Long-Period Oscillations in the Meteor Region

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ABSTRACT

Meteor wind data taken over Atlanta (34°N, 84°W) during the three-year interval 1974–77 are analyzed for periodic fluctuations of a recurrent nature. Power spectra and cross spectra of the zonal and meridional velocities between 80 and 100 km are constructed for several samples.

Ensemble statistics indicate the regular appearance of periods near 17, 8, 5, 2, 1.6 and 1.2 days. Most of these display smaller spectral values near 90 km. The general seasonal behavior has maximum values in winter and minimum values in summer, paralleling the observed variation of traveling wave energy flux in the stratosphere.

The regularity with which these oscillations appear, tempts an association with the periods of atmospheric normal modes.

1. Introduction

Of the numerous investigations that have examined upper atmospheric data, many have reported cyclic fluctuations of periods ranging from a day to a few weeks. Although they employed observations of a different nature, from varying levels and locations over the globe, several of these studies have noted a few common, recurrent periods.

A significant peak in the coherence between southern latitude ionosonde measurements and stratospheric temperatures was found near a period of 5 days (Fraser and Thorpe, 1976). This peak, which was evident in both summer and winter, was later identified (Fraser, 1977) with the wavenumber 1; Haurwitz free oscillation, observed at lower levels by Madden and Julian (1972) and Madden and Stokes (1975). A similar disturbance has also been noted in stratospheric radiance measurements (Rodgers, 1976), in tropical pressure data (Burpee, 1976), and in partial reflection observations (Manson *et al.*, 1978).

Two-day oscillations have been observed in meteor wind measurements taken over Sheffield, England) (Muller and Kingsley, 1974), Durham, New Hampshire (Clark, 1975), Obninsk, Russia, and Garchy, France (Kingsley *et al.*, 1978). Apparently, this fluctuation has been evident in data taken over Sheffield since long-term recordings began there in 1966. It has also been a recurrent feature of the partial reflection measurements at Saskatoon, Canada (Manson *et al.*, 1978).

A 10–15 day fluctuation has been observed in E region ionosonde measurements, and was found to be well correlated with the wavenumber 1 component of stratospheric radiance during autumn and winter (Cavalieri, 1976). Oscillations of comparable period were also noted during autumn and winter in a 10 mb analysis constructed from rocket and rawinsonde data (Finger *et al.*, 1966), and in the coherence spectra between ionosonde and stratospheric temperature measurements (Fraser and Thorpe, 1976). Recently, Madden (1978) has identified a 16-day, wavenumber 1 traveling disturbance in sea-level pressure data with a higher degree Haurwitz free wave.

In this article, we present an analysis of meteor wind data for recurrent oscillations of periods between 1 day and 3 weeks. Several samples of suitable length were available from the Georgia Tech facility in Atlanta during the years 1974–77. Spectral statistics were generated for each sample and averages were taken over the ensemble.

2. Data and analysis

The Georgia Tech meteor wind facility in Atlanta (34°N, 84°W) became operational on an intermittent basis in 1974. In the three years that followed, a number of samples were collected of suf-

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ficient length for the investigation of periodicities in excess of a day. These span the height range 70 to 120 km and range in length from 1 to 7 weeks.

The meteor technique is a one-dimensional Doppler system, observing randomly occurring events (meteor trail drifts). Hence, the observations (line-of-sight velocities) are random linear combinations of the velocity components. It is a difficult but essential task to estimate the individual velocity components. For the type of analyses performed here, where the periods being sought are unknown *a priori*, it is crucial that this estimation be performed without biasing the spectral content of the fields. This was accomplished by regressing the data on a spline basis set over height and time (Salby, 1978). Vertical velocities were neglected, since they were expected to be comparable to the estimation noise. This estimation error was greatest near the upper and lower extremities of the data. Therefore, only velocities between 80 and 100 km were used in the subsequent analyses. Time series of the zonal and meridional velocities were then obtained at various heights.

Power spectra and cross spectra were computed with a fast Fourier transform technique at uniformly spaced frequencies. The sample intervals used in this study were of insufficient length to permit statistical smoothing, increasing the number of degrees of freedom, etc.; however, a reasonable ensemble (29 samples) was obtained over the three-year period.

Averages were formed over this ensemble, but because of the different sample lengths, the frequencies where spectral values were computed varied from sample to sample. To allow for this, ensemble statistics were computed in a histogram fashion by dividing the frequency range into intervals and grouping the spectral content in each. Aside from this ensemble base for statistics, we also relied upon the inherent ability of the power spectrum and cross spectrum to resolve discrete spectral content over a finite interval.

For an infinitely long sample interval, the contribution to the power spectrum from a discrete spectral component is a single spectral value with zero frequency spread. For a finite interval, however, the contribution "leaks" to adjacent frequencies, and side lobes are formed about the primary spectral peak (see Bath, 1974). The detrimental feature here is that adjacent peaks may contaminate each other by this leakage and result in broadening of the spectrum in their vicinity. It can be shown that the "quality" or ability of the power spectrum to resolve a discrete component at a particular frequency is proportional to the number of cycles of that component contained in the sample. This ergodic nature implies that the sample interval may be viewed as an ensemble of events, each being one cycle of the discrete component. The spectral quality at the kth frequency is then proportional to k. Reasonable quality is usually achieved away from the first few frequencies, and spectral values for these are neglected in the following analyses.

Long-term trends over a sample were removed by differentiation (finite differencing). The procedure for retrieving the actual spectra from those of the differenced time series is outlined in the Appendix.

Power spectra of the zonal velocity $S(u)$, the meridional velocity $S(v)$, and the cross spectrum between the two time series $S(v \times u)$ were calculated for each sample at different heights between 80 and 100 km. Ensemble statistics were generated by defining the following random events:

(a) a local maximum (spike) in either $S(u)$ or $S(v)$
(b) coincident local maxima in $S(u)$ and $S(v)$
(c) a local maximum in $|S(v \times u)|$
(d) $|\arg[S(v \times u)] \pm 90°| < 45°$.

Oscillations in excess of a day are likely to result from planetary waves traveling through the region of observation. It is conceivable that a traveling disturbance might result in the occurrence of event (a) but not in event (b). Even in the absence of mean wind variations, the meridional and zonal velocities of Rossby waves display different horizontal character (see Kasahara, 1976). Thus, a spectral component of the zonal time series could be large at some location while that of the meridional time series might be comparable to the noise. The last event stems from the equations governing large-scale linear atmospheric disturbances. These imply that in the absence of viscosity, the zonal and meridional velocities are in quadrature. It should be noted that the effect of leakage from adjacent frequencies is more severe on the phase of the cross spectrum than on the other spectral quantities, since they are non-negative, and side lobes from adjacent frequencies can only increase their values.

3. Results

Fig. 1 shows the probability densities for events (a)–(d) as a function of frequency and period. These densities were formed using a frequency resolution of 0.04 cycle per day (cpd). All of the densities have local maxima near periods of 5, 2.2, 1.6 and 1.2 days. Events were also observed regularly near periods of 16.7, 3 and 1.4 days. Aside from the studies mentioned in the Introduction which have reported oscillations of 16, 5 and 2 days, local maxima appear repeatedly near 1.4 and 1.6 days in the spectra presented by Clark.

Fig. 2 shows $|S(v \times u)|^2$ for two samples. A 2.2-day oscillation is the dominant feature of the first cross spectrum (23 September–2 October 1975, 100 km), while a 5.3-day oscillation is easily distinguished in the second (19 November–31 December 1976, 80 km).

Local maxima in the spectra examined here were most isolated for the higher frequencies. This may be due to either the increased resolving capability (quality) at this end of the spectrum, or the spectral content at the lower frequencies being more closely spaced. In support of the latter, Rossby frequencies, which are expected to figure heavily in this range, become more closely spaced with decreasing frequency.

Several of the broad maxima in Fig. 1 exhibit finer detail when the frequency resolution is doubled. The corresponding probability densities are shown in Fig. 3 for the same four events. In particular, the broad maximum near 5 days now reveals several distinct local maxima near 8, 6, and 4 days. Apparently, these features are not due to the variation in sample length from one data set to another. Fig. 4 shows coincident local maxima in $S(u)$ and $S(v)$ which occurred near 0.17 (5.9 days) and 0.21 (4.8 days) cpd for the same data sample (23 June–4 August 1975, 90 km). The peaks in the probability densities near 5.9 and 4.4 days are consistent with numerous observations of the 5-day wave from the lower atmosphere, and similar periods noted in the upper atmosphere by Fraser and Thorpe, and Manson *et al.* The latter study also observed a recurrent 8-day oscillation, and Rodgers noted a 9-day peak in the power spectrum for the wavenumber 1 component of stratospheric radiance. A local maximum is easily distinguishable in all four events near a period of 2.1 days. There also appears to be a separate contribution in the vicinity of 3 days.

We have divided the ensemble of samples into seasons. The probability densities of events (a) and (b) are shown in Fig. 5. The quasi-2-day oscillation

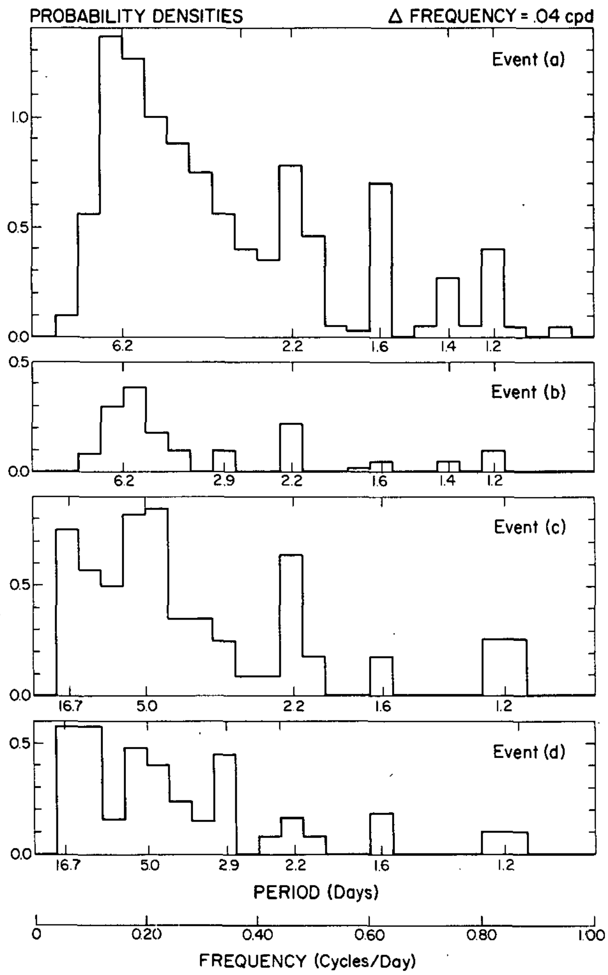

FIG. 1. Probability densities of events (a)–(d) (see text for definition) using a frequency increment of 0.04 cpd.

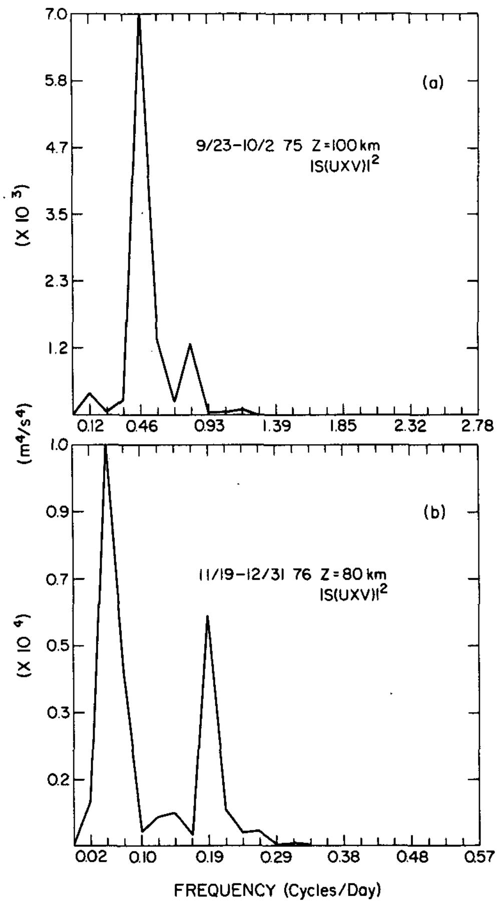

FIG. 2. Cross spectral magnitude between meridional and zonal velocities for (a) 23 September–2 October 1975 at 100 km and (b) 19 November–31 December 1976 at 80 km.

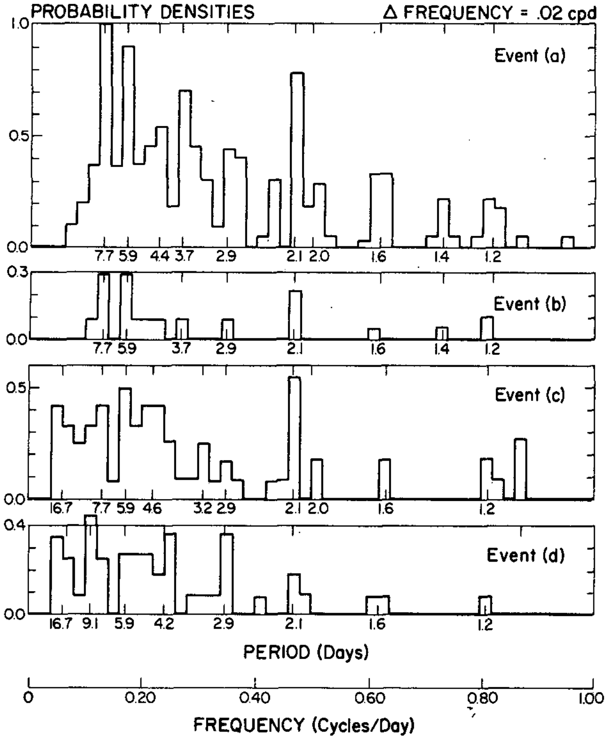

FIG. 3. As in Fig. 1 with a frequency resolution of 0.02 cpd.

occurred most frequently in the autumn and summer samples. Aside from being identified solely with event (a), the period seems to be slightly shorter in winter and spring. A 3-day periodicity is most evident in the autumn and winter samples, while 4–6 day oscillations were observed in all of the seasons.

A rather general feature of many of these regularly observed oscillations was a minimum in the associated spectra near 90 km. Fig. 6 shows several sample profiles of $|S(v \times u)|$ normalized by the 80 km values for frequently observed periods.

The mean seasonal variation of $|S(v \times u)|$ is presented in Fig. 7 for the same periods. Oscillations with periods of 5 and 20-days display maximum amplitudes in winter, while those with periods of 2 days exhibit maximum values in autumn. This is in conflict with the seasonal behavior of the 2-day oscillation presented by Kingsley *et al.* (maximum values in summer), but agrees with the general seasonal character of the spectra examined here, i.e., maximum values in winter, minimum values in summer. It also parallels the seasonal variation of the vertical growth rate (Deland and Johnson, 1968) and vertical energy flux (McNulty, 1976) of traveling waves in the stratosphere, and the seasonal variation of ionosonde fluctuations (Fraser, 1977).

4. Discussion and conclusions

The meteor wind time series examined here, support the contention of earlier studies, that oscillations of periods near 5, 2 and 15–20 days occur frequently at ionospheric heights. In addition, an 8-day oscillation was discernible in the probability densities when finer resolution was employed. Periods of 1.6 and 1.2 days appeared distinctly in all of the random events examined.

The recurrence of these fluctuations must be attributable to either forcing mechanisms operating regularly at these frequencies, or to the fact that these periods represent preferred time scales of

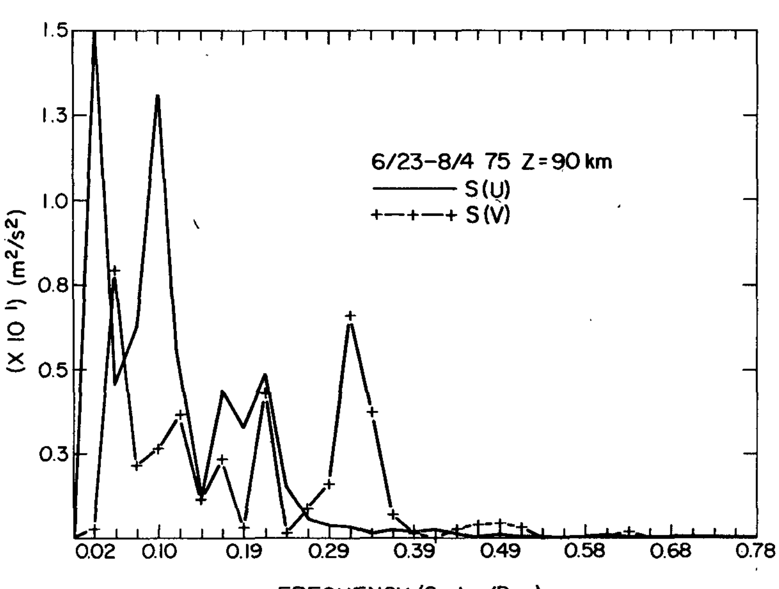

FIG. 4. Power spectra of zonal (u) and meridional (v) velocities for 23 June–4 August 1975 at 90 km.

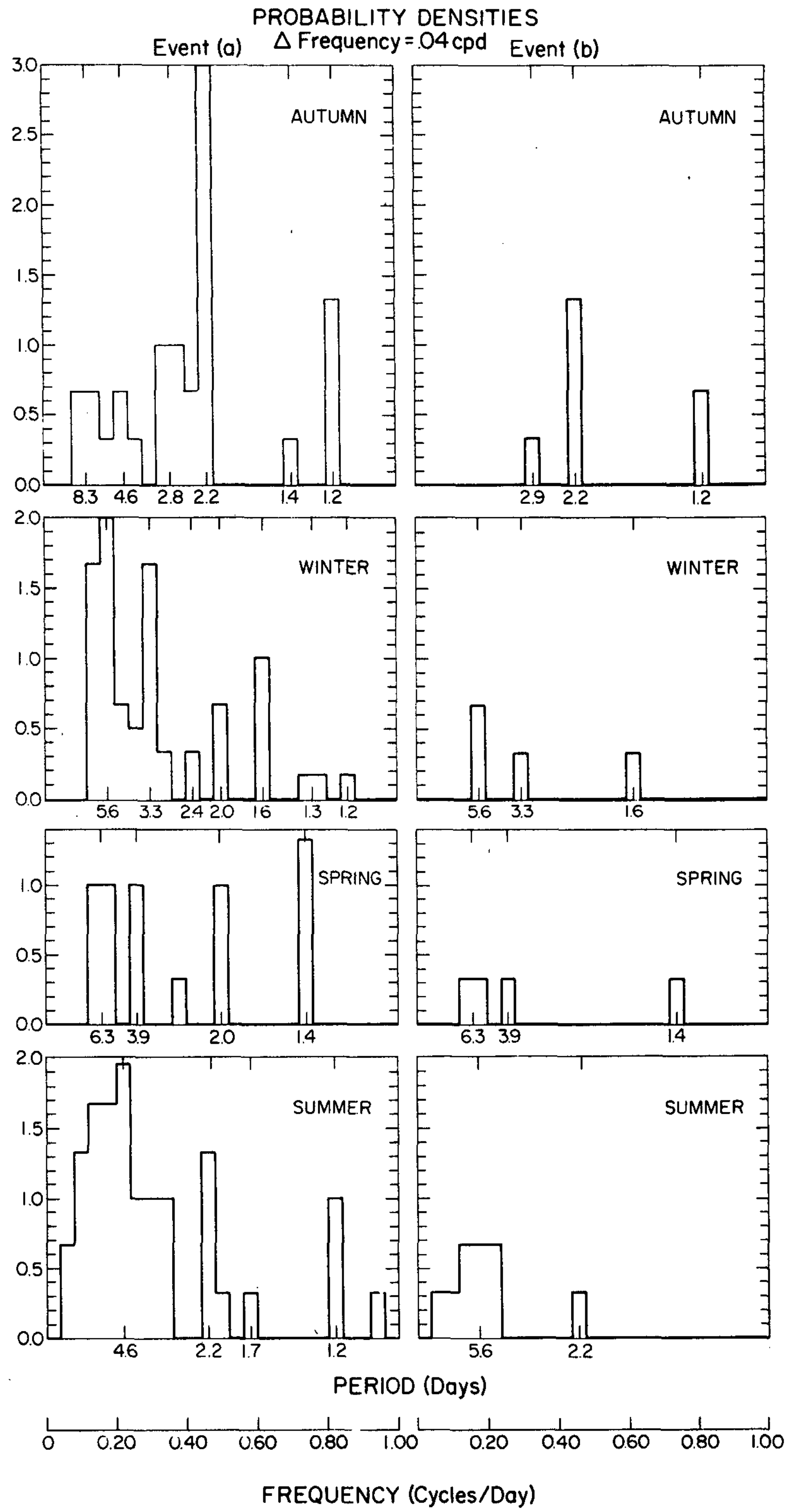

FIG. 5. Probability densities for events (a) and (b) (see text for definition) by season.

oscillation. Although instability may serve as an example of the former, the second explanation seems the more likely of the two.

Free oscillations, or normal modes as they are often referred, have the property that energy flow is inhibited in the vertical. This is in contrast to vertically propagating waves, where disturbance energy flows readily out of a layer. Normal modes can be

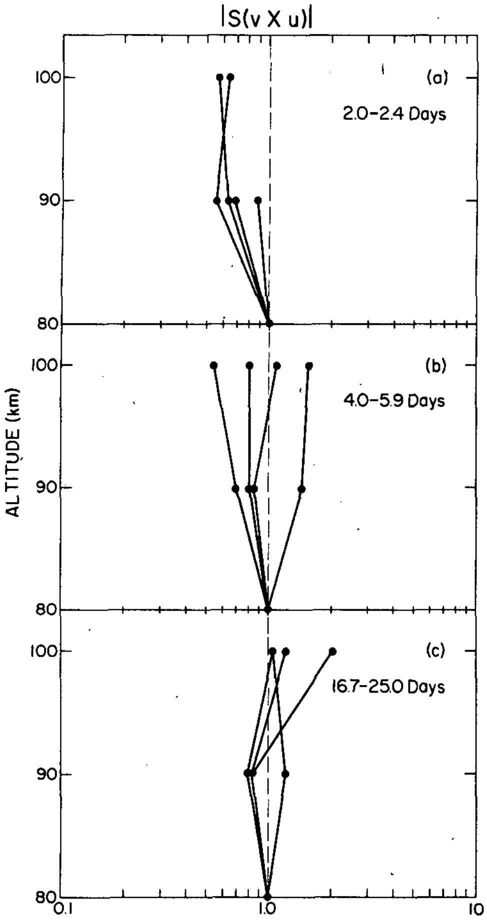

FIG. 6. Normalized spectral profiles for regularly observed periods.

stimulated by various forms of noise or unsteadiness. Once excited, the disturbance energy remains in a layer over a long period compared with other types of waves (Salby, 1979). Because of this property, such disturbances are prime candidates for the regular oscillations that have been observed.

If driven by the unsteady character of the troposphere as has been suggested (Geisler and Dickinson, 1976), they might also account for the observed seasonal variation in intensity. The "quiet" summer months of the lower atmosphere would coincide with passive stimulation, while the "noisier" winter months would result in more active excitation and greater amplitudes.

Table 1 lists the eigenperiods for these modes in an atmosphere with realistic temperature structure, for several wavenumbers m and meridional indices n. These correspond to solutions of Laplace's tidal equation with an equivalent depth of roughly 10 km (Salby, 1979). Also shown are the periods of modes vertically ducted in the stratosphere and mesosphere by variations in buoyancy. These too have restricted vertical energy flow at these levels.

Fluctuations of periods near 5 and 16 days have been linked in the lower atmosphere to Haurwitz free oscillations of wavenumber 1. Since ionosonde data, from heights comparable to the meteor region, has revealed a 10–15 day wavenumber 1 oscillation (Cavalieri, 1976), one may speculate that the 16-day oscillation seen here and in ionosonde data are related to the Haurwitz wave observed in the troposphere. One is also tempted to link periods from Table 1 with several of the features observed. In particular, the first three Rossby-gravity modes ($m = n$) have periods of 1.2, 1.6 and 2.1 days. Actual identification, however, requires observation of the complete horizontal structure as well as the temporal behavior.

Many of the oscillations discussed were evident year-round. Fluctuation intensities for most were

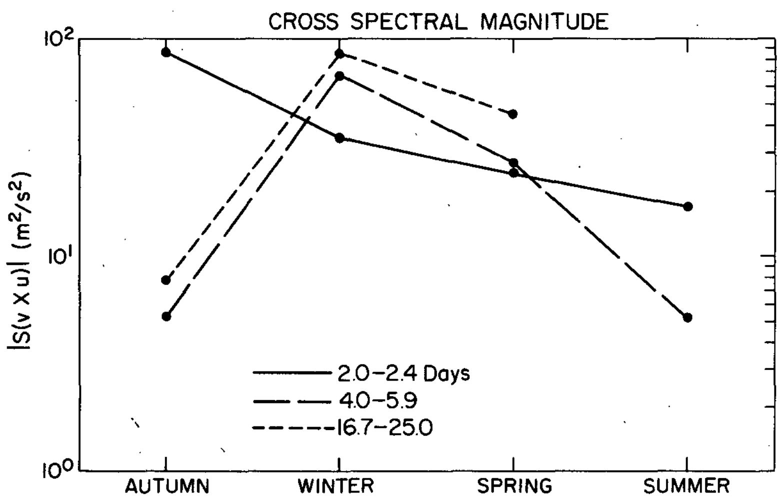

FIG. 7. Mean seasonal behavior of the magnitude of the cross spectrum for regularly observed periods.

TABLE 1. Rossby periods for equivalent depths of 9.9 and 6.3 km and several horizontal modes (m,n)

	n	Period (days) h = 9.9 km	h = 6.3 km
	1	1.2	1.3
	2	5.1	6.1
$m = 1$	3	8.3	9.6
	4	12.5	14.7
	5	17.2	19.2
	2	1.6	1.9
	3	3.7	4.5
$m = 2$	4	5.9	7.0
	5	8.5	10.0
	6	11.6	13.2
	3	2.1	2.2
	4	3.6	4.2
$m = 3$	5	5.6	5.8
	6	7.6	8.2
	7	10.0	10.4

greatest during winter and smallest during summer, consistent with the notion of forcing by unsteadiness from below. At first glance this seems to contradict the larger amplitude of the 5-day wave in the summer mesosphere, predicted by Geisler and Dickinson (1976). That study, however, used equivalent forcing in each hemisphere. If unsteadiness is the driving agent for this mode, the increased response in the summer hemisphere should probably be weighted against the seasonal variation in excitation.

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APPENDIX

Detrending and Recoloring

Standard spectral techniques are employed for analysis of the data. Unfortunately, it is usually quite evident that the time series contain substantial trends which must be removed in order that these be used. These trends are either seasonal in nature or due to longer period oscillations which cannot be resolved in the given sample period.

The trends are assumed to be piecewise polynomial and hence may be removed by differentiation. Practically, however, there is a limit to how many times this may be done without altering the spectral content, because of discretization. The velocity functions may be written as

$$u(t) = p(t) + \sum_{k=1}^{n/2} f_k \exp[i(2\pi k/T)t], \tag{A1}$$

where $S(u) = |f_k|^2/2$ is the power spectrum of u at the kth frequency, T the sample interval, $n/2$ the number of frequencies and $p(t)$ a piecewise polynomial function. The mth derivative is approximately

$$u_{(t)}^{(m)} = \frac{\hat{u}^{(m)}(t)}{h^m}, \tag{A2.1}$$

where $\hat{u}^{(m)}$ is the mth difference and h is the difference increment. Hence the mth difference of u is

$$\hat{u}^{(m)} = p_{(t)}^{(m)} + h^m\left(\frac{i2\pi}{T}\right)^m \times \sum_{k=1}^{n/2} f_k k^m \exp[i(2\pi k/T)t]. \tag{A2.2}$$

Assuming the trend to be eliminated, the power spectrum of this new function, $\hat{u}^{(m)}$, is recognized as

$$S(\hat{u}^{(m)}) = \frac{1}{2}\left|\left(\frac{i2\pi}{T}\right)^m h^m k^m f_k\right|^2 \tag{A3.1}$$

or

$$S(\hat{u}^{(m)}) = \left(\frac{2\pi}{T}\right)^{2m} h^{2m} k^{2m} \frac{|f_k|^2}{2} = \left(\frac{2\pi k h}{T}\right)^{2m} S(u). \tag{A3.2}$$

By taking

$$h = \Delta t = T/n \tag{A4}$$

the original spectrum (recolored) in terms of that of the differenced function is

$$S(u) = \left(\frac{n}{2\pi k}\right)^{2m} S(\hat{u}^{(m)}). \tag{A5}$$

In a similar fashion, the magnitude and argument of the cross spectrum between two time series u and v are related to those of the differenced series by

$$|S(v \times u)| = \left(\frac{n}{2\pi k}\right)^{l+m} S(\hat{v}^{(m)} \times \hat{u}^{(l)}), \tag{A6.1}$$

$$\arg S(v \times u) = \arg S(\hat{v}^{(m)} \times \hat{u}^{(l)}) + (m - l)\frac{\pi}{2}. \tag{A6.2}$$

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