Reprinted from JOURNAL OF THE ATMOSPHERIC SCIENCES, Vol. 39, No. 11, November 1982
American Meteorological Society
Printed in U. S. A.

Fine Altitude Resolution Radar Observations of Upper-Tropospheric and Lower-Stratospheric Winds and Waves

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(Manuscript received 28 July 1981, in final form 26 July 1982)

ABSTRACT

Preliminary results of wind velocity measurements made using the Arecibo 430 MHz radar are presented. These measurements were made in the altitude range between 10 and 30 km, with a time resolution of 1–2 min, and an improved altitude resolution of 150 m. A few interesting phenomena such as a quasi-stationary wavy structure and short period sinusoidal oscillations are discussed.

1. Introduction

Recent improvements in MST radar facilities and associated experimental techniques, in response to the requirements of the detailed study of middle atmospheric dynamics, have made it possible to observe the middle atmosphere with much finer spatial and temporal resolution than before (see reviews by Balsley and Gage, 1980; Rottger, 1980; Woodman, 1980). For the Arecibo 430 MHz radar, a height resolution of 150 m was achieved without sacrificing the signal-to-noise ratio and thus the time resolution (1–2 min), by introducing a complementary pulse coding scheme (Woodman, 1980). Although this height resolution is still not sufficient to study the microstructure of the stratospheric turbulence, it seems to be sufficient to separate individual scattering layers (Sato and Woodman, 1982b). It should be noted that it is important to be able to separate discrete layers for an accurate velocity measurement, because, when a range gate sample contains echoes from two or more layers moving at different velocities, a change in the relative strength of these layers causes a spurious oscillation in the observed Doppler velocity. The short time-resolution obtained, combined with the sensitivity and accuracy of the Arecibo radar, permits the study of wave dynamics throughout the gravity wave, tidal and planetary wave frequency range.

We will examine here a few of the most interesting examples found in a series of more than 200 hours of upper-tropospheric and lower-stratospheric observations recently carried out with the 430 MHz Arecibo radar, in order to demonstrate the potential of radar techniques (and the Arecibo radar in particular), and the importance of a good height and temporal resolution in improving understanding of the dynamics of the stratosphere. We present the vertical structure and time evolution of a long-period wave, with a period of about four days with a vertical wavelength of 1–3 km, and of two other quasi-sinusoidal oscillations with periods of about three and 25 minutes observed just below the tropopause.

2. Experiment

The instruments and the experimental techniques are reported elsewhere (Woodman, 1980; Sato and Woodman, 1982a). Wind velocities are measured by tilting the antenna beam 7.5–15° from the zenith and by measuring the Doppler shifts of clear air turbulence backscattered echoes. The antenna position was switched between eastward and northward within the above zenith angles in order to obtain the two horizontal wind components. On some occasions, the same direction was observed continuously for several hours in order to see uninterrupted short-time-scale temporal variations. The receiver cutoff and the signal-to-noise ratio and/or signal-to-clutter ratio restricted the height range to 10–30 km. The upper limit of the height where reliable data can be obtained varies from day to day between 20 and 30 km. The data were processed and integrated on-line over one or two minutes, and stored on magnetic tapes in the form of frequency power spectra. The wind velocity was deduced by an off-line analysis program (Sato and Woodman, 1982a), which includes the elimination of strong ground clutter echoes.

3. Results

Fig. 1 shows altitude profiles of wind velocity measured every two minutes. Profiles are plotted side-by-

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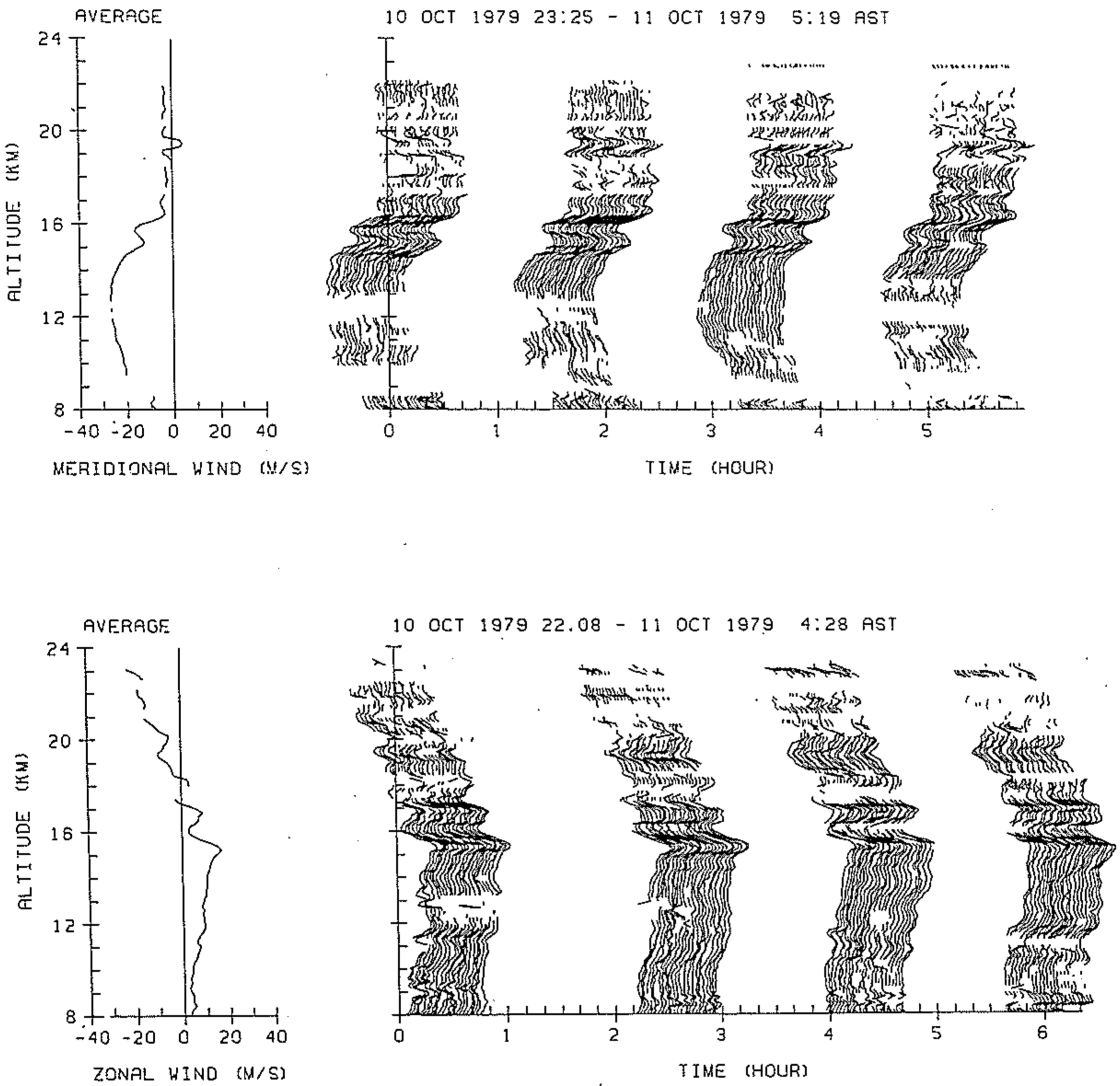

FIG. 1. Zonal and meridional wind velocity versus height and time. Height profiles are plotted side-by-side, spaced according to the observed time. The time scale is measured from the beginning of observed time. Zero hours correspond to the times indicated above the profiles.

side according to their time of observation. The velocity scale for the individual profiles is the same as the average profile on the left. Blank parts of each profile indicate poor data quality due to bad signal-to-noise ratios, or ground clutter problems (usually, velocities too close to zero).

The most apparent feature in these profiles is the consistency of the wind velocity in time. This is especially true of the wavy structure at 15–18 km which remains almost unchanged throughout the period depicted in the figure. This structure has an apparent vertical wavelength of $\sim$1.5 km and a horizontal amplitude of $\sim$5 m s^{-1}. Fig. 2 shows 10-hour mean profiles of the zonal and meridional wind components. The phase difference between the two components indicates that the direction of the flow associated with this structure rotates clockwise when traced upwards.

Although these features seem similar to those of diurnal tidal oscillations, which are reported in Fukao *et al.* (1981), this structure is distinguished from tidal oscillations by the long-term temporal behavior. Weinstein *et al.* (1966), and more recently Cadet and Teitelbaum (1979) observed similar mesoscale structure in the lower stratosphere by successive balloon experiments and discussed it in terms of quasi-inertial oscillations and quasi-inertial gravity waves. In particular, the waves with very short vertical wavelength of about 1 km found by Cadet and Teitelbaum look quite similar to our case. They applied a high-pass filter to each wind profile to pick up only those structures with the vertical wavelength of less than 2 km. Fig. 3 shows one-hour averaged wind profiles (thin lines) and those after low-pass filtering with 3 km cutoff (thick lines). The structures in the 14–17 km region show a descending phase in time, which changes, at the most, 180° in 48 hours, indicating periods longer than about 96 hours. This characteristic time is too long for an inertial gravity wave, since the inertial oscillation period is about 38 hours at the latitude of Arecibo (18.3°N). Thus this wavy structure is more likely an equatorial planetary wave such as a mixed Rossby–gravity wave. The very short apparent vertical wavelength may be explained by a Doppler shift effect. The vertical wavelength of a wave propagating westward in the eastward zonal mean flow is shorter than if it propagated in the zero wind profile (Cadet and Teitelbaum, 1979). The difference of the vertical wavelength amounts to 1.5–3 km for the present case when the zonal wind velocity is 5–10 m s^{-1}. An alternative approach, suggested by one of the reviewers, is that the small vertical wavelength could result from approaching a critical level, coincident with the shear region evident in the mean wind corresponding to this altitude.

A corresponding wavy structure can be seen in the temperature data of the same period. Fig. 4 shows four temperature and Brunt-Väisälä frequency profiles obtained from the rawinsonde observations at San Juan, Puerto Rico (70 km east of Arecibo). Symbols denote data points, and the lines are interpolated values using a spline interpolation technique. The line of 10 October above 18 km is dubious because of sparse sampling points. The wavy structure is more pronounced in the profile of the Brunt-Väisälä frequency. The vertical wavelength changes from about 1.5 to 2.9 km, and agrees well with that of the velocity structure. The amplitude in temperature is 1–3 K, which agrees with the typical value of the equatorial mixed Rossby–gravity wave (e.g., Holton, 1975). The phase of temperature maxima seems, on the other hand, to coincide with the eastward velocity maxima, ~90° different from the theoretical relation for the mixed Rossby–gravity mode, which predicts the coincidence of temperature maxima with the northward velocity maxima. It is, of course, difficult to determine the phase accurately from the given intervals of the temperature data.

It should be noted, as an additional discrepancy from theoretical expectations, that the time history of the waves at any one altitude is not as sinusoidal as their altitude behavior. In most cases they loose their periodic identity in less than their expected period. In fact, it is not uncommon to see in our data, relatively large deviations in velocity, confined to a few hundred meters, persisting for several hours and eventually disappearing without showing any spatial or temporal oscillation.

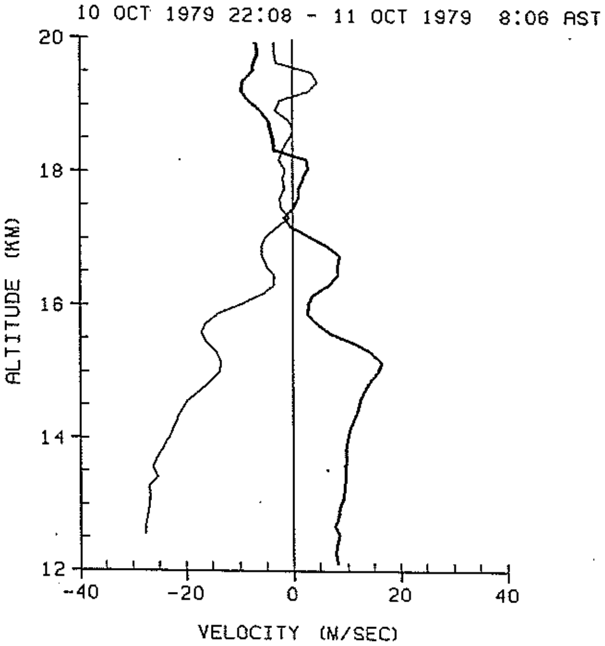

FIG. 2. 10-hour average altitude profile of the zonal (thick line) and meridional (thin line) wind components.

Although smaller in amplitude compared to the oscillations discussed above, there also exist substantial temporal variations in the observed velocity at shorter time scales. Oscillations corresponding to the solar diurnal tide have been identified, but they will be reported separately (Fukao *et al.*, 1981). Shorter time-scale oscillations corresponding to gravity-wave modes are discussed below.

Fig. 5 shows an example of low-passed velocity time series at the 12–16 km height range. The system measures the radial component of the wind velocity, from which the horizontal component can be estimated if the vertical component is assumed to be much smaller than the horizontal component. This is a good assumption for the periods selected by the filter. However, since this is not the case for short period waves with frequencies close to the Brunt-Väisälä frequency, both the horizontal and radial velocity scales are shown in Fig. 5. A pronounced periodicity of about 25 minutes exists over the entire plotted height range for about two hours. A cross-correlation analysis revealed less than two minutes of phase difference, if any, over 4 km of height difference. This good phase coherency suggests that this wave is propagating almost horizontally. The horizontal wavelength of this wave, estimated using the dispersion relation for an isothermal atmosphere, (e.g., Hines, 1960) is about 300 km. Such a pure sinusoidal wave is, however, a selected example of a gravity wave which persists for such a long period during our observations. Oscillations of comparable magnitude and period are often observed, but not in so well organized a sinusoid as this example.

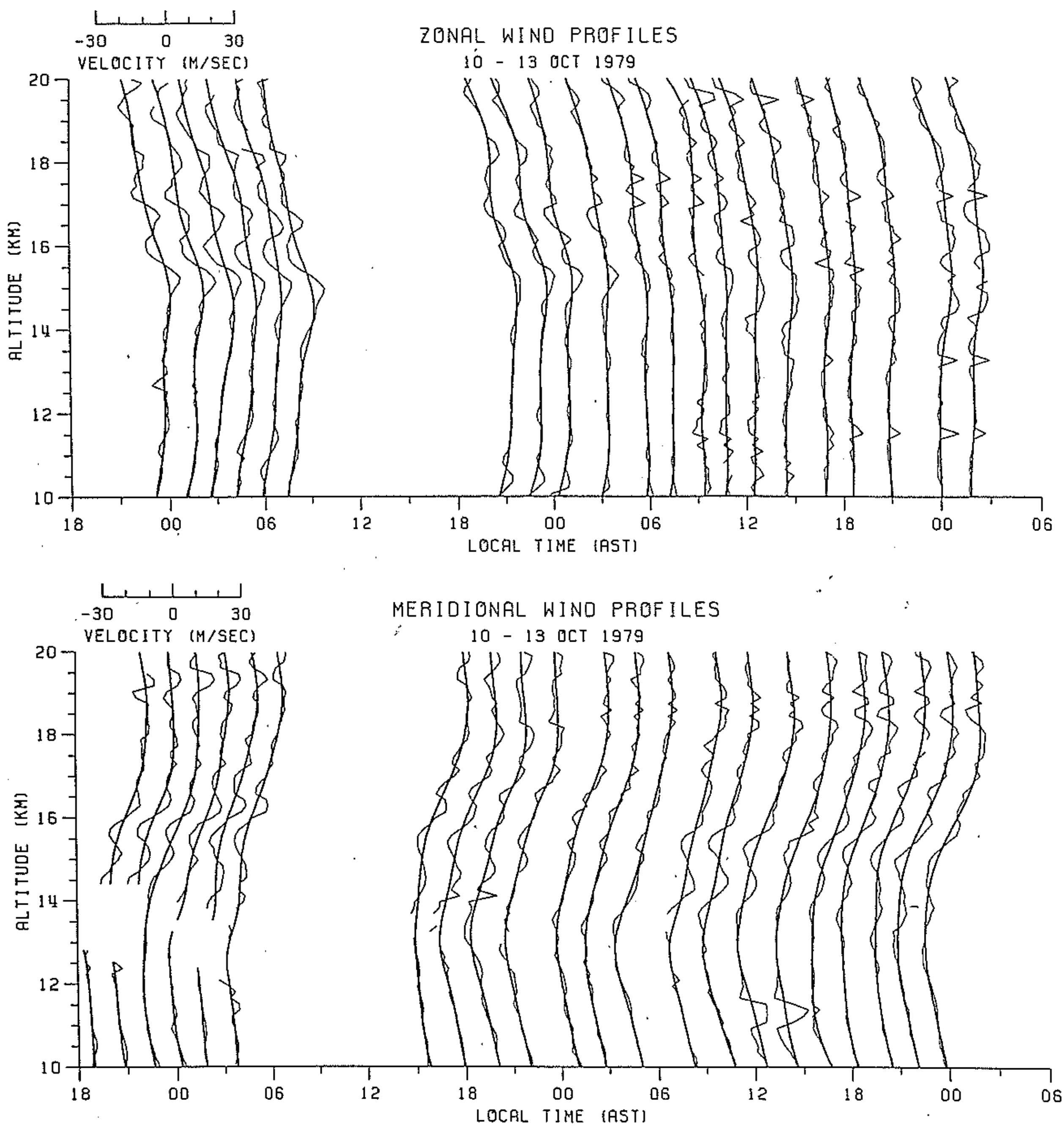

FIG. 3. One-hour-average zonal and meridional wind profiles (thin lines) and smoothed profiles with a 3 km cutoff filter (thick lines) over 54 h.

In addition, similar purely sinusoidal oscillations (or waves) are also observed with shorter time periods. Fig. 6 is an example of a short period oscillation (about three minutes in this case). Changes in the power of the backscatter echoes are usually associated with this type of event. Shown on the right of the figure are three height profiles of the echo power averaged over 30 minutes each. The third, which corresponds to 60–90 minutes on the timescale on the left, is 2–8 dB larger than the other two, showing a good coincidence between the amplitude of the oscillation and enhanced radar returns. This suggests that these waves are breaking into turbulence. It is also interesting to notice that the appearance of the shorter period waves and the turbulence enhancement occurs at a time and location where the longer period waves, shown in Fig. 5, clearly decay. This suggests a nonlinear generation mechanism where the

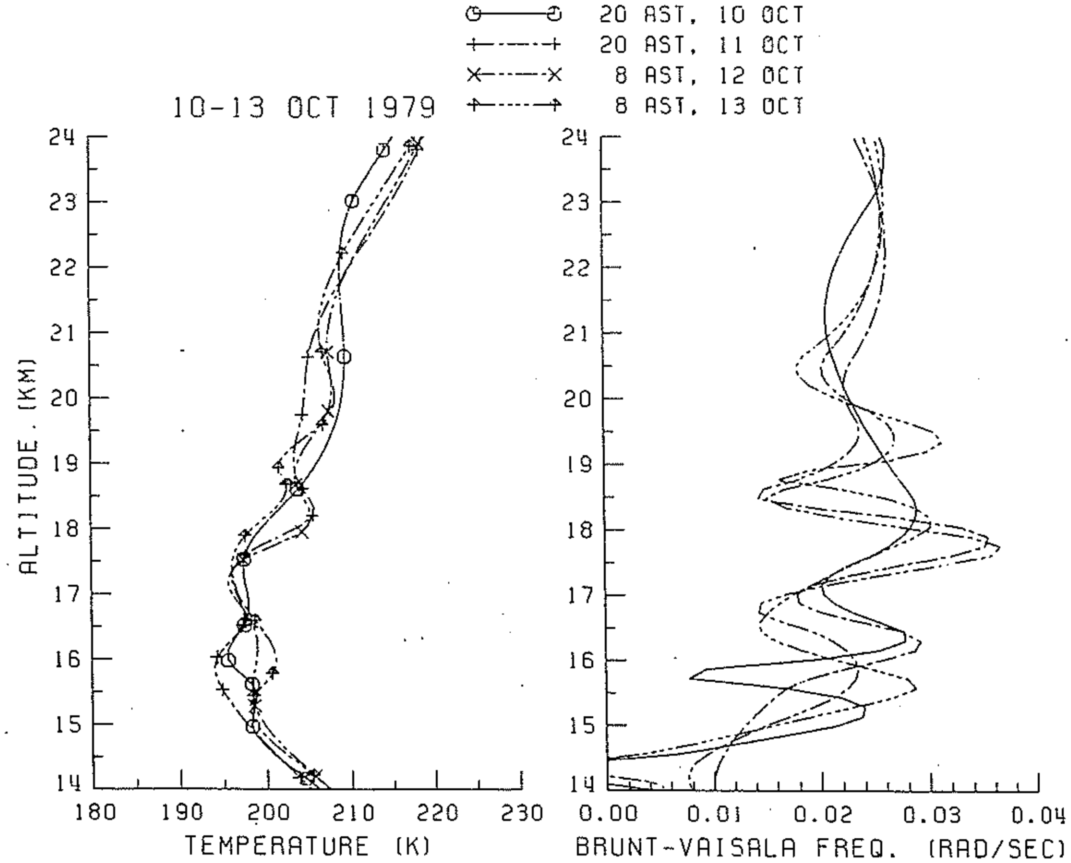

FIG. 4. Temperature and the Brunt-Väisälä frequency obtained from four rawinsonde flights at San Juan, Puerto Rico. Symbols denote data points. Lines are deduced by a spline interpolation.

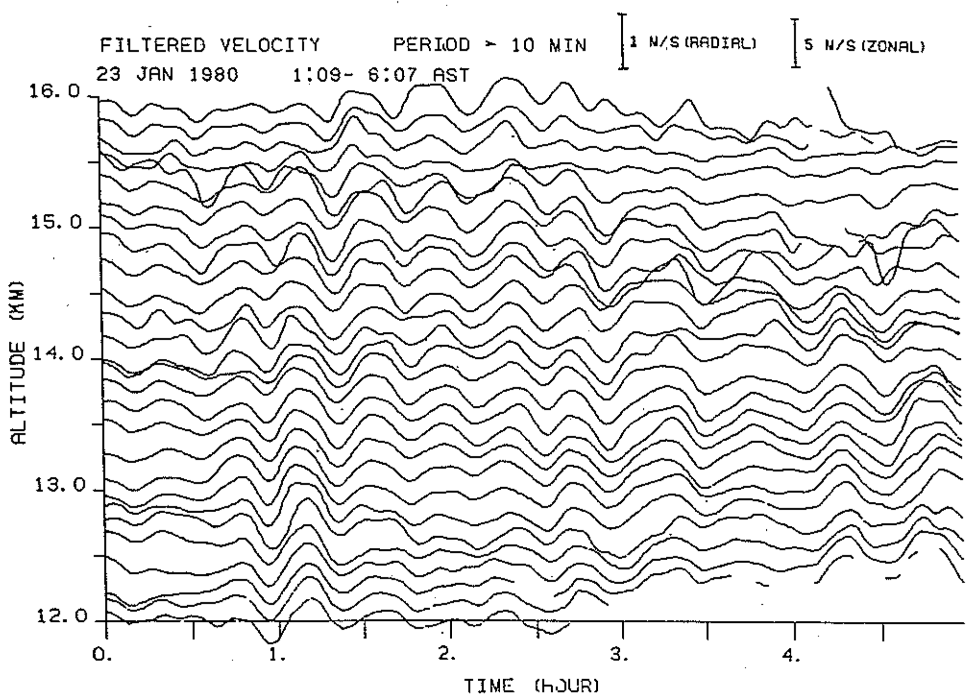

FIG. 5. Temporal variation of the wind velocity at 28 heights between 12 and 16 km. The time series was filtered by a low-pass filter with a cutoff period of 10 min. The antenna was pointed 10° from zenith in the zonal plane.

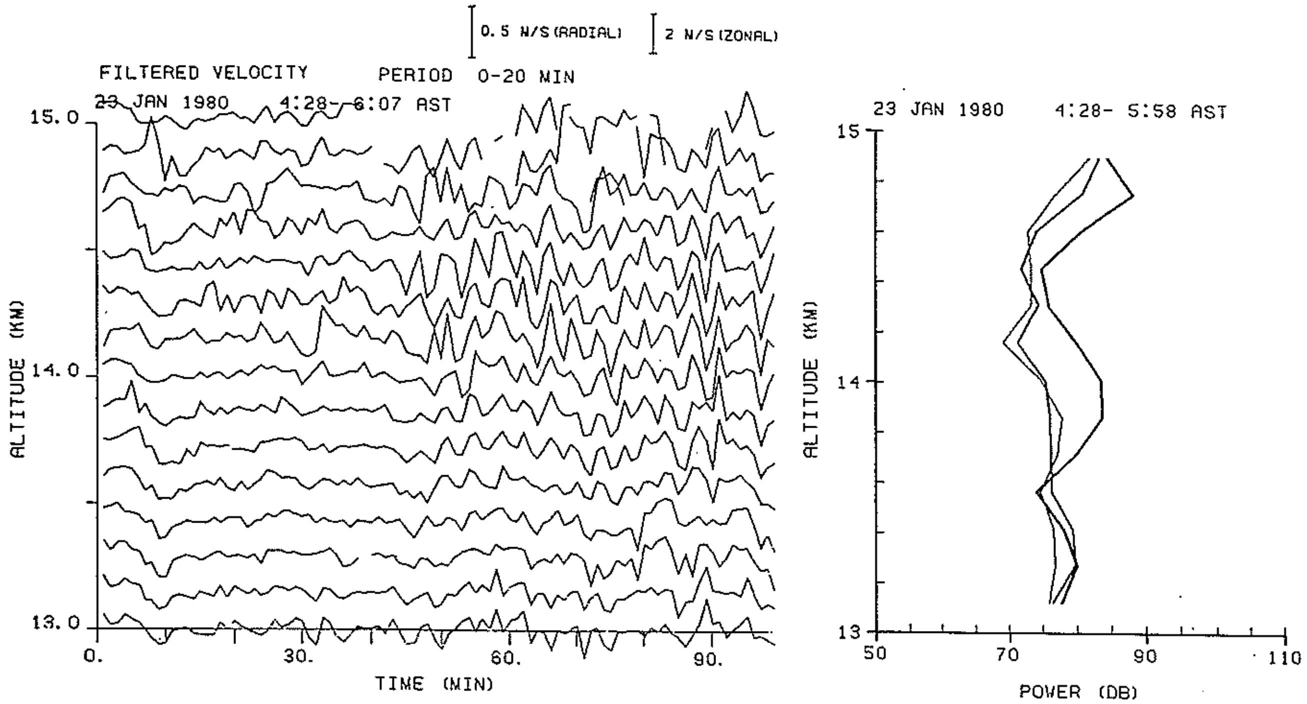

FIG. 6. As in Fig. 5, but for a different filtering (0–20 minutes high-pass filter), and for a different height and time. 30 min average echo power for the same period are plotted on the right. Three lines correspond to three consecutive blocks of time in increasing order of line thickness.

shorter period waves get their energy from the longer period ones. It may also be that the longer period waves are dissipated more efficiently through turbulent viscosity due to the turbulent enhancement discussed above.

The period of three minutes is smaller than the Brunt-Väisälä frequency for this altitude. It would appear, then, that they are outside the regime of acoustic–gravity waves, but it should be kept in mind that this is the frequency observed on the ground, Doppler-shifted by the wind velocity at the altitude of the wave. Therefore, it is possible for the wave to have a period longer than the Brunt-Väisälä period in its own frame of reference, provided the horizontal wavelength is short enough.

Similar oscillations of 4–8 min period have been observed in lower height regions by other radars, and are discussed in terms of the Kelvin-Helmholtz instability (Van Zandt *et al.*, 1979; Klostermeyer and Ruster, 1980). Klostermeyer and Ruster found a good agreement between the height variation of observed amplitude and phase of the oscillation and a theoretical calculation. The characteristic feature of their results is the amplitude minimum and the rapid phase change around the central height where the background wind shear exceeds the critical shear condition.

No similar behavior is found in our case; the strongest shear is observed around 15 km height, and no clear oscillation of similar period can be found above that height. Also, no appreciable phase variation with height can be seen. We cannot, therefore, give a similar explanation for our results. This event requires further study. Other alternative generating and amplifying mechanisms are currently under study.

4. Concluding remarks

The three wave events presented above, at three different time scales, including those of the order of minutes, illustrate the potential of the Arecibo radar, and MST radars in general, in studying the dynamics of the atmosphere. The advantage of radars for the study of atmospheric wave dynamics over more conventional techniques, such as balloons, rockets and satellites, is evident from our results. The possibility of simultaneously giving a temporal and spatial description with good accuracy and resolution is unprecedented. The events presented here also illustrate that the dynamical behavior of velocity perturbations is more complicated than our simple theoretical expectations. Nevertheless, we have attempted an explanation and hope that, by communicating our results, we will stimulate other colleagues to give their own interpretation for the discrepancies. A network of a few properly spaced radars would give a much desired horizontal coverage, greatly improving the spatial description of these events and giving a better understanding of their origin and behavior.

Acknowledgments. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under contract with the National Science Foundation. This work was supported partially by the National Aeronautics and Space Administration under NASA Order No. W-14,569.

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