter months and above 5 ms^{-1} in the summer months occurring at virtually all frequencies within the spectral window over the five years considered.

3.2 Seasonal and interannual variations

The spectrograms of Fig. 2 indicate that the low-frequency components of the motion field exhibit both seasonal and inter-annual variability. As an example of the latter, the data for the meridional winds in 1993

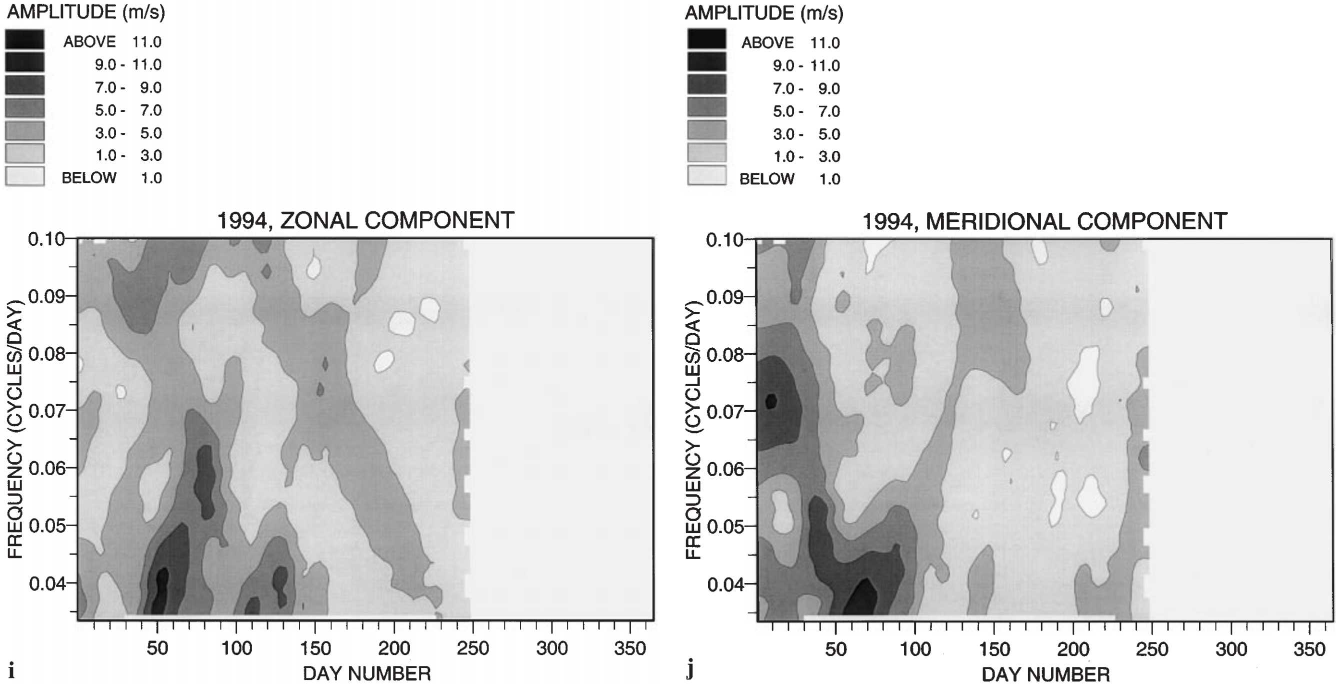

Fig. 2i, j.

(Fig. 2h) reveal a strong burst of activity (amplitude > 11 ms^{-1}) at a frequency of about 0.057 cycles/day (a wave period of 17.5 days) between day numbers ~40 to 90. In contrast, the equivalent data for 1992 and 1994 (Fig. 2f, j) display no such feature.

To clarify this type of behaviour and to provide a simple measure of wave activity the data of Fig. 2 were reprocessed to yield a time series of the maximum amplitude recorded, regardless of frequency, in either the zonal or meridional periodograms in the frequency range 0.035–0.1 cycles/day. Figure 3 presents these curves for each of the years of observation. Again, the larger amplitudes in the winter months are clearly evident, as is the secondary maximum in activity in late summer and autumn. The data from 1990, 1992, 1993 and 1994 all suggest that minimum wave activity within this frequency range occurs between late June and late August (day numbers ~170–240) with amplitudes as low as about 4 ms^{-1} recorded for 1990, 1993 and 1994 and about 5 ms^{-1} in 1992. The data from 1991 include an interval of about 85 days during which no recordings were made which unfortunately covers these months.

In addition to the basic seasonal trends, the degree of interannual variability is seen to be considerable. During the winter maximum, the amplitudes of the largest wave bursts vary from about 7 ms^{-1} in 1992 to in excess of 14 ms^{-1} in 1991. During the secondary, summer/autumn maximum the peak amplitudes range from values as small as about 5.5 ms^{-1} in 1993 to about 10 ms^{-1} in 1990. The curves for individual years also show a variety of forms. For instance, 1992 is characterised by a quiet early winter (day numbers ~0–70), a sharp maximum in late winter (day numbers ~70–120) and a lengthy late-summer/autumnal secondary maximum (day numbers ~240–320). In contrast, 1993 has a long-lasting winter maximum (day numbers ~30–120) and an early and short secondary maximum (day numbers ~200–240).

3.3 Hodographs and wave polarisation

Inspection of Fig. 2a–h suggests that oscillations in this period range can have quite different amplitudes in the zonal and meridional components. To further investigate this behaviour, the time series of hourly zonal and meridional velocities were band-pass filtered to reveal

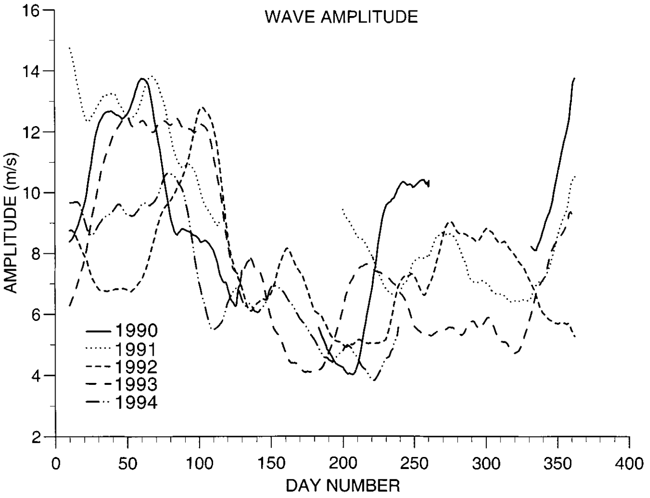

Fig. 3. Amplitudes of the largest spectral signature in either zonal or meridional winds in the frequency range 0.1–0.035 cycles/day (10–28 days period) as a function of time for the years 1990–1994

oscillations over an approximate frequency range corresponding to that of the spectrograms of Fig. 2. A second-order Butterworth recursive filter was used with the 1% and 99% transfer points of the filter set to 0.09 and 0.07 cycles/day, respectively, (high-frequency cut-off) and 0.025 and 0.045 cycles/day, respectively, (low-frequency cut-off). The band-pass filter required continuous, evenly-spaced data, so short gaps in the data were filled by interpolation.

The band-passed time series were then used to produce hodographs of the zonal and meridional winds for particular wave bursts apparent in Fig. 2. Only data corresponding to intervals where one wave burst was present at a time was considered to avoid possible contamination arising from superposition of the signal from multiple, simultaneously-present oscillations. A further possible problem in band-passing data to reveal the presence of these low-frequency signals is that the filter itself may falsely generate such signals even if they are not actually present in the data: effectively there is "noise" in the filter's output . To assess the Butterworth filter's performance in this regard, the zonal and meridional wind time-series data were randomised, such that each velocity value was re-assigned to a randomly selected time value from the data set. The randomised data thus had the same variance as the original data, but all phase information associated with any oscillations present was destroyed. The randomised data were then band-pass filtered with the filter characteristics set as described. The amplitude of the resultant signals was always $< \sim 2\ \mathrm{ms}^{-1}$ and we suggest that this may be taken as a noise level for this filter with the specified parameters.

Figure 4a–d presents the four clearest hodographs derived from the band-pass filtered data. Figure 4a, b presents examples of data from the winter months: day numbers 1–110 in 1990 and 1–130 in 1993, respectively. Figure 4c, d presents equivalent data for the summer/autumn months: day numbers 190–290 in 1991 and 230–310 in 1992 respectively. In each case, the hodograph is not plotted for those hours where no data were available within the time interval considered. The sense of rotation of each hodograph is indicated by arrows.

The data from the winter months (Fig. 4a, b) suggests that when the oscillations are largest, there is a tendency for them to be elliptically polarised, of anticlockwise rotation and aligned with the long axis slightly clockwise of north-south. However, it should be noted that at smaller amplitudes the behaviour is less clear and the sense of rotation becomes confused, probably indicating the effective resolution of this method of analysis. The corresponding data for the summer/autumn motions (Fig. 4c, d) yield hodographs which are less clearly defined because the amplitudes are smaller, but suggest that the oscillations are also elliptically polarised and are aligned at about 90° to the winter orientation, i.e., slightly clockwise of east-west. In general the hodographs for the other episodes of activity were too noisy for simple conclusions to be drawn, either because more than one frequency was present or because of small amplitudes.

4 Discussion

The behaviour of the long-period oscillations revealed in the data taken during winter by the meteor-radar at Sheffield (53.5°N) seem to be in general agreement with the observations made during January–March 1979 at Saskatoon (52°N) and Obninsk (54°N) by Forbes *et al.* (1995). The largest winter amplitudes measured over the approximate period range 10–28 days in our study vary from about 7 to $13\ \mathrm{ms}^{-1}$ (Fig. 3). This is in good agreement with the amplitudes of about $10\ \mathrm{ms}^{-1}$ reported by Forbes *et al.* (1995) and the amplitudes of 10–20 ms^{-1} reported by Kingsley *et al.* (1978) using an early version of the radar used for the present study. In every year considered, oscillations occur over a wide range of periods and significant activity is evident over the entire period range 10–28 days. This raises the question as to what extent it is even meaningful to talk about a "16-day" wave, certainly the character of the oscillations are very different from the well-known quasi-2-day waves which exhibit a very limited range of periods.

Jacobi *et al.* (1998a) presented mean monthly zonal and meridional annual spectra based on LF D1 observations at Collm (52°N) over the period 1983–95. These studies show that the low-frequency components of the zonal motion field (frequencies < 0.1 cycles/day) displays strongest activity from about February to mid-April with a maximum in occurring in March, in good agreement with the results presented in Sect. 3.2. However, the corresponding meridional spectral power reported by these authors is significantly smaller.

The secondary maximum in late summer/autumn reported in Sect. 3.2 is not readily apparent in the 13-year average of the monthly mean data of Jacobi *et al.* (1998a). These authors also presented data for individual years over the 1983–95 period, but based on standard deviations of band-pass filtered velocity time series, rather than amplitudes or powers, thus making direct comparisons difficult. Nevertheless, their data for the 14–18 day period band (frequencies of 0.07–0.056 cycles/day) and the 9–11 day period band (frequencies of 0.11–0.091 cycles/day) overlap with periods covered in the spectrograms of Fig. 2a–j. Careful comparison reveals that many, but not all, of the features observed in the meteor-radar data of this work can be related to equivalent features in their LF D1 measurements. In particular, the secondary summer/autumn maxima occurring in 1990–93 (Fig. 3) all correspond to times of increased standard deviation in the 14–18 day period band data of Jacobi *et al.* (1998a). The lack of a significant secondary maximum in the mean spectra of Jacobi *et al.* (1998a) appears to be due to the general absence of such features in the years prior to 1989–90 in their data for this period band.

Observations made at higher latitudes by Williams and Avery (1992) using an MST radar at Poker Flat (65°N) revealed very much smaller wave amplitudes in winter ($< 2\ \mathrm{ms}^{-1}$ at heights above 85 km) during 1984. Also evident was a striking burst of activity where amplitudes exceed $6\ \mathrm{ms}^{-1}$, centred at a height of about

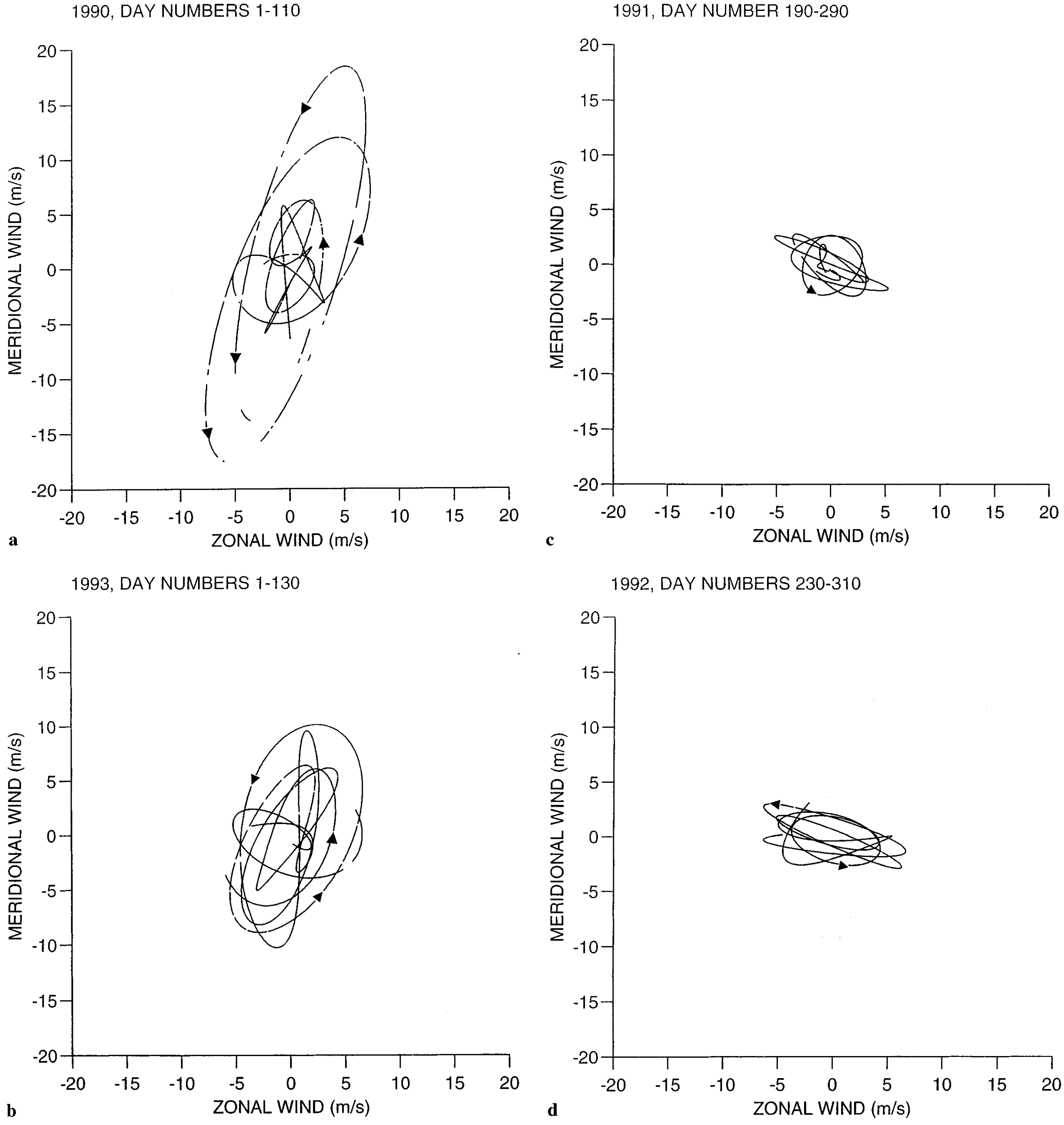

Fig. 4a–d. Hodographs for **a** day numbers 1–110 in 1990, **b** day numbers 1–130 in 1993, **c** day numbers 190–290 in 1991, **d** day numbers 230–310 in 1992. In all cases sections corresponding to interpolated data are not plotted. The sense of rotation of each hodographs is indicated by the *arrows*

85 km and which lasted for a little over a month in late-June/July. The short duration of this event is rather reminiscent of that reported here as occurring in the zonal winds in the summer of 1993 (Figs. 2g, 3).

Interannual variability of the 16-day wave has been addressed by Espy *et al.* (1997) and Jacobi *et al.* (1998a, b). Espy *et al.* (1997) derived mesopause-region temperatures from night-time measurements of the OH rotational band during day numbers 170–235 (late June–late August) of 1992–95 over Stockholm (59.5°N) and identified the thermal signature of the 16-day wave in 1992 and 1994, but not 1993 or 1995. The authors attributed this phenomenon to the westward phase of the QBO blocking the cross-equator propagation of the wave from a source in the winter hemisphere. In other words, supporting the idea that the wave observed in the summer hemisphere has propagated across the equator from the winter hemisphere rather than being excited *in situ* (Forbes *et al.*, 1995; Espy *et al.*, 1997). However, it should be noted that in the modelling study of Forbes *et al.* (1995) the cross-equator propagation pathway was found to be at mesopause heights and so would be largely unaffected the influence of the stratospheric QBO.

Lastovicka (1993) used 30-years of daytime radiowave absorption data measured by the A3 method to infer planetary-wave activity at MLT heights. No simple relationship was found between the QBO and planetary-wave activity, at least for wave periods less than 10 days. However, Lastovicka (1993) noted that apparent short-term correlations could be found in the data and this suggests that caution is needed in interpreting the results from studies, such as this one, based on only a few years of observations.

In contrast to the observations of Espy *et al.* (1997) the present work suggests that a short but significant burst of wave activity took place in the zonal and meridional winds at mid-latitudes towards the middle of August in 1993 when amplitudes reached up to 7 ms^{-1} ($\sim$ day number 220; Figs. 2g, h, 3). A similar burst of activity is also apparent on close inspection of the zonal wind results of Jacobi *et al.* (1998a) although their corresponding meridional winds do show a distinct minimum in activity for these day numbers during 1993.

These latter observations suggest that either: (1) *in situ* generation of the wave at MLT heights takes place in summer, perhaps due to the momentum deposition by gravity waves being modulated by gravity-wave/planetary-wave interactions in the troposphere and lower stratosphere, or (2) the equatorial barrier formed by the westward phase of the QBO is permeable to at least some wave activity, or (3) the propagation across the equator takes place at MLT heights. The more detailed study of QBO effects by Jacobi *et al.* (1998b) deduced a statistically significant dependence of the activity of 12–25 day planetary waves on the phase of the QBO, but again found that activity was not extinguished during the westward phase of the QBO.

The peak amplitudes observed for episodes of wave activity in summer range from about 7 ms^{-1} in 1993 to about 11 ms^{-1} in 1990 (Fig. 3). The hodographs of Fig. 4c, d reveal that the oscillations are generally zonal, in excellent agreement with the model predictions of Forbes *et al.* (1995). However, the data from the winter months often include predominantly meridional oscillations (e.g., Fig. 4a, b) in disagreement with these model predictions. The significance of this is not clear.

5 Conclusion

Nearly five years of meteor-region wind measurements have revealed a low-frequency motion field where oscillations with periods between about 10–28 days occur in "bursts" of activity often of only a few cycles duration; these are identified as the "16-day" planetary wave. The oscillations can be asymmetric with regard to zonal and meridional amplitudes, but in some of the clearer cases are predominantly zonal in summer and meridional in winter. Wave activity is strongest from January to about mid-April with amplitudes of up to about 14 ms^{-1}, has a minimum centred about late June to early July and then displays a second, smaller, maximum in the late summer and autumn where amplitudes range from about 7–10 ms^{-1}. There is considerable inter-annual variability. In contrast to the results of Espy *et al.* (1997), but in broad agreement with the equivalent data of Jacobi *et al.* (1998a), some wave activity is present in all summers, regardless of the phase of the equatorial QBO. This suggests that the westward phase of the QBO is not an impermeable barrier to inter-hemispheric ducting of the 16-day wave, that it is generated *in situ* in the summer hemisphere, or that the wave crosses the equator at MLT heights above the influence of the QBO.

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