JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A8, PAGES 7547–7556, AUGUST 1, 1985

Fine Structure in Mesospheric Wind Fluctuations Observed by the Arecibo UHF Doppler Radar

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Mesospheric short-period wind fluctuations are investigated, using two sets of daytime wind data obtained on 15 consecutive days in August 1980 and March 1981 by the UHF Doppler radar at Arecibo, Puerto Rico (18.4°N, 66.8°W). The wind fluctuations are found to have a conspicuous recurring structure with periods of 10–20 min on a vertical scale less than a few kilometers. This structure, appearing as a "grill pattern" in the time-height sections of wind velocity, seems to indicate that both upward and downward propagating waves with similar wave parameters exist simultaneously in this height range. The wave energy is shown to be almost equally distributed between the upward and downward propagating waves. The frequency power spectrum has a falling gradient gentler than that of the $f^{-5/3}$ and even of the f^{-1} power law (f is frequency). Occurrence of these waves seems to be related to strong wind shears associated with long-period internal inertia-gravity waves present in the mesospheric region.

INTRODUCTION

The MST (mesosphere-stratosphere-troposphere) radar technique, which can continuously observe the mesospheric wind profiles, is generally realized to be one of the most powerful tools for investigating gravity waves in the mesosphere [e.g., *Balsley and Gage*, 1980]. A number of observational studies have been made on the mesospheric gravity waves on various spatial and temporal scales, according to data span and to time or height resolution of the observations [e.g., *Woodman and Guillén*, 1974; *Rastogi and Bowhill*, 1976; *Miller et al.*, 1978; *Fukao et al.*, 1979]. Nevertheless, the morphology of gravity waves in the mesosphere is yet poorly understood. On the other hand, recent theoretical developments have shown an important role that gravity waves probably play in determining the energy and momentum budgets of the mesosphere [*Lindzen*, 1981; *Holton*, 1982]. It is therefore strongly desired to study further the gravity wave modes dominating in the mesosphere.

There have been two kinds of approaches in the MST radar aided research on gravity waves. In one approach, vertical propagation of solitary waves or noticeable wave packets is examined in detail in order to determine the wave modes [e.g., *Smith and Fritts*, 1983]. The other approach is concerned with statistical investigation of the frequency spectra of long-term records of wind fluctuations without analyzing the individual wave modes [e.g., *Carter and Balsley*, 1982]. In this study, mesospheric wind motions observed at Arecibo, Puerto Rico (18.4°N, 66.8°W), are analyzed, taking the merit of each approach into account. In particular, small-scale gravity waves with periods shorter than 60 min and vertical scale less than 6 km are extensively investigated, making the best use of the fine resolution of the current observation, i.e., 2 min in time and 600 m in height.

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Paper number 4A8432.
0148-0227/85/004A-8432$05.00

At first, we present some examples of the short-period fluctuations appearing in the time-height sections of wind velocity and examine the features of the individual wave motions. Spectral analysis is then performed with respect to both frequency (or period) and wave number (or wavelength) in order to show the dominant period and vertical wavelength of these small-scale gravity waves. Finally, the energy source of the present oscillations is discussed in relation to the shear instability due to the background atmospheric motions.

OBSERVATION AND DATA ANALYSIS

Mesospheric wind observation for 15 consecutive days was carried out twice, once on August 1–15, 1980, and again on March 6–20, 1981, with the use of the Arecibo Doppler radar operating at a frequency of 430 MHz. The observational period on each day was limited to 2–8 daytime hours. The details of the experimental technique employed for the present observation were previously described by *Harper* [1978] and *Fukuyama* [1981]. Some observational results related to waves with a period of several days together with the atmospheric tides have been already reported elsewhere [*Hirota et al.*, 1983; Y. Maekawa et al., unpublished manuscript, 1985]. Also, gravity waves with a period of a few hours or longer observed in the same data were investigated by Y. Maekawa et al. (unpublished manuscript, 1985).

The wind velocity is determined from the mean Doppler shift of the scattered echoes caused by the line-of-sight component of the ambient atmospheric motion. The wind observation at Arecibo is usually made by tilting the antenna beam direction by more than 10° from the zenith. The horizontal velocity is calculated from the line-of-sight velocity thus obtained, by a simple transformation which assumes that the vertical velocity is negligibly small compared with the horizontal one on a time scale longer than about 1 hour. For the present observation the antenna beam was tilted from the zenith by 15° toward the west in August 1980, while the beam position was alternately changed from 15° west of the zenith to 15° south of the zenith once or twice an hour in March 1981.

The current observation was made, unless otherwise mentioned, with a time resolution of 2 min and a height resolution of 600 m, which were achieved by using the 13-element Barker code. With this time and height resolution the incoherent scatter echoes were detected at an interval of 600 m over the 73- to 95-km height range.

In this study, wind velocities in the line-of-sight direction (15° west or south from the zenith) are investigated without being transformed to the horizontal velocity because atmospheric motions with periods shorter than 60 min, to be discussed in the following, have, in general, a considerable vertical component.

OBSERVATIONAL RESULTS

Figure 1 shows a time-height section of fluctuating wind component from the mean wind in the line-of-sight direction observed on August 3. The contour is drawn at 2 m s^{-1} intervals, and the shaded (unshaded) area indicates velocity toward (away from) the radar. The 15- to 20-min data gaps appearing every 50 min were used for operation in a plasma-measuring mode (K. Fukuyama, personal communication, 1984). No radar operation was performed during the period of 1110–1150 LT. In order to selectively take out short-period wind oscillations, a high-pass filter with cutoff period of 60 min is applied to the observed fluctuations at each height. The filtering is performed on the basis of all available data even when data do not exist in either the forward or the backward direction in order to make the most use of all data points. However, no systematic distortion seems to appear in the contour even near the data gaps. It is apparent from this figure that quasi-periodic wind oscillations with a dominant period of 10–20 min exist throughout the observational height range. The averaged amplitude is 2–5 m s^{-1}; it is slightly larger with increasing height. The phase variation of these oscillations is quite complicated, and fluctuations on a fine vertical scale seem to coexist with those on a larger vertical scale.

In order to separate fluctuations on different vertical scales, another numerical filter with cutoff length of 6 km (10 height levels) is applied to the wind height profiles obtained every 2 min. The filtering is also performed up to the top and bottom of the observed height range, although the data points in either side are not available there. Figure 2 shows the result for fluctuations on a vertical scale larger than 6 km in the form of a contour plot similar to Figure 1. The 10- to 20-min oscillations are clearly observed with the phase tilted slightly downward. This is an indication that the oscillations are gravity waves propagating upward from below the mesosphere [e.g., *Fukao et al.*, 1979; *Miller et al.*, 1978].

On the other hand, the fluctuations on a vertical scale less than 6 km are depicted in Figure 3 by subtracting the fluctuating component of Figure 2 from that of Figure 1. Also, a quasi-periodic structure on a fine temporal and spatial scale is observed at every observational time and height. This structure seems to show that both upward and downward propagating waves, which are probably small scale internal gravity waves, coexist in this height range. This structure, which may be called a "grill pattern," is found for the first time by the current high-resolution observation.

The grill pattern is considered to reflect a real physical phenomenon, since the pattern, though very complicated, apparently has characteristic scales larger than the sampling intervals in time and height. Still, it seems necessary before proceeding further to prove more evidently that the pattern is not caused by random statistical error attending our wind velocity estimation. For this purpose, the above analysis is applied for computer-generated pseudorandom data allotted to the same data points as in Figure 1. Standard deviation of the random fluctuation is chosen to be 2 m s^{-1}, which is of the same order as that of the observed wind fluctuations. The same filterings as mentioned above are performed in both the time and the vertical direction. Figure 4 illustrates the filtered result in the same time-height section as Figure 3. There appears a complicated fine structure which varies on time and height scales as small as the sampling intervals. The pattern looks like a mosaic structure composed of numerous small rhombi. Note that the rhombi are partially lined up in parallel with the diagonal lines of the data points shown near the right edge of the diagram. This depends on our contour-plotting computer program; in case the value at some data point is enhanced, it draws contours connecting the nearest four data points to make a rhombus. Compared with this mosaic, the grill pattern in Figure 3 has a distinctly larger correlation in time and height. This is different from the random fluctuation. Thus the stripes of the grill pattern of the observed wind fluctuations are not due to random statistical error but represent phase propagation of traveling waves, or internal gravity waves. This point will be further discussed in the next section, evaluating the frequency and vertical wave number spectrum of the fluctuations.

Another example of the small vertical scale wind fluctuations on August 14 is presented in Figure 5. The zonal wind was almost continuously observed at time intervals of 2.3 min on this day. Also, the grill pattern is found in it, but the vertical scale of this grill pattern is a little smaller than that of August 3. Thus we always find fluctuating wind components with a period of 10–20 min and a vertical wavelength of 2–5 km on other observational days in August, although these wave parameters vary more or less from day to day.

Similar fluctuations with amplitudes of 2–5 m s^{-1} are also always found in the wind velocities observed in March 1981. At this time both zonal and meridional wind velocities were measured, although available data were only obtained at the height of 80–95 km during 40–50 min in each direction per day. A few examples on March 11, 12, and 16 are given in Figure 6, when data length is fairly long. The contour intervals and the convention of wind direction are the same as those in Figures 3 and 5. The same filtering as mentioned above is performed in the vertical direction, while no time filter is applied because of the short extent of the data. The zonal component is distinguished from the meridional one by darker shades of the contour maps.

It should be noted that the temporal and vertical structure of the wind fluctuations are quite similar between the zonal and meridional components. A change should be observed between the two patterns if the waves are predominantly traveling in one direction. Hence the associated internal gravity waves may propagate in any direction on the horizontal plane or, in other words, have an "isotropic" horizontal structure. Considering the duration of the observed wind oscillations, these gravity waves are thought to be distributed widely in the horizontal direction at the height range considered, although we only obtain information in two beam directions.

SPECTRAL ANALYSIS

In this section, dominant period and vertical wave number of these oscillations will be investigated with the aid of a space-time spectral analysis [*Hayashi*, 1977]. Figure 7 shows a two-dimensional power spectrum with respect to period and vertical wave number (or vertical wavelength) averaged over

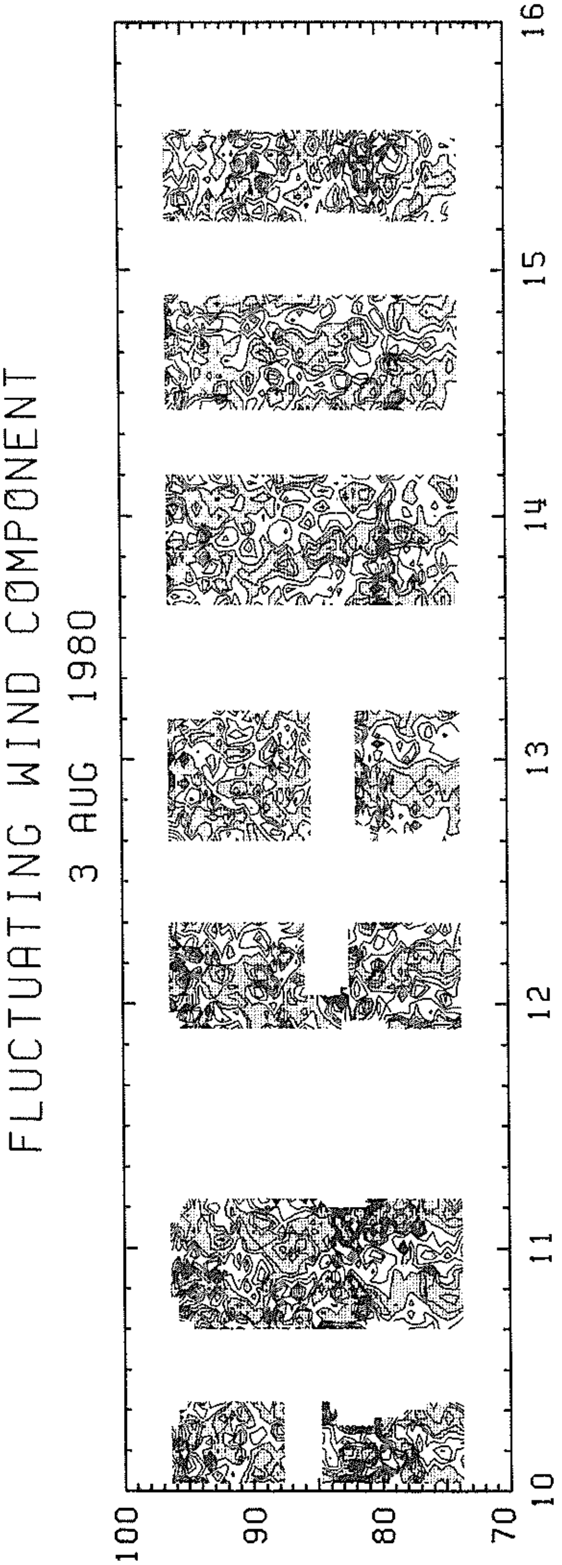

Fig. 1. A time-height section of the short-period (<60 min) wind fluctuations observed on August 3, 1980. The contour is drawn at 2 m s^{-1} intervals, and the shaded (unshaded) area indicates line-of-sight velocity toward (away from) the radar.

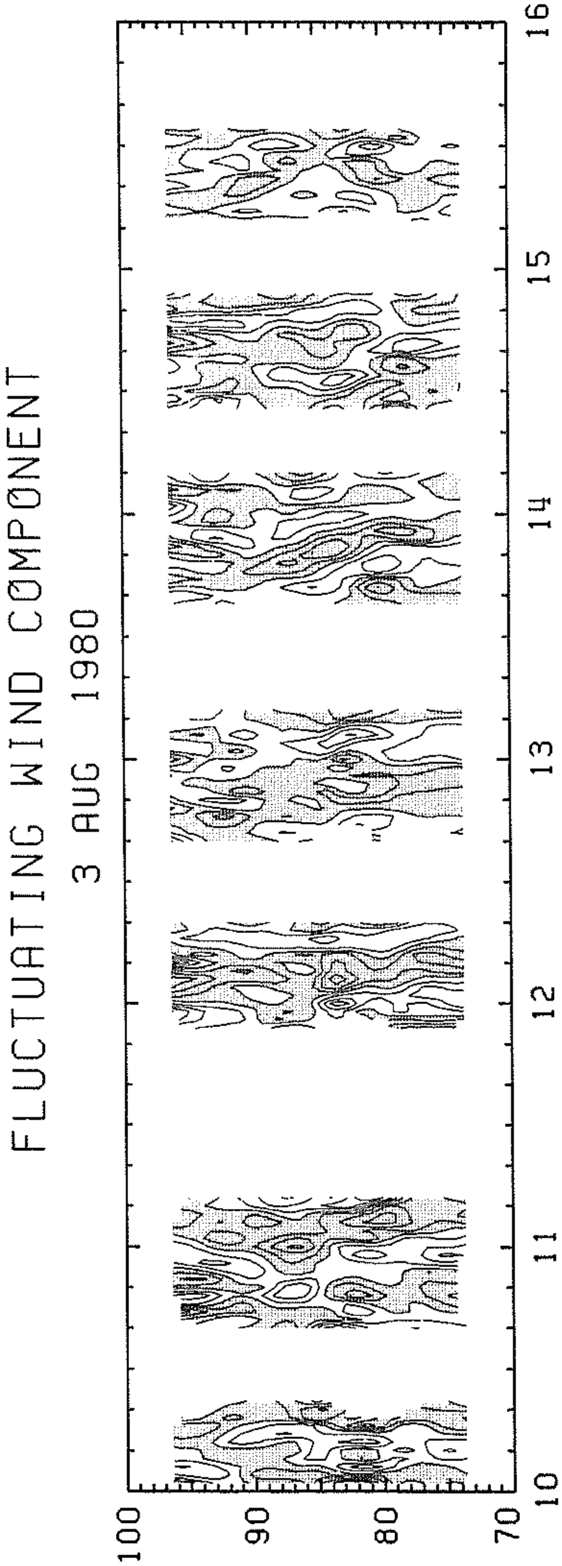

Fig. 2. Same as Figure 1 except for those fluctuations on the vertical scale larger than 6 km.

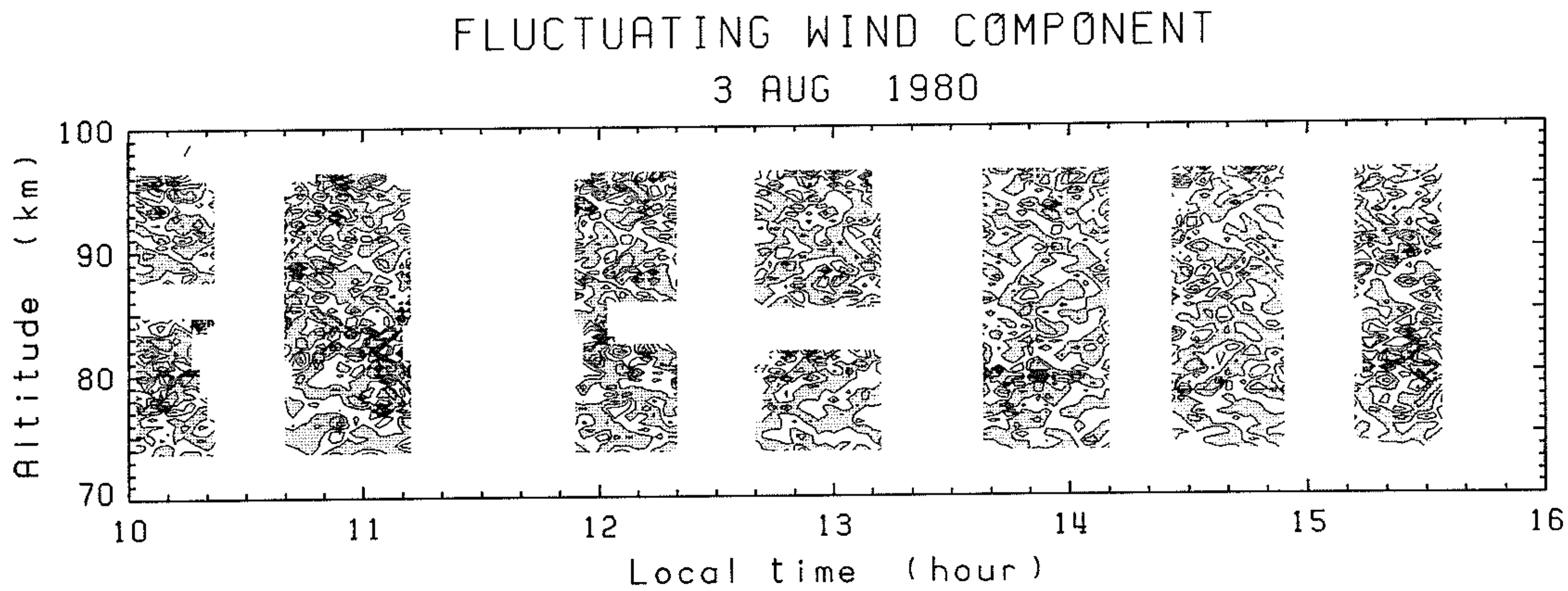

Fig. 3. Same as Figure 1 except for those fluctuations on the vertical scale smaller than 6 km.

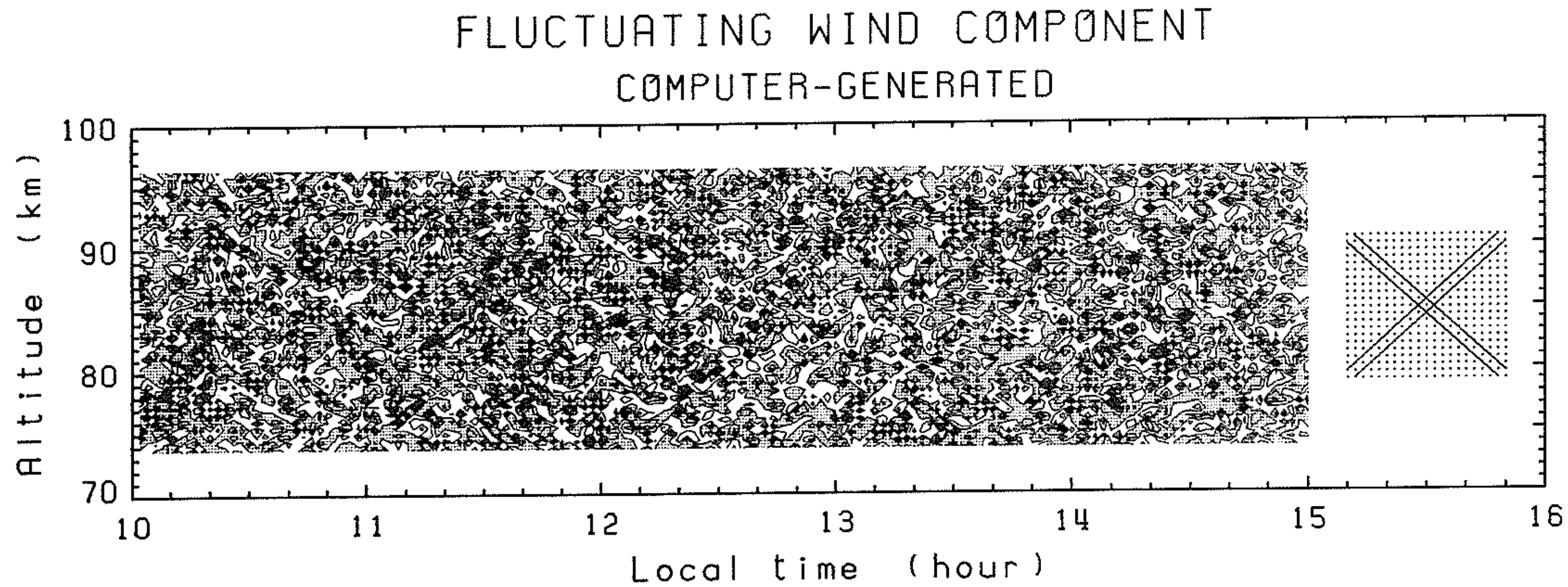

Fig. 4. A time-height section of computer-generated random fluctuation with standard deviation of 2 m s^{-1} analyzed in the same way as in Figure 3. The contour intervals are 2 m s^{-1}. Dot pattern near the right edge of the diagram indicates some of the data points, while thin solid lines are the diagonal lines of the data points (see text).

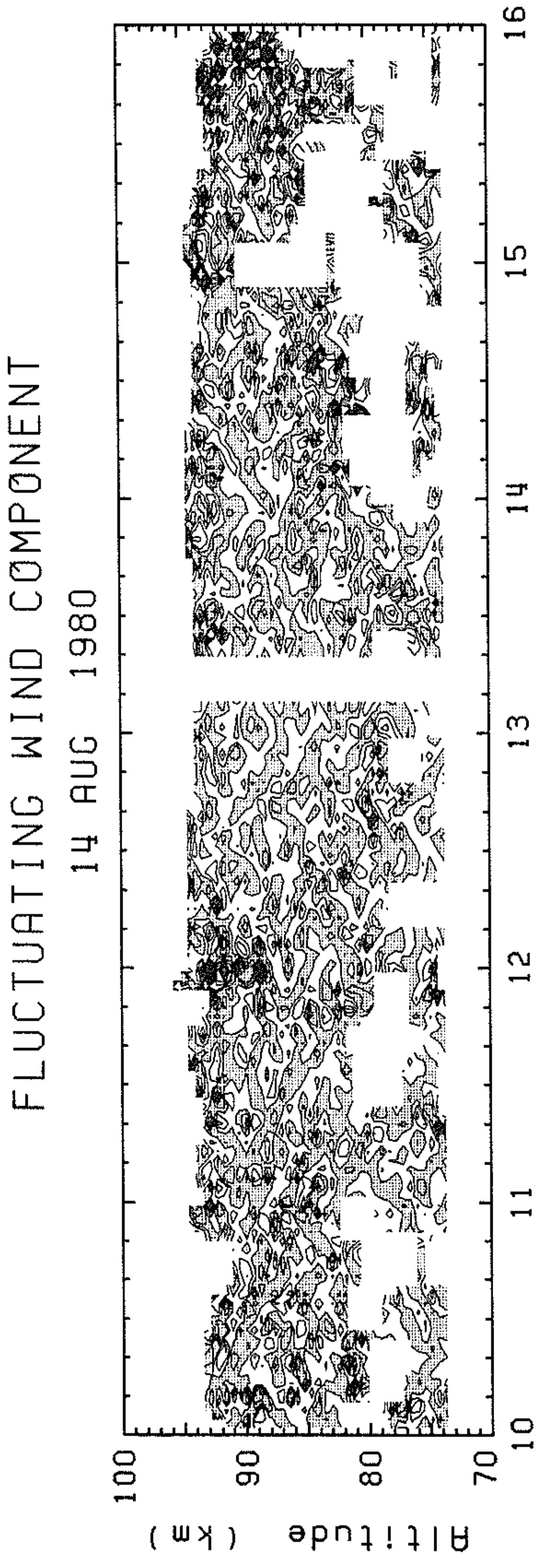

Fig. 5. Same as Figure 3 except for those fluctuations on August 14, 1980.

August 1–15, 1980. The fundamental period is chosen to be 4 hours so that the longest continuous wind data are available in the height range of 73–95 km on almost all observational days. The vertical wave number in cycles per kilometer (cpkm) is the reciprocal of the vertical wavelength (km). A positive (negative) wave number means that the phase of the oscillation propagates upward (downward) with time. The mean power spectral density averaged over vertical wave number is given against period on the bottom of the figure. In order to emphasize vertical wavenumber characteristics, the two-dimensional power spectrum is normalized by the mean power spectral density at the corresponding periods. The contour lines are drawn at 3-dB intervals with respect to values larger than the mean power spectral density.

The dashed curves indicate the theoretically allowed largest vertical wave number or the minimum vertical wavelength ($\lambda_{z,\min}$) of the internal gravity waves in the presence of the atmospheric eddy viscosity η [*Hines*, 1960]:

$$\lambda_{z,\min} = \left(\frac{(2\pi)^3\eta}{\omega[1-(\omega^2/\omega_B{}^2)]}\right)^{1/2} \quad (1)$$

where ω and ω_B are the angular frequency and the Brunt-Väisälä frequency, respectively. The eddy viscosity is chosen to be 100 $m^2\ s^{-1}$, and the Brunt-Väisälä frequency to be 0.021 rad s^{-1} (5 min in period), which are considered to be typical in the mesospheric height [*Allen et al.*, 1981; *Hocking*, 1983]. It is apparent from the figure that the oscillations are almost confined to the theoretically allowed area between the curves of the minimum vertical wavelength (or the maximum vertical wave number). The minimum vertical wavelength limit is not formed for the random fluctuations shown in Figure 4. Therefore these wind oscillations, including the smaller-scale oscillations with a period of 10–20 min and a vertical wavelength of 2–5 km, are regarded as being caused not by the random fluctuation but by the internal gravity waves. However, it should be noted that there is a reasonable agreement between the theoretical curves and the observed spectra, although the theoretical frequency is the intrinsic one relative to the background flow, while the observed frequency is probably largely Doppler shifted. Clearly, further observations to prove this are important.

In the period range less than 60 min, the two-dimensional power spectrum seems to be divided into two characteristic components. One is the "ridge" component near zero wave number, and the other is the component scattered in both positive and negative wave number regions. They correspond to larger and smaller vertical-scale oscillations shown in a different way in Figures 2 and 3, respectively. The two kinds of oscillations are observed to exist in the whole period range from 6 to 60 min. The dominant vertical wavelength of the larger vertical-scale oscillations is estimated to be 10–20 km (downward phase propagation) from Figure 7, while that of the smaller scale is distributed in the 2- to 5-km range (both downward and upward phase propagation).

Next, we present the frequency power spectra for the respective vertical-scale oscillations in the period range of 6–60 min in Figure 8. The solid (dashed) lines indicate the negative (positive) wave number, namely, the downward (upward) phase propagation.

In the case of the larger vertical scale (right), the spectral component of the downward phase propagation exceeds that of the upward one by nearly a factor of 2 in almost every period. This suggests that the net energy transport associated with these wind oscillations is upward in this height range.

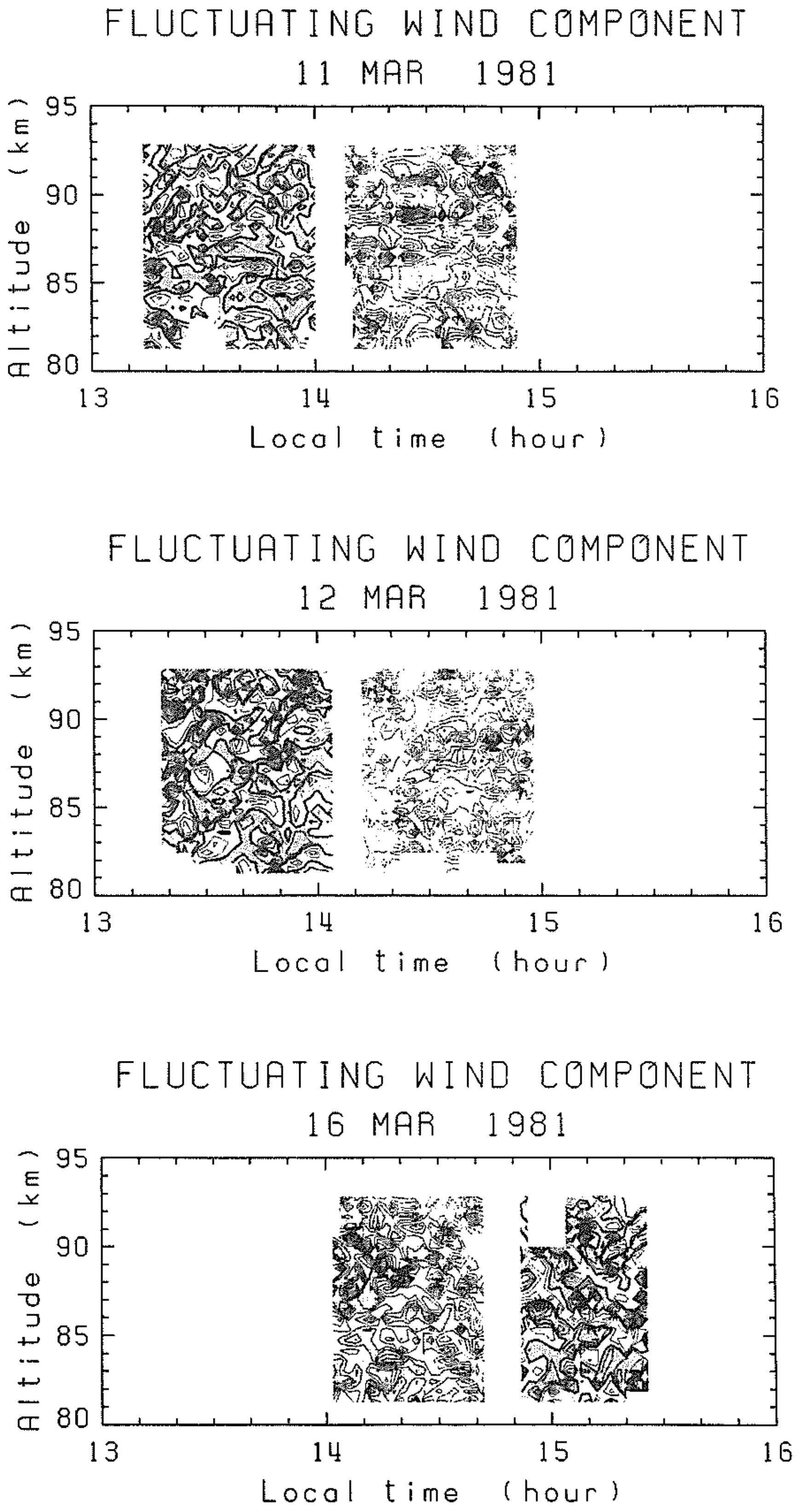

Fig. 6. Wind fluctuations with vertical scale smaller than 6 km observed on March 11, 12, and 16, 1981. No time filter is applied. Zonal component is shown by dark-shaded area, and meridional by light-shaded area.

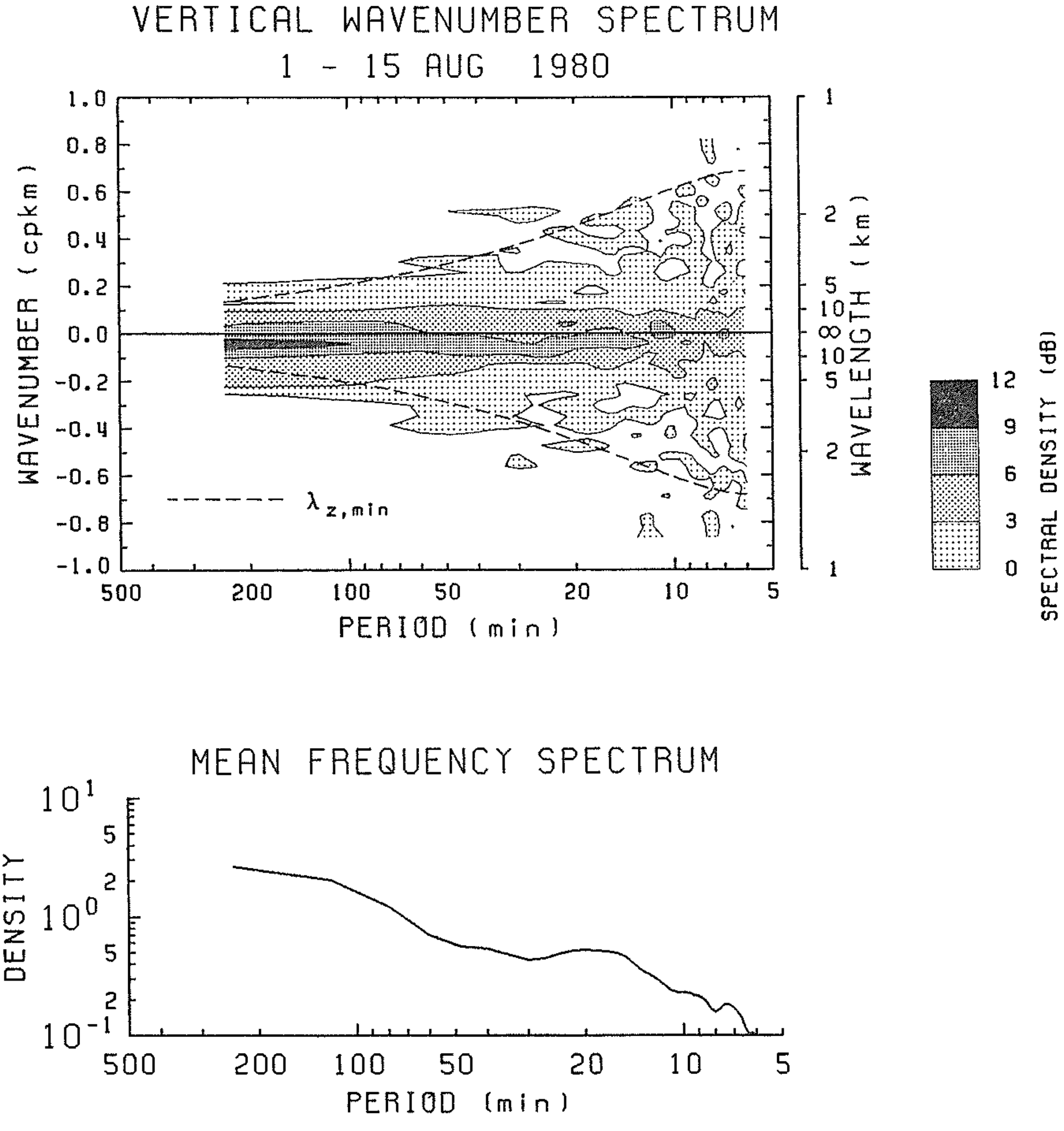

Fig. 7. Two-dimensional power spectrum with respect to period and vertical wave number (or wavelength) in the height range of 73–95 km, averaged over 1–15 August 1980 (top). Contour lines are drawn at 3-dB intervals with respect to values larger than the mean frequency power spectral density shown at the bottom. Dashed lines correspond to the theoretically allowed minimum vertical wavelength ($\lambda_{z,\min}$).

The spectral density, as a whole, decreases with decreasing period or in proportion to about f^{-1}, although a fairly large fluctuation is observed. Considering that the spectral density in the shorter-period range may be overestimated owing to the dominance of vertical wind motions, this result may be consistent with the horizontal velocity spectrum following the $f^{-5/3}$ power law which has been recently reported in other long-term mesospheric observations [*Carter and Balsley*, 1982; *Balsley and Carter*, 1982; *Vincent*, 1984].

The spectrum of the smaller vertical-scale oscillations (left), on the other hand, shows a different feature. It is seen that the upward and downward propagating components have nearly equal energy over the observed period range. In addition, the spectral power is comparable to that of the larger vertical-scale oscillations in the period less than 20 min, so that these smaller scale oscillations in this period range are not negligible in the fluctuating winds. The velocity amplitude in the line-of-sight direction (15° toward west from zenith) is 2–3 m s^{-1}. It is also noticed that the spectrum has a falling gradient gentler than $f^{-5/3}$ and even gentler than f^{-1}.

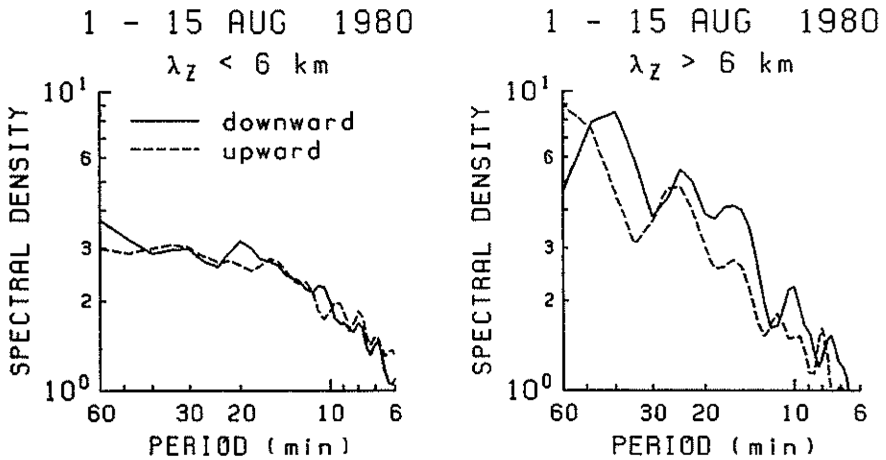

Fig. 8. Frequency power spectra of the wind fluctuations on the vertical scale larger (right) and smaller (left) than 6 km. The abscissa represents periods. Solid and dashed lines indicate the downward and upward phase propagations, respectively.

DISCUSSIONS AND CONCLUDING REMARKS

In this study, a vertical structure of the mesospheric short-period (<60 min) wind oscillations is investigated by using the high-resolution wind data obtained at Arecibo (18.4°N, 66.8°W). The wind oscillations are found to have a conspicuous recurring pattern with a dominant period of 10–20 min on a vertical scale less than a few km. This pattern, which appears as a grill pattern in the time-height sections of wind velocity, is formed by intersecting contours of the upward and downward propagating waves. This indicates that both upward and downward propagating waves with similar wave parameters exist simultaneously in this height range. The spectral analysis shows that the wave energy is almost equally distributed between the upward and downward propagating waves. The gradient of the power spectrum is smaller than that of the $f^{-5/3}$ and even of the f^{-1} power law. These characteristics cannot be explained in terms of the turbulent energy cascading process among various upward propagating tropospherically generated gravity waves, unlike the case of larger vertical-scale wind oscillations [*Balsley and Carter*, 1982]. Therefore another mechanism seems to function to excite these oscillations.

It should be noted here that the vertical wavelength of these wind oscillations is typically 2–5 km, only about twice the minimum vertical wavelength ($\lambda_{z,\min}$) in the period range of 10–20 min as shown in Figure 7. These gravity waves are therefore considered to be strongly damped by viscosity as they propagate through the observational height range. Nevertheless, these oscillations are always found in every height, so that we consider that their energy source exists within the observed height range.

In the mesospheric heights a strong wind shear due to the background flow is possibly the primary energy source of the short-period oscillations under consideration [*Hirota et al.*, 1983]. Figure 9 shows the horizontal wind profiles averaged over a period of 1 hour or more and their vertical shears observed on March 11, 12, and 16, 1981. Thick and thin lines indicate zonal (u_0; du_0/dz; z is height) or meridional (v_0; dv_0/dz) wind and wind shear, respectively. Dot-dashed lines mean the absolute shear (dU_0/dz) on the horizontal plane:

$$\frac{dU_0}{dz} = \left[\left(\frac{du_0}{dz}\right)^2 + \left(\frac{dv_0}{dz}\right)^2\right]^{1/2} \tag{2}$$

It is evident from the figure that a large wind shear of the order of 20–40 m s^{-1} km^{-1} is present at various heights at intervals of some 5 km. This strong shear yields the Richardson number,

$$Ri = \frac{\omega_B{}^2}{(dU_0/dz)^2} \tag{3}$$

of 0.25–1.0 for the typical Brunt-Väisälä period ($T_B = 2\pi/\omega_B$) of 5 min. Therefore the mesospheric atmosphere is thought to be quite unstable at various heights, as shown on the rightmost diagrams in Figure 9. In August 1980 the wind shear due only to hourly zonal wind exceeds this critical value occasionally. Moreover, Figure 9 shows that the mean horizontal wind varies more than 100 m s^{-1} in magnitude in the height range considered. The smaller vertical-scale oscillations presumably have horizontal phase speeds comparable to this mean wind velocity. Therefore these wind oscillations are likely to interact with the mean wind and to be generated by shear-induced instabilities within the observed height range. It is, however, very difficult to give the one-to-one correspondence between wind oscillation (Figure 6) and wind shear (Figure 9). One reason is that the mesospheric wind shear generally has a multilayered structure, so that the separation of shears cannot be made on a vertical scale comparable to the vertical wavelength of the short-period gravity waves. Another reason is that the observed gravity waves seem to be the internal modes ("neutral" internal gravity waves) [*Lindzen*, 1974]. They transport energy away from a shear layer, so that an enhancement of the oscillations cannot be directly related to the strong shear layer. This situation is quite different from that of the evanescent Kelvin-Helmholtz type gravity waves which have been observed during the tropospheric jet stream passage [*VanZandt et al.*, 1979; *Klostermeyer and Rüster*, 1980].

Additional analysis on the same mesospheric data has shown that the hourly wind field in Figure 9 is mainly composed of the diurnal atmospheric tide and long-period internal inertia-gravity waves (10–20 hours) (Y. Maekawa et al., unpublished manuscript, 1985). The characteristics of the tide are consistent with the theoretical values of the propagating diurnal mode. On the other hand, the internal inertia-gravity waves are thought to be considerably dissipative in this height range, since the amplitude is shown to be almost constant

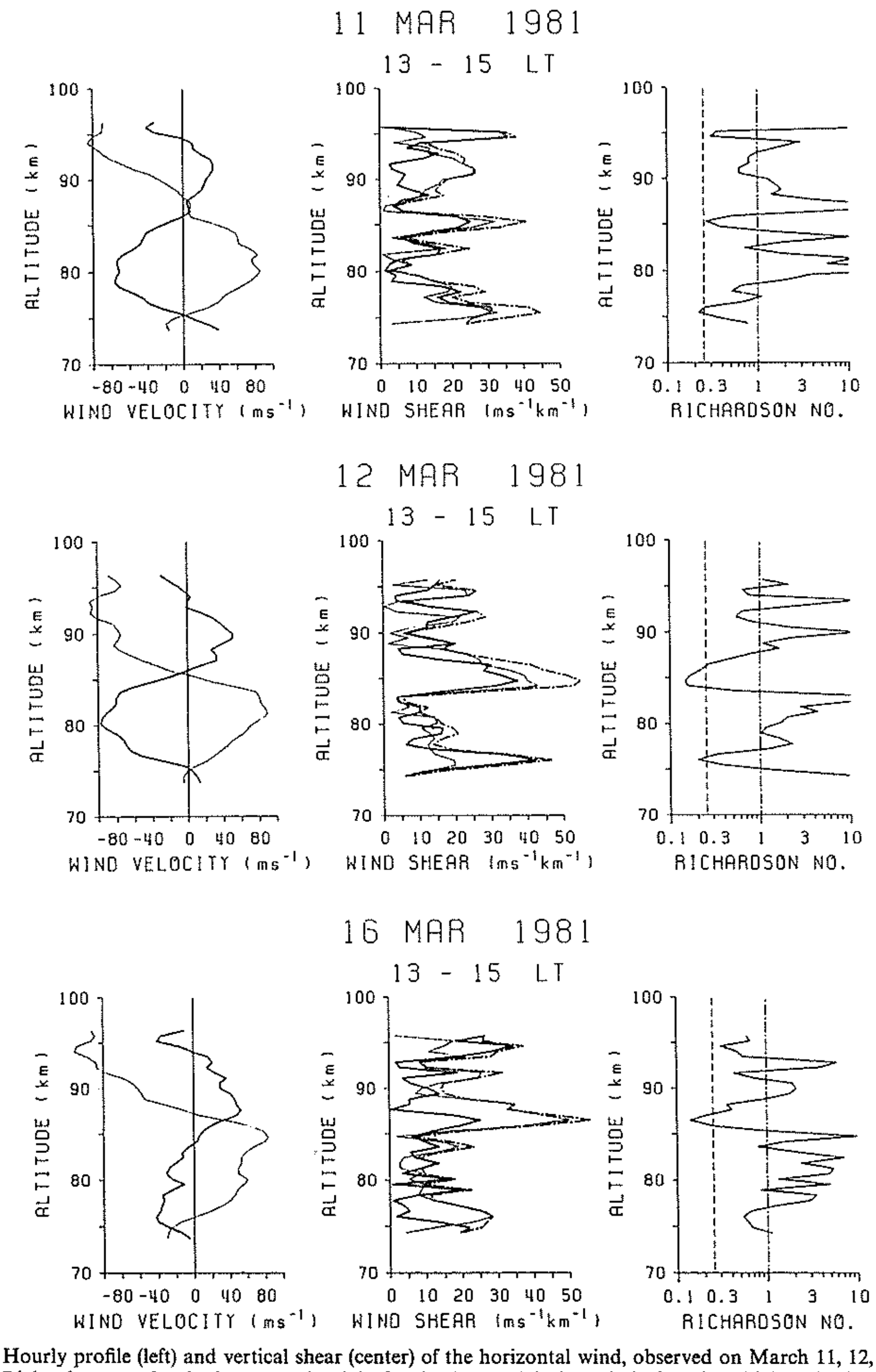

Fig. 9. Hourly profile (left) and vertical shear (center) of the horizontal wind, observed on March 11, 12, and 16, 1981. A deduced Richardson number is shown on the right for the Brunt-Väisälä period of 5 min. Thick and thin lines are zonal and meridional components, respectively, while dot-dashed lines show the absolute shear of the horizontal wind.

with increasing height despite the exponential decrease of the atmospheric density. The vertical wavelength of these internal inertia-gravity waves is inferred to be 5–10 km, being comparable to the mean interval of strong vertical wind shears in Figure 9. Therefore some portion of the energy flux transported by the long-period gravity waves may be extracted through the shear instability and supplied to the smaller-scale wind oscillations in the mesosphere.

The nature of such fine vertical-scale short-period oscillations should be of course further investigated. Seasonal and local dependences of these oscillations are especially of interest. In order to study the excitation mechanism in more detail, it is above all necessary to determine the horizontal scale and the propagation direction on the horizontal plane by simultaneous multibeam observations.

Acknowledgments. The authors thank I. Hirota, Geophysical Institute of Kyoto University, for interesting suggestions and constructive comments. Support for this research was provided by the Nissan Science Foundation of Japan. The Arecibo observatory is operated by Cornell University under contract with the U.S. National Science Foundation.

The Editor thanks D. A. Carter and R. A. Vincent for their assistance in evaluating this paper.

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(Received December 3, 1984;
revised April 12, 1985;
accepted April 15, 1985.)