Long-Period Meteor Wind Oscillations

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Long-period meteor wind oscillations

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Records obtained with the Sheffield meteor wind radar have been subjected to harmonic analysis resolving a longest period of 130 h. The spectra of oscillation generally show three distinct peaks: periods near 12, 24, and, surprisingly, between some 35 and 72 h. The 24 and 12 h peaks can be readily accounted for as the effect of the solar diurnal and semidiurnal tides but regular oscillations with periods in excess of one day appear more difficult to explain. Although upward propagation of long period waves is severely restricted there seems to be some evidence that the primary source of these oscillations lies in the lower atmosphere as shown by the correlation between meteor winds and the variation of atmospheric pressure as well as tropospheric winds near the principal meteor collecting areas.

1. INTRODUCTION

Upper atmospheric wind observations using the radio meteor method have now been carried out systematically for some years, notably during the I.Q.S.Y. 1964–5. Conforming to earlier patterns and those recommended during such international cooperative years data were usually recorded over periods not exceeding 24 h on individual days, usually once a week. The meteor wind radar at Sheffield was used in this manner during the I.Q.S.Y. obtaining 24 h data sets over a total period of 18 months. The results of these observations published by Muller (1966) are essentially based on harmonic data analysis resolving a 'steady prevailing', 24, 12 h and higher harmonic components. It has been found in the past that 24 h data sets are not exactly matched by a harmonic series whose fundamental period is 24 h because the data at the beginning and the end of the set tend to differ appreciably. This effect can be interpreted in terms of slow changes of the so-called steady prevailing component in the wind and such changes make it difficult to resolve the fundamental component of the time series. Although a 24 h component has always been quoted in the past one should regard these values as less significant except in cases where the diurnal component predominates in the spectrum. We felt already during the I.Q.S.Y. the need for more extended periods of observation in order to resolve 24 h harmonic components with greater reliability. As a first attempt a 3-day continuous run was carried out at Sheffield in August 1966 using the original I.Q.S.Y. wind radar at 25 MHz. Meanwhile a high-power radar with increased resolution had been completed at Sheffield and was first operated during a 2-day run in August 1968. A number of interesting features were observed in the recorded meteor wind profiles, notably the existence of oscillations whose periods exceed one day, and these results stimulated interest in a more extended run which took place, at the same time of the year, in 1969 and lasted for $5\frac{1}{2}$ days.

The present paper is primarily concerned with the resolution of oscillations in the upper atmospheric wind, of very long periods paying only little attention to the short period-section of the spectrum. While we are now in a fair position to account for the diurnal and semi-diurnal oscillations in the wind patterns, applying the dynamical theory of the atmosphere, we are finding it very difficult to explain the presence of oscillations whose periods are of the order of days. The structure of the wind indicates wave-like motions on a planetary scale such as the

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waves which have been known for some time to exist in the troposphere. However, due to the structure of the middle atmosphere, upward propagation to the meteor zone of such waves is severely restricted, particularly during the summer months, although the theory allows for the leakage of planetary wave energy into the meteor zone at certain times of the year. Alternatively, we may consider an indirect mechanism where short period atmospheric gravity waves generated at discontinuities in the lower atmosphere propagate obliquely to meteor heights where they then dissipate part of their energy causing temperature gradients which in turn give rise to fluctuations in the wind. In order to investigate the degree of coupling between the different layers of the atmosphere we have carried out a study of tropospheric parameters about the times of our meteor wind runs, involving pressure profiles at sea level, general synoptic charts, and aerological data up to the 50 mbar† level. Identical mathematical methods of analysis have been applied to both meteor wind – and tropospheric data and a significant correlation between phenomena at the two atmospheric levels has been obtained. Although the present data are probably too intermittent to provide conclusive information on the coupling mechanism the method itself appears very suitable for such studies. While the data used in this present work were being analysed additional long-period meteor wind runs have been conducted, particularly during the winter season and the results of these observations are to be presented and discussed in a subsequent paper.

2. TECHNIQUE

The coherent pulse backscatter radar used in this work has been described in some detail in two previous papers by Muller (1966, 1970). The essential features of the apparatus are two pulsed transmitters and associated receivers operating at 25 and 36 MHz respectively and incorporating aerial systems whose beam-width is typically 25° both in the vertical and horizontal at 36 MHz and whose mean beam elevation is nearly 30°. Aerials are directed NW and SW resolving SE and NE components respectively (using to the ionospheric convention

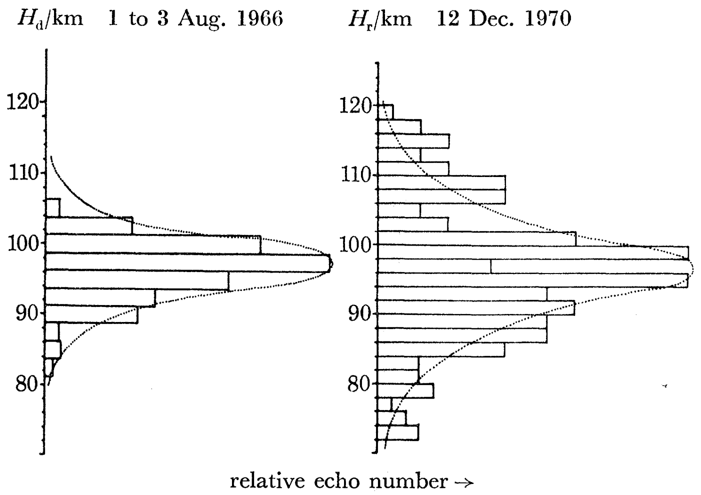

FIGURE 1. Distribution of meteor echo rates as a function of height. In the left-hand diagram heights are based on the ambipolar diffusion coefficient obtained from the echo decay of underdense type meteors. In the right-hand diagram heights were determined direct with the height finding equipment at the Sheffield meteor wind station.

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† 1 mbar = 10^2 Pa.

where the wind direction is that into which the wind blows). During a meteor wind run data are recorded alternately on two aerials, each aerial being in operation for some 5 to 10 min. Data are averaged and apply to an average height which is close to 97 km as shown in figure 1. In the left-hand section of the figure the distribution of meteor echo numbers as a function of height is based on the ambipolar diffusion coefficient calculated from the echo decay time constant using only so called underdense type meteors. In the right-hand section of figure 1 the distribution is based on true echo heights determined with a newly developed phase comparison technique installed recently at Sheffield. The meteor echo rate varies diurnally and seasonally and in this present investigation the peak rates of usable meteor echoes are found to be about 500 per hour in the early hours of the morning dropping to 50 per hour at the time of the diurnal minimum. An average observed echo rate of about 200 per hour was found adequate to resolve winds reliably over long periods. Since we use two separate aerials in this investigation we obtain two individual sets of (horizontal) wind velocity data in each run. These represent time-series which are subjected to harmonic analysis. We must bear in mind that the wind components resolved in this fashion apply to regions of the atmosphere whose centres are separated by several hundred kilometres in the horizontal and that therefore only wind systems with sufficiently large horizontal scales are resolved with this technique. Such large scales are however expected with wind oscillations whose periods are in excess of one day.

3. Analysis of data

In an earlier paper by Muller (1966) a description is given of how a Fourier-series containing five harmonic terms is fitted to the data, involving a least squares method. Because of the general lack of agreement of the data at the beginning and end of our time series as mentioned in §1 a harmonic series appears less suitable to fit a time-limited data series and a new method has been adopted in this present work. This method involves a leasts squares polynomial fit to the data, developed essentially by H. Alleyne at Sheffield and will be described in detail elsewhere. The fitted polynomial may then be subjected either in parts or as a whole to harmonic analyses of various forms utilizing an I.C.L. 1907 (64 K) computer. Our program 'Aspectrum' is of particular interest for the detailed resolution of harmonic features since the length of a harmonic series may be extended from a minimum of 12 h in steps up to 216 h, and the starting hour may be delayed in discrete steps, the phase of each harmonic component being adjusted accordingly. In this fashion average harmonic coefficients are derived for each mode of oscillation and a quasi-continuous spectrum is obtained for each individual wind component. In addition, auto- and cross-correlation analyses have been carried out but important phase information is usually lost in this type of analysis.

4. Presentation of results

Average horizontal wind components applying to an average height of 97 km for the period 1 to 3 August 1968 are shown in figure 2. The smooth curves represent the best fitting polynomials which are seen to match the individual data points quite well. The numbers shown correspond to the number of meteor records contributing to a data point and indicate the degree of reliability of a measurement in terms of the 95 % confidence limits (see Fig. 3 in Muller 1966). Figure 2 shows that the wind is predominantly semidiurnal, but we also recognize a much slower oscillations in both wind profiles whose period is considerably longer than one day. Since this long-term oscillation appears to be significant we have subjected the whole 72 h series to our Aspectrum analysis, referred to in §3, in order to obtain a smooth spectrum of

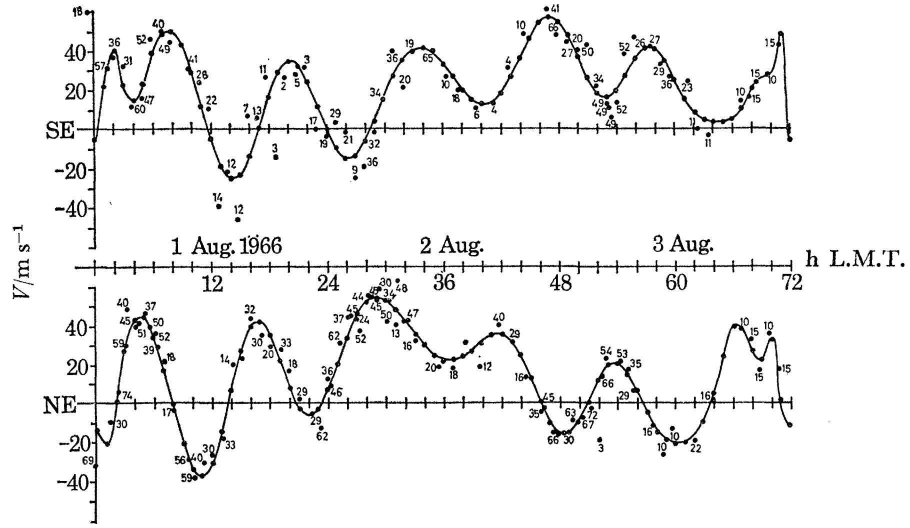
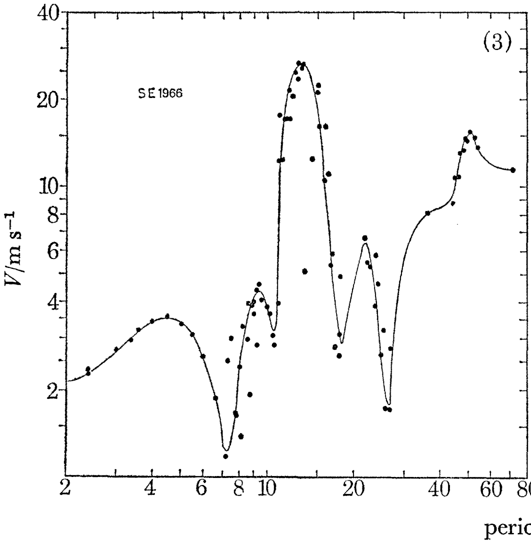


FIGURE 2. Horizontal SE and NE wind components at Sheffield applying to an average height of 97 km for the period 1 to 3 August 1966. Numbers refer to the number of meteor records contributing to each data point. The smooth curves represent the best fitting polynomials to the data.



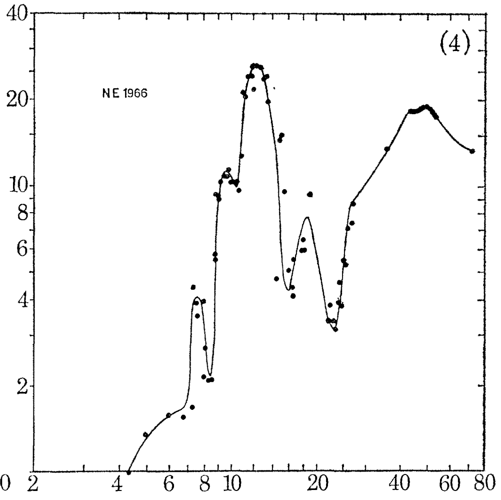


FIGURE 3. Amplitude spectrum of the 97 km SE wind component at Sheffield between 1 and 3 August 1966.

FIGURE 4. Amplitude spectrum of the 97 km NE wind component at Sheffield between 1 and 3 August 1966.

oscillations. The amplitude spectrum of the SE-component of figure 2 is shown in figure 3. We note the dominance of the 12 h oscillation which is evidently the effect of the well-established semidiurnal tide at meteor heights. There is also a broad spectrum of short-period modes, possibly the effects of internal atmospheric gravity waves, some response near 24 h and, surprisingly, a significant peak near a period of 2 days, in fact very close to 51 h, with an amplitude comparable to that of the semidiurnal oscillation.

Figure 4 shows the amplitude spectrum of the NE component displayed in figure 2 and it is seen that the basic features of the spectrum agree well with those shown in figure 3, the peak near 51 h being quite pronounced. Bearing in mind that the two orthogonal wind components are measured quite independently and apply to regions which are well separated geographically we may conclude that the horizontal scale of these oscillations is quite considerable. The systematic phase difference observed in the two components would indicate the presence of wave-like motions similar to the planetary waves reported in the lowest part of the atmosphere.

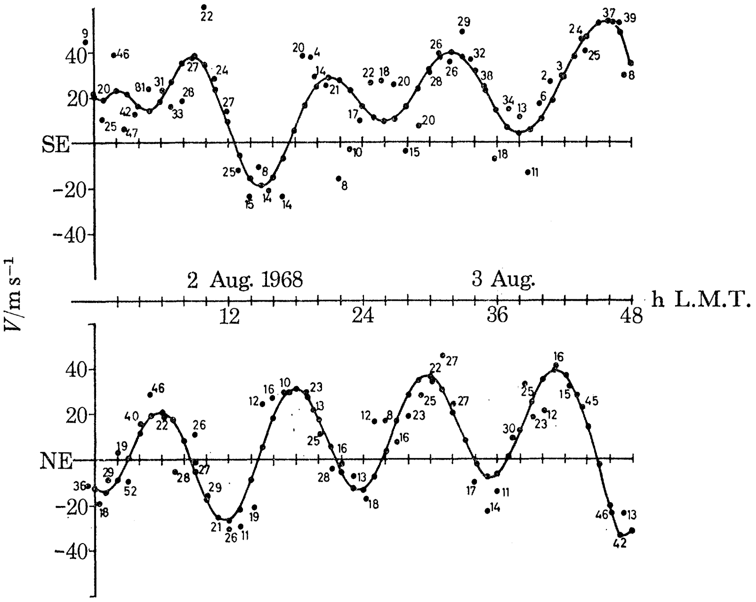


FIGURE 5. Horizontal SE and NE wind components at Sheffield applying to an average height of 97 km for the period 2 to 3 August 1968. Numbers refer to the number of meteor records contributing to each data point. The smooth curves represent the best fitting polynomials to the data.

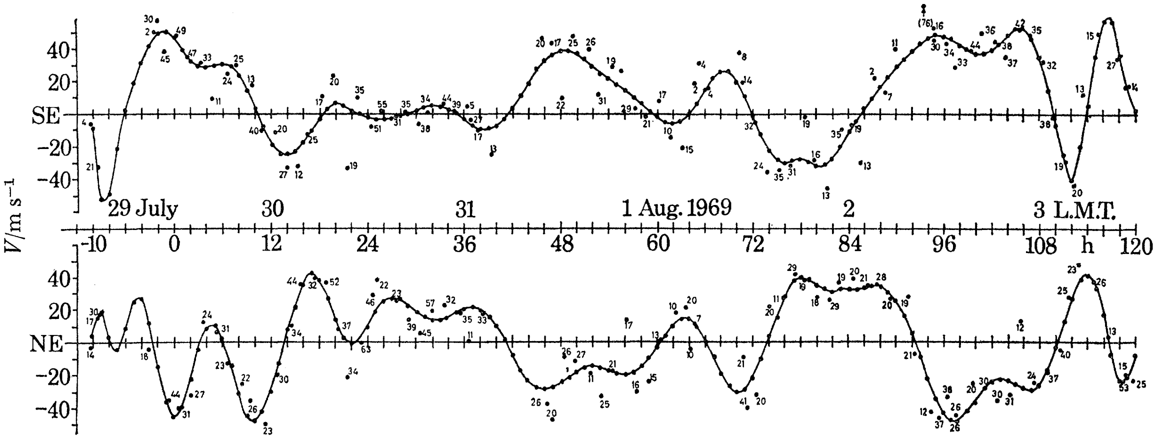


FIGURE 6. Horizontal SE and NE wind components at Sheffield applying to an average height of 97 km for the period 29 July to 3 August 1969. Numbers refer to the number of meteor records contributing to each data point. The smooth curves represent the best fitting polynomials to the data.

Since the first discovery of an oscillation with a period of nearly 2 days we have conducted further extended runs at about the same time of the year. Figure 5 shows the results of a 2-day run in 1968 which compare well with the 1966 data but although we recognize a mode with a period of about 2 days its amplitude is comparatively small. This appears to be an important result which we shall refer to again when discussing the coupling between different atmospheric levels.

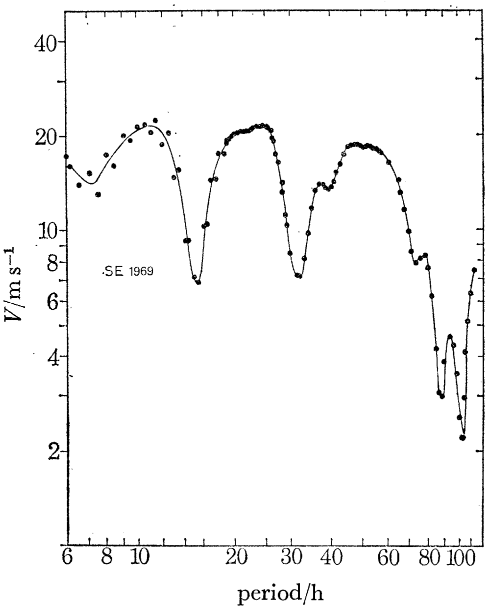


FIGURE 7. Amplitude spectrum of the 97 km SE wind component at Sheffield between 29 July and 3 August 1969.

The longest run conducted at Sheffield so far took place in July/August 1969 and was specially arranged in order to look for oscillations whose periods might exceed 3 days. Figure 6 shows the SE and NE wind profiles obtained over 130 h, the time 0 h being designated to 0 h L.M.T. on 30 July 1969. The structure of the two profiles appears somewhat more complex than on previous occasions; apart from pronounced semidiurnal oscillations, evidently modes with periods well in excess of one day are present. Much more detail is obtained from the corresponding amplitude spectra. In figure 7 we notice that the SE-wind spectrum has a very distinct structure: a peak near 12 h which is obviously the semidiurnal tidal component, another peak near 24 h which may be attributed to the diurnal tidal wind, and a fairly broad spectrum of oscillations with periods ranging from about 35 to 72 h showing a slight peak near 2 days. A very similar spectrum has been obtained for the NE component shown in figure 6.

These results covering three years, show quite clearly that long-period oscillations exist in the wind system at meteor heights. Although there appears to be some connexion with the Earth's rotational period (peaks near 48 h) it would not seem appropriate to seek an interpretation of these phenomena in terms of tidal effects. We are more inclined to see them as the effects of planetary type waves which appear to exist on a global scale.

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5. Discussion and interpretation of results

Since there is evidence accumulating that the atmosphere is a continuum and that all layers are interacting with each other we must seek to establish a connexion between the meteor wind oscillations described above and other phenomena observed in the neighbouring regions of the atmosphere or even those a considerable distance away. The search for coupling effects in the intermediate atmosphere should ultimately lead to the primary energy source for these oscillations, and all indications are that this source is located below and not above the meteor region. Since the greatest abundance of synoptic data applies to the lowest tropospheric levels we have begun our search for corresponding phenomena by examining data obtained on a routine basis at various meteorological stations, either in the form of entries in the registers or summarized in the daily weather charts published by the Meteorological Office. The choice of tropospheric

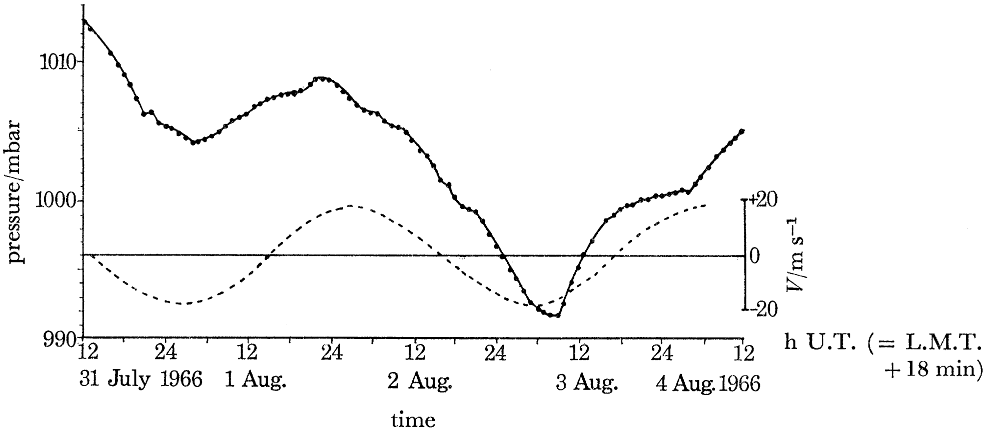

Figure 8. Sea-level atmospheric pressure at Valley in Anglesey (—) together with the 51 h meridional wind at 97 km recorded at Sheffield (----).

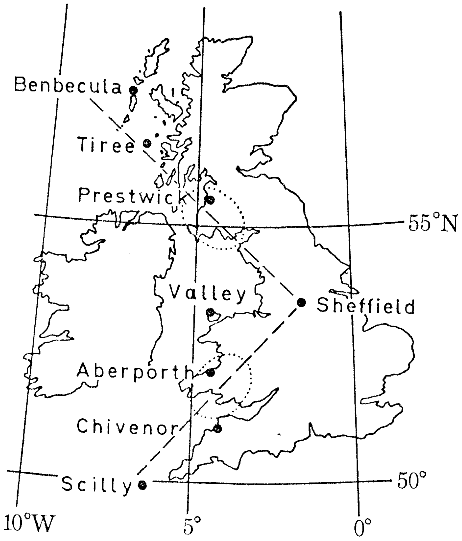

Figure 9. Location of meteorological stations at which atmospheric pressure data used in this investigation were recorded. The two principal meteor collecting areas over which winds are observed from Sheffield are also shown.

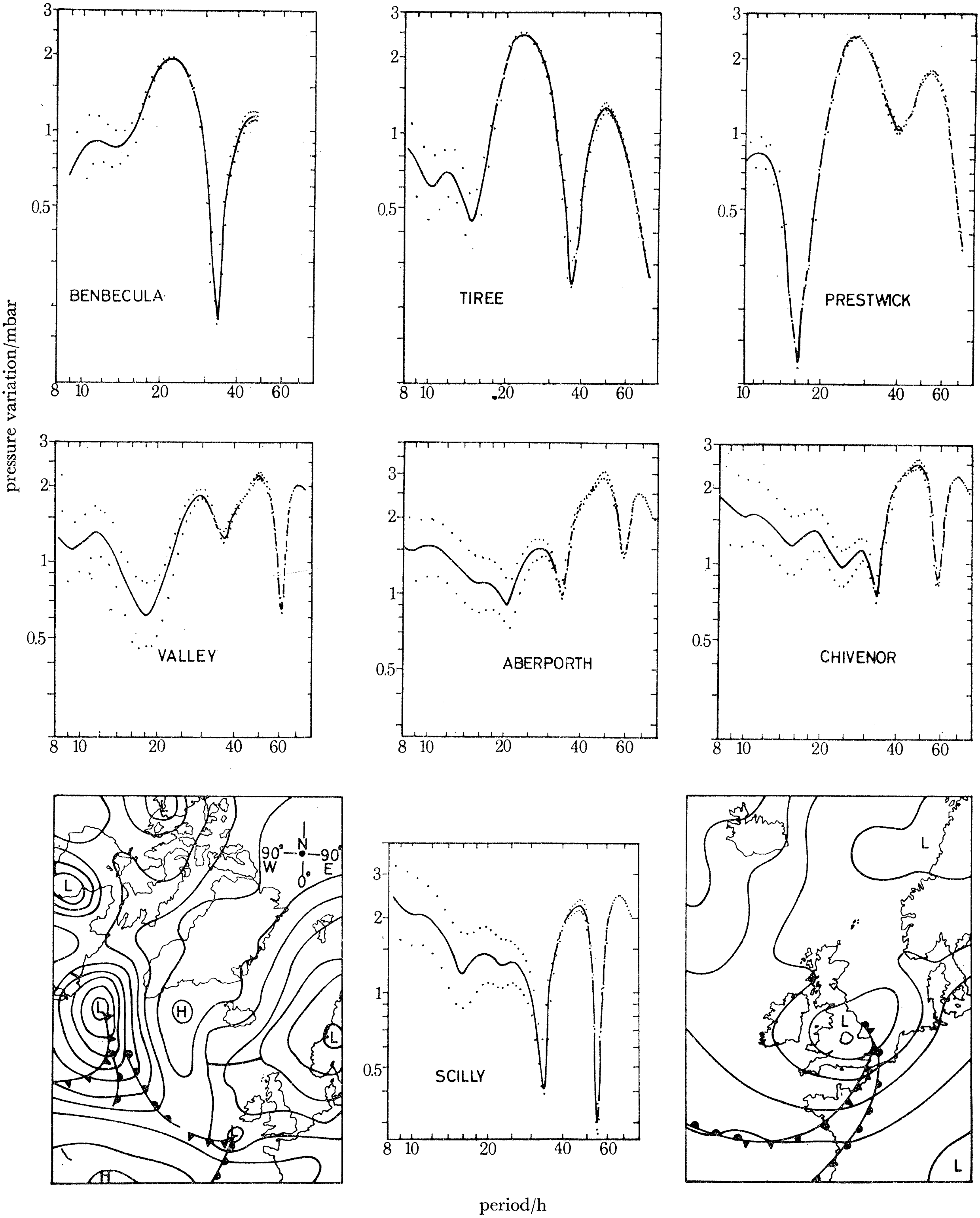

Figure 10. Amplitude spectra of sea-level atmospheric pressure fluctuations for various meteorological stations for the period 29 July to 5 August 1966, together with synoptic pressure charts for 12h00 31 July 1966 (left) and 06h00 1 August 1966 (right) based on the *Daily Weather Report* by the Meteorological Office.

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levels also seemed appropriate since it has been known for some time that pressure and wind oscillations with periods in excess of one day can exist in the lower atmosphere.

Figure 8 shows the sea-level atmospheric pressure variation at Valley in Anglesey together with the 51 h meridional meteor wind component for the August 1966 period of observation. It is seen that both curves show certain corresponding features which would indicate some degree of coupling between the two layers of atmosphere concerned here. It was found that the meteor wind oscillations are also correlated with sea-level pressure variations recorded at greater distances from the radar and a systematic analysis of pressure data has been carried out using records from seven meteorological stations whose locations relative to the meteor collecting areas are shown in figure 9. Figure 10 shows the results of harmonic analysis in the form of amplitude spectra for the various stations for July–August 1966 and it is seen that the long period features of the spectra are quite well matched by those in the corresponding meteor wind spectra, peaks in the amplitude distribution all being close to a period of 2 days.

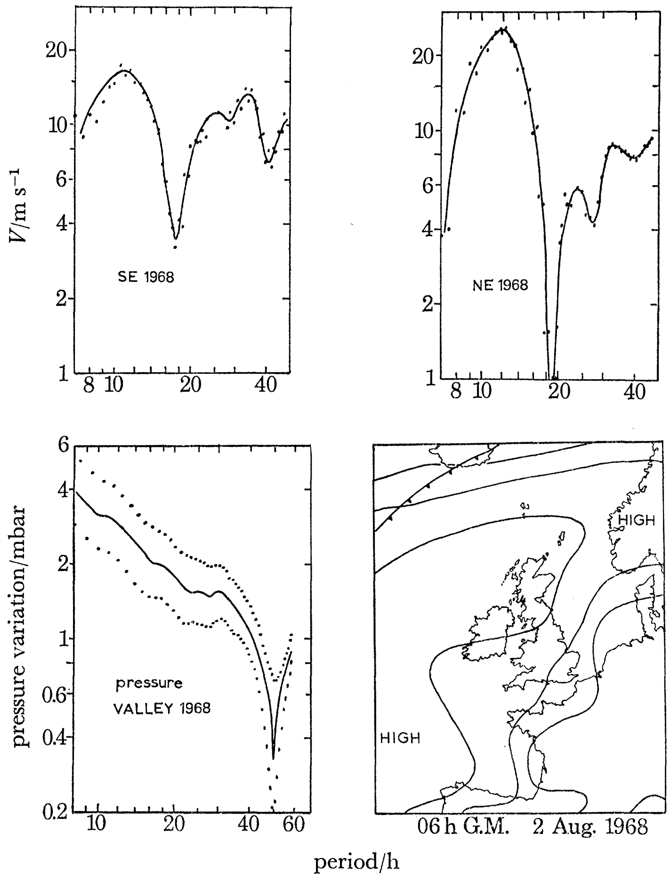

FIGURE 11. Amplitude spectra of the 97 km SE and NE wind components at Sheffield between 2 and 3 August 1968 together with the amplitude spectrum of sea-level atmospheric pressure fluctuations at Valley in Anglesey for the period 31 July to 4 August 1968 and a synoptic pressure chart based on the *Daily Weather Report* by the Meteorological Office.

As a point of interest, all pressure spectra show a peak near 12 h of about 1 mbar which is related to the solar semidiurnal pressure tide and the resolution of this component illustrates the sensitivity of the type of analysis applied in this work. Figure 10 also shows the general synoptic pressure situation for the time of our meteor wind observations and we note the presence of alternate highs and lows in the north polar region and numerous fronts, particularly in the vicinity of the British Isles. Figure 11 shows the relevant material used in the comparison of atmospheric parameters for the August 1968 period of observation. The wind amplitude spectra at the top correspond to the two-meteor wind profiles shown in figure 5, and the diagram at the bottom shows the amplitude spectrum of the sea-level atmospheric pressure oscillations at Valley. As already mentioned in §4 the amplitude of a meteor wind oscillations with a period near 2 days was found to be smaller in 1968 than during the preceding and succeeding years

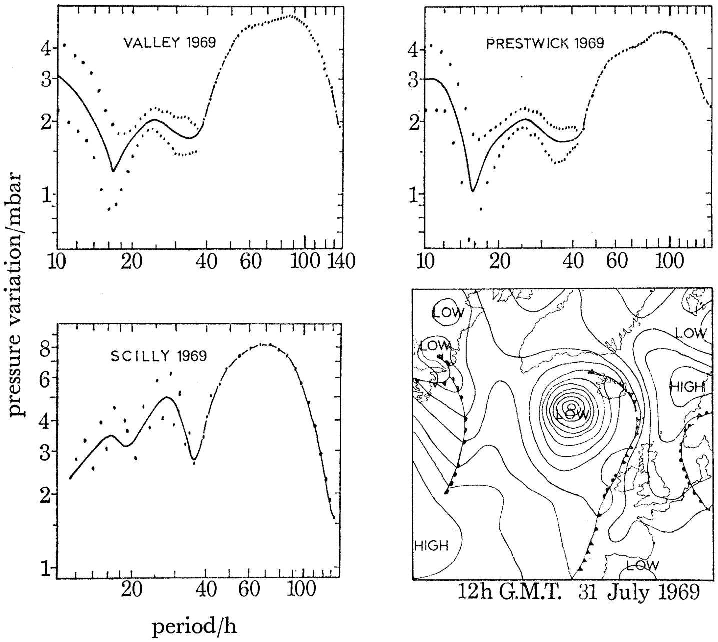

FIGURE 12. Amplitude spectra of sea-level atmospheric pressure fluctuations in three locations near the principal meteor collecting areas used at Sheffield for the period 27 July to 4 August 1969 together with a synoptic pressure chart based on the *Daily Weather Report* by the Meteorological Office.

and this may be used as an argument in favour of coupling between the higher and lower atmospheric levels for, as seen in the pressure spectrum in figure 11, there is a pronounced minimum near a period of 2 days and we also observe a tendency for the spectrum to decay toward longer periods. The general pressure situation is, as evident from the chart in figure 11, very stable – there is high pressure everywhere near the British Isles and we note the general absence of frontal systems except for a weak cold front over Iceland.

Figure 12 refers to the comparison for the 1969 observations described in §4. We find broad spectra of long-period oscillations in the pressure data matching almost perfectly those resolved in the meteor wind. As in 1966 we notice alternate highs and lows in the synoptic charts and there are numerous fronts near the British Isles.

We may therefore tentatively assume that the coupling from below is established by our observations. It was mentioned above that the observed oscillations may be interpreted as the effect of large-scale wave motions of the planetary type and it is thus of particular interest to discuss the possibility of such wave-like disturbances to propagate from the lower levels to meteor heights. Some relevant information may be obtained by an analysis of the phase of the various oscillations involved and in figure 13 the results of a phase comparison are shown for the 1966 data. The top section of the diagram displays the phases of the 51 h pressure

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oscillations for the various meteorological stations shown in figure 9. Below we find the phases of the various wind components resolved by the Sheffield radar. It is seen that the 51 h wind may be represented by a clockwise rotating vector whose motion is indicated by the solid diagonal lines. Such a wind system may be explained as the result of a regular pressure oscillation whose phase is readily computed. In figure 13 it is seen that the pressure phase, thus derived for meteor heights is considerably delayed, about 41 h, relative to the sea-level pressure phase.

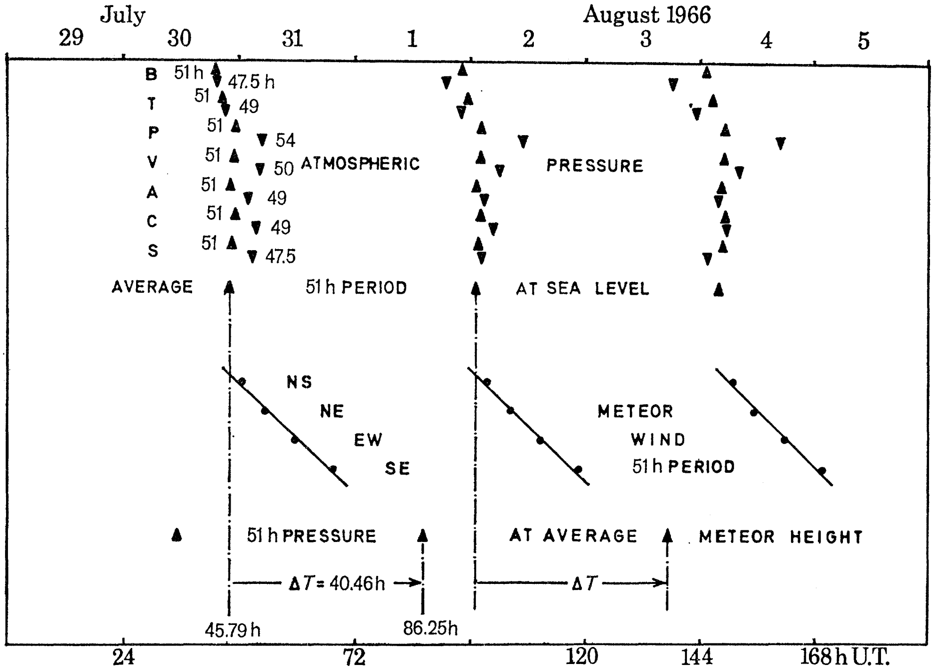

FIGURE 13. Phase diagram showing at the top the phase of the 51 h sea-level atmospheric pressure oscillation for various stations identified by capital letters which correspond to the names shown in figure 9. Below, the phases of various components of the 51 h wind resolved for 97 km at Sheffield are shown. The average pressure phase at sea level and that at meteor heights are shown individually in order to illustrate the phase lag between the two pressure oscillations.

A similar result is obtained for the 1969 data sets where the following features were observed:

period/h	delay/h
96	51 ± 3
72	68 ± 7
48	26 ± 2

Additional information concerning the presence of long-period oscillations in the tropospheric levels has been extracted from the *Daily Aerological Record* published by the Meteorological Office, although the data are not as frequent as the pressure readings at sea level. Figure 14 clearly shows the presence of long-period fluctuations in the zonal wind using data for Aughton, Lancs., and these display a regular 2-day periodicity at the 300 mbar level (*ca.* 10 km altitude), although this mode is less well defined below and much less so above this level.

Atmospheric waves of long periods and large horizontal scales have been discussed theoretically in the past, notably in a paper by Charney & Drazin (1961) using simple atmospheric models. It is of interest to look at figure 15 which contains some of the results of the theory by Charney & Drazin concerning the existence of internal (propagating) modes at the various atmospheric levels. We see that during the summer and winter seasons the square of the refractive index $\nu^2 > 0$ for various wavelengths both in the troposphere and at meteor heights which indicates that internal waves can exist at these two levels, in accordance with the meteorological observation and the findings described in this work. However, there is a considerable height range in the middle atmosphere where $\nu^2 < 0$ in summer and only external (evanescent) waves can exist. This means that most of the wave energy will be reflected at the critical layer where $\nu^2 = 0$ and any wave energy leaking through the boundary will become severely attenuated with increasing height. The change of ν^2 is essentially due to the presence

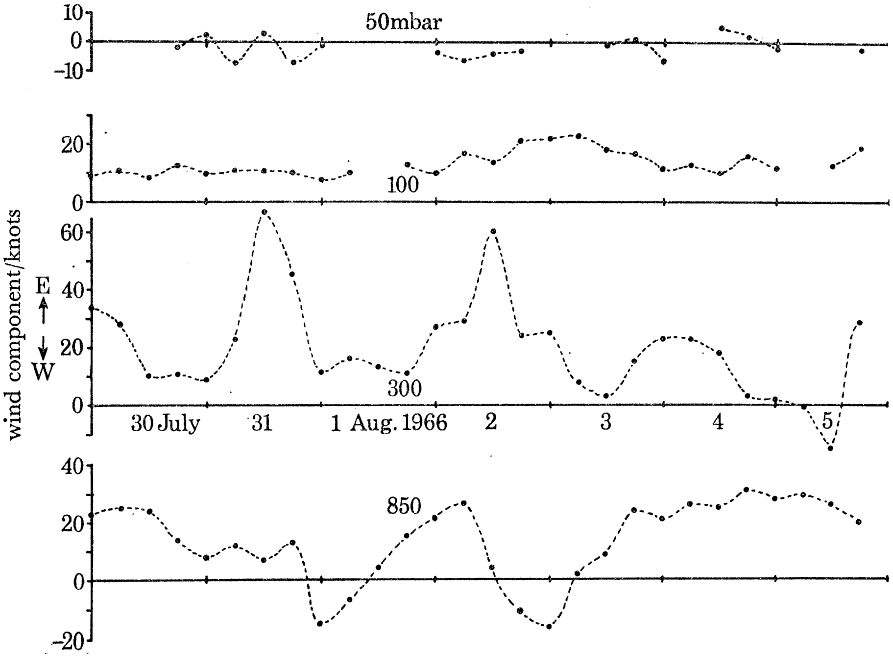

FIGURE 14. Zonal wind components (in knots; 1 knot ≈ 0.5 m s^{-1}) at various atmospheric levels recorded at Aughton, Lancs, and published in the *Daily Aerological Record* by the Meteorological Office.

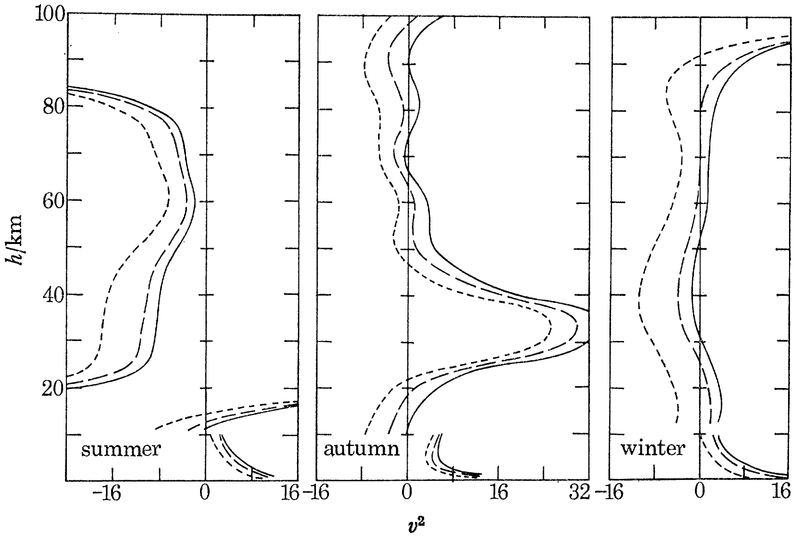

FIGURE 15. The square of the index of refraction for atmospheric waves for summer, autumn and winter averaged between 30 and 60° N after Charney & Drazin. ----, λ = 6000 km; — —, λ = 10000 km; —, λ = 14000 km.

of strong stratospheric winds but since these winds vary seasonally the propagation of planetary waves is affected accordingly. Figure 15 shows that the conditions for vertical propagation are more favourable in winter and the autumn when appreciable amounts of planetary wave energy may reach meteor heights. Difficulties exist when interpreting the present findings on the basis of direct upward propagation of planetary waves since all our observations described in this paper took place during the summer season. But although it is obvious that the bulk of wave energy will be reflected somewhere in the middle atmosphere we should bear in mind that very small amounts of energy are sufficient to cause the wind amplitudes observed in the meteor zone and that the possibility of leakage through the atmosphere cannot be ruled out entirely.

Alternatively, we may consider the possibility of an excitation of long-period wind oscillations at meteor heights due to varying amounts of gravity wave energy being dissipated in the meteor zone. The possibility of such short-period gravity waves travelling obliquely from sources in the troposphere up to meteor heights has been considered by Hines (1968). Such waves may be generated by the passing of frontal systems in the lower atmosphere and the modes surviving up to meteor heights would propagate obliquely, reaching the meteor zone some 1600 km from the source and travelling at a speed of about 3 km/h involving a delay of some 30 h. We assume that the gravity wave energy is partly dissipated in the meteor zone through viscous effects causing thermal gradients which give rise to a wind system whose behaviour corresponds to the varying intensity of incident gravity waves. It will be quite difficult to trace the source of such gravity waves in detail, but the pressure profiles which we analysed in this study should at least provide some useful reference. The delay observed in the propagation of the 2-day mode ranging from 25 to 41 h would certainly match the 30 h value quoted for internal gravity waves.

6. CONCLUSION

It is evident that all the observational material accumulated in this study indicates a comparatively close coupling between the phenomena in the lowest levels of the atmosphere and in the region where meteors are available for wind studies. While the theory allows for the presence of long-period oscillations both in the troposphere and at meteor heights it generally precludes the propagation of long-period wave energy to the upper levels of the atmosphere. We must therefore consider the possibility that the coupling between the observed phenomena is effected indirectly, possibly involving short period atmospheric waves acting as a carrier.

We are now awaiting the results of our extended winter runs which should provide further useful material in this matter.

The author is indebted to Mr H. Alleyne from the University of the West Indies for providing the necessary mathematical framework used in the analysis of the data, details of which will be published in a subsequent paper by Alleyne & Muller, also for the sharing of extended meteor wind runs and the engineering of the Sheffield height and direction finding equipment. He also wishes to thank Professor T. R. Kaiser, head of the Sheffield Space Physics Group for his considerable interest in this work, the Meteorological Office for the supply of valuable data and the Science Research Council for material grants towards this investigation.

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C.w. radar continuous wind measurements over France

(SUMMARY ONLY)

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A c.w. radar based at Garchy, France (47° N) since 1965 yields zonal wind measurements from meteor trails observations. Its high sensitivity enabled us to obtain both a high measuring rate, and an altitude resolution of the order of 1 km. A continuous reconstitution of the zonal wind variations with respect to height and time could also be obtained.

Many improvements were recently carried out: since 1969, the data analysis is completely made by a computer, from the recognition of each meteor echo up to the reconstitution of the wind profile and of its Fourier components. A rapid periodic switch of the frequency of the radar is used to eliminate aircraft echoes. A second radar, similar to that of Garchy but movable, has been built; a set of experiments can now be planned with these two radars: simultaneous measurement of the zonal and meridional winds above the same region, study of the wind variations with respect to latitude, etc.

Atmospheric waves observed over Garchy (47° N)

(SUMMARY ONLY)

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The zonal wind measured at Garchy from meteor trail observations, in the altitude range 80 to 105 km, exhibits four main components:

(1) The prevailing wind, presenting regular seasonal variations, similar to those observed by many other European stations.

(2) The diurnal tide; it has often a vertical wavelength of 20 to 30 km, and has so strong phase variations within a few days that its instantaneous period can be significantly different from 1 day. However, a few records in summer show regular diurnal oscillation without any phase propagation, likely corresponding to an 'evanescent mode' predicted by theory.

(3) The semi-diurnal tide, of very large vertical wavelength, following the same regular seasonal variations as above the other European stations. However, a semi-diurnal oscillation of much shorter wavelength (about 20 km) has been found in January 1970.

(4) Gravity waves of period 2 to 6 h, propagating with a downward phase speed and a vertical wavelength between 15 and 40 km.