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VHF Radar Observations of Wind Velocities at the Arecibo Observatory

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Abstract. Further measurements carried out in December 1980 and January 1981 with the SOUSY-VHF-Radar at the Arecibo Observatory in Puerto Rico are presented. An example of mesospheric turbulence echoes recorded during a solar flare is described, and it is concluded that the echo detectability strongly depends on the background electron density profile. The resulting limitations to measure winds in the mesosphere are outlined. Average profiles of zonal and meridional wind velocities indicate signatures of the diurnal tide in the height region 60–80 km. A long-period oscillation of 6 days, found in the zonal but not in the meridional winds in the mesosphere, can presumably be explained by a Kelvin wave.

Key words: Mesosphere – Stratosphere – Troposphere – Tides – Planetary waves – Winds – VHF radar

Introduction

The SOUSY-VHF-Radar was operated with the Arecibo Observatory antenna dish during a common project "Radar Studies of the Middle Atmosphere at 50 and 430 MHz" of the Max-Planck-Institut für Aeronomie and the Arecibo Observatory/National Astronomy and Ionosphere Centre. Four campaigns of several weeks duration were carried out in 1980 and 1981 at the Arecibo Observatory (18.3° N, 66.8° W) in Puerto Rico. First results obtained in April/May 1980 with a low-power VHF radar transmitter (4 kW), and a description of the equipment were published by Röttger et al. (1981). During a campaign in December 1980/January 1981 a higher power transmitter was used as well as an upgraded computer control was partly applied. The transmitter was operated at 30 kW pulse peak power and 4% duty cycle. Using the Arecibo dish, the antenna gain was 40 dB. This yielded an average power aperture product of $5 \cdot 10^7$ W m^2. Some longer term measurements were carried out in order to investigate tides and planetary waves in the lower and middle atmosphere. In this paper some typical results are selected and briefly described, such as indications of the diurnal tide and signatures of a Kelvin wave in the mesosphere.

General Signal Characteristics

Power Profiles and Interference

The altitude range of reliable VHF radar echoes normally covered the upper troposphere and lower stratosphere (8–25 km) and the mesosphere between about 60 and 85 km. At ranges larger than about 20 km strong scatter from ocean surface waves (sea-clutter) occurred which normally extended to ranges of 50–60 km. Occasionally sea-clutter was also observed out to ranges of 100 km when tropospheric ducting caused propagation beyond the horizon. The sea-clutter sometimes complicates the evaluation of signals from the middle stratosphere and mesosphere, whereas ground-clutter is a minor problem. Man-made interference occasionally was strong in the morning hours (09-12 AST) when ionospheric propagation from the US mainland was possible (Röttger, 1980).

Variation of Stratospheric and Mesospheric Echoes

It is known that stratospheric echoes are due to turbulence causing refractivity changes by temperature variations, but mesospheric echoes are additionally strongly influenced by the electron density profile of the ionospheric D region (e.g. Ecklund and Balsley, 1981) and exhibit typical seasonal variations (Czechowsky et al., 1979). The latter echoes therefore are only observed during daylight hours, which complicates for instance the analysis of tidal variations. Another limitation exists since the turbulence occurs in layers, which often confines the radar echoes to rather thin regions of several 100 m vertical extent, although layers as thick as several kilometers were also observed. However, it never was found that evaluable echoes were observed through the entire altitude region between 60 and 85 km for the given power aperture product $5 \cdot 10^7$ W m^2. Additionally the echoes indicate quite some temporal variation.

The layered structure of intermittent turbulence as well as the varying electron density profile do not allow the determination of high resolution (<1 km) wind profiles throughout the entire mesosphere. To illustrate the evident temporal and spatial variation, a contour plot of signal strength is presented in Fig. 1. It is recognized that strong signals were almost continuously observed in the low altitudes up to some 20 km. Two stronger layers occurred at about 14 km and 17–18 km where the upper tropospheric winds showed the strongest shear. Some spurious contour lines in Fig. 1 at ranges between 20 and 50 km are due

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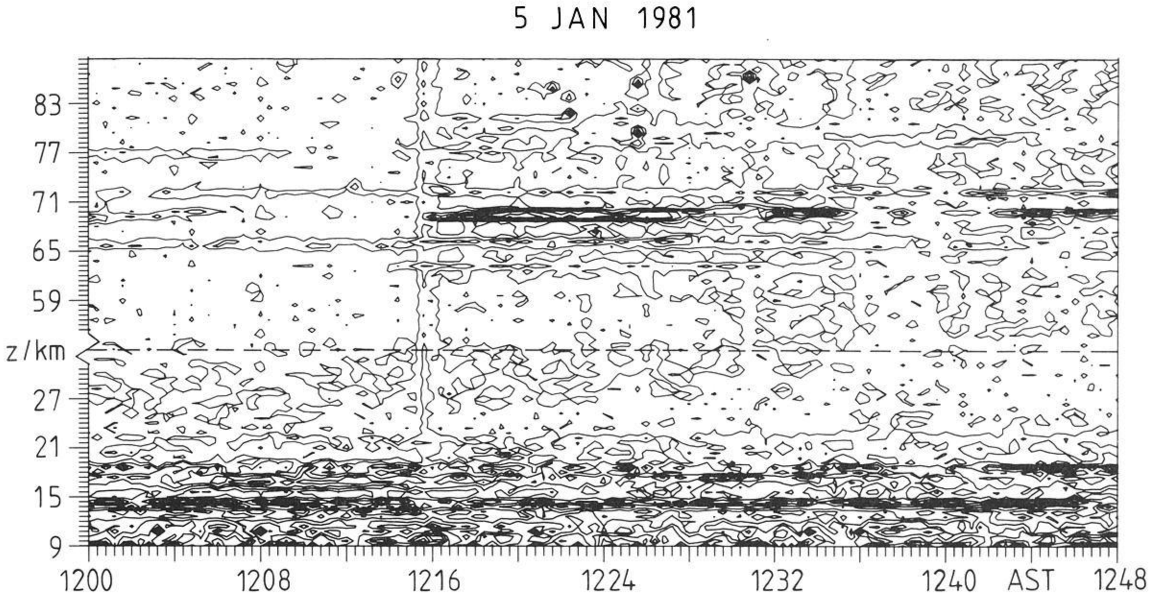

Fig. 1. Contour plot of received power (signal + noise) as function of height z and time (AST = Atlantic Standard Time). The power difference between the contour lines is 2 dB. Because atmospheric signals were not received in the height range 33–53 km, this range is suppressed in the plot. Measurements were carried out with peak power of 30 kW and antenna beam pointing at a zenith angle of 2.7°

to sea-clutter signals. In the mesosphere four separated regions of turbulence scatter were detected after 1200 AST between 65 and 78 km altitude. At 1215 AST a noise burst was observed, followed by an abrupt increase of signal strength of turbulence scatter. The noise burst was due to enhanced solar radio emission during an H_α solar flare (Solar-Geophysical Data Prompt Reports, 1981). The enhanced noise level must have been picked up through an antenna sidelobe pointing to the sun. The simultaneously increased flux of UV and X-ray radiation also resulted in an enhancement of the D region electron density which caused sudden increase of turbulence scatter strength by some ten dB. Simultaneous incoherent scatter observations with the 430-MHz radar showed an increase of the mean D region electron density by a factor of 5–8 (personal communication from J. Mathews and M. Sulzer, 1981). However, even the abnormally high electron density still did not yield a continuous power profile of turbulence scatter. The reason is that the mesosphere was not totally turbulent, but the turbulence was confined to intermittent layers. Because of lack of scatter from "non-turbulent" regions, continuous, high-resolution wind profiles cannot be obtained with a VHF radar with a given power-aperture product of $5 \cdot 10^7$ W m^2. These observations also show that a sudden increase or even moderate variation of signal strength cannot at all be attributed to an increase of turbulence strength, but rather an enhancement of electron density or electron density gradient.

Wind Observations

To obtain indications on tidal and planetary wave variations, a longer observation period evidently is necessary to smooth the short-term fluctuations. A long-term operation was performed at the Arecibo Observatory from 10 December 1980 until 18 January 1981. Since the observatory schedule did not allow continuous radar operation during such a long time period, two hours were only allotted almost every day around noon hours. Continuous runs were carried out during a couple of days only.

Although the VHF radar observations do not yield continuous wind profiles during 24 h a day, they extend the lowest height range which is normally covered by meteor or partial reflection measurements at low latitudes (e.g. Bernard et al., 1981; Vincent and Ball, 1981). Incoherent scatter measurements of velocities in the middle mesosphere need a very high power-aperture product (e.g. Mathews et al., 1981). VHF radar measurements with comparatively low power normally have sufficient signal-to-noise ratios in the height region 65–80 km (occasionally up to 90 km), which is not covered by meteor radars. The lowest heights between 65 and 70 km are mostly not reached by partial reflection measurements. We therefore regard our VHF radar observations as a useful complementary information on winds in these lower heights.

The prevailing wind due to the global circulation, planetary waves, tides as well as gravity waves contribute to the observed wind velocities. It is likely that short-period gravity wave oscillations are smoothed out when averaging the data over 1 h. When measuring at the same time of every day, velocities caused by the tides should be rather similar if their forcing or propagation does not change from day to day. Any variations of the wind velocity, e.g. measured every day around noon time, can therefore be regarded as being due to air motions introduced by planetary waves since the prevailing wind changes at periods much longer than those of planetary waves. Because the forcing and propagation of tides are also influenced by temperature and wind variations due to planetary waves, the day-to-day variations of velocity at a given height level have to be caused anyhow by planetary wave disturbances. The separation of tides from the background wind can either be done by recording the diurnal variation (1), or by averaging many sample profiles taken at a constant time to deduce the vertical profile of tidal winds. We essentially report here results obtained with the latter approach (2), the analysis

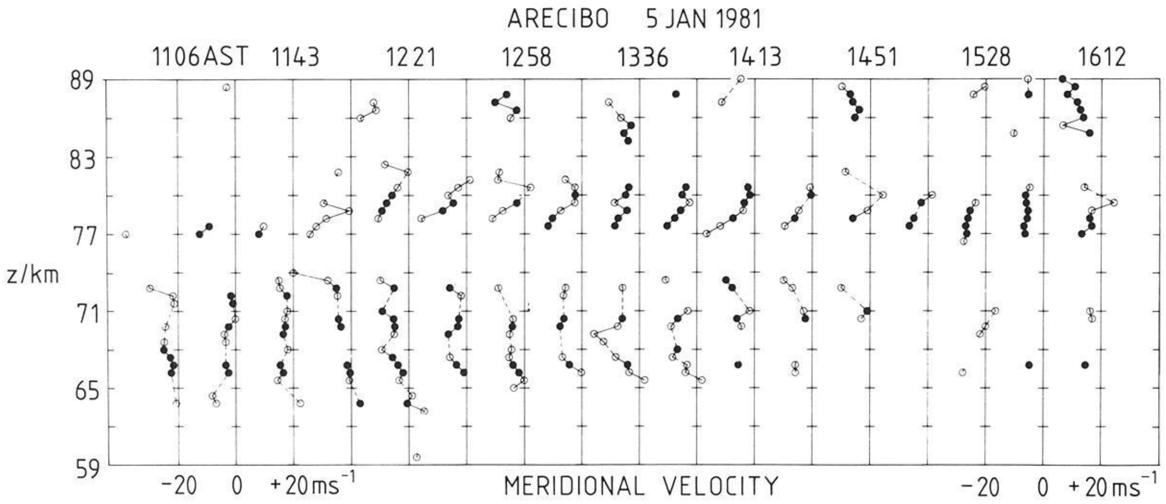

Fig. 2. Meridional velocity v, averaged over 18 min. Open circles denote SNR < 3 dB, closed circles SNR > 3 dB. Since SNR is deduced from the spectrum analysis, the reference level is different from that used in Fig. 1

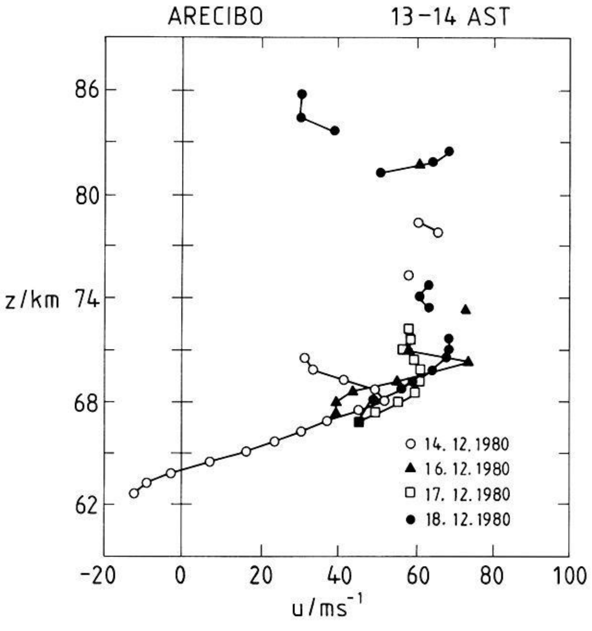

Fig. 3a. Zonal velocity u as function of height z

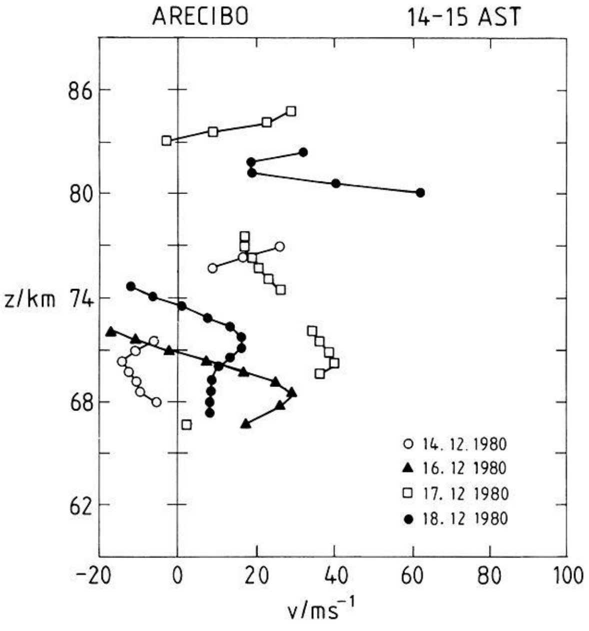

Fig. 3b. Meridional velocity v as function of height z

of continuous radar operations to obtain diurnal variations (1) is still in progress.

Search for Tidal Variations

Horizontal velocities were determined from the Doppler spectra if the signal-to-noise ratio (SNR) exceeded a sufficient level. The velocity data were averaged over time intervals of 18 min or longer. An example of height profiles of the meridional velocity in the mesosphere is presented in Fig. 2. It shows an average southward wind component of about 10 m s^{-1}, decreasing to zero velocity around 65 km altitude. The velocity variability from profile to profile is most likely caused by non-properly smoothed gravity wave oscillations which often had a substantial velocity amplitude of several m s^{-1}. During the course of the day the average wind profiles indicate quite a persistency, and tidal wind variations cannot readily be recognized.

During the observations in December 1980 and January 1981 two dominating regions of echoes existed: region 1 between 65 and 73 km, and region 2 between 77 and 82 km, which are also found in the longer-term statistical analysis (ref. Fig. 4). The lower boundary of region 1 increased in height during the afternoon hours, which presumably was due to the diurnal variation of electron density. The upper boundary of region 1 as well as the lower boundary of region 2 kept the same altitude, whereas the upper boundary of region 2 had a tendency of downward progression. Some sporadic echoes were also detected in the upper height region between 85 and 90 km. Turbulence layers generated by wind shear due to the dominating diurnal tide should move downwards by several kilometers during 5 h. Since there is no clear indication on this expectation, it must be

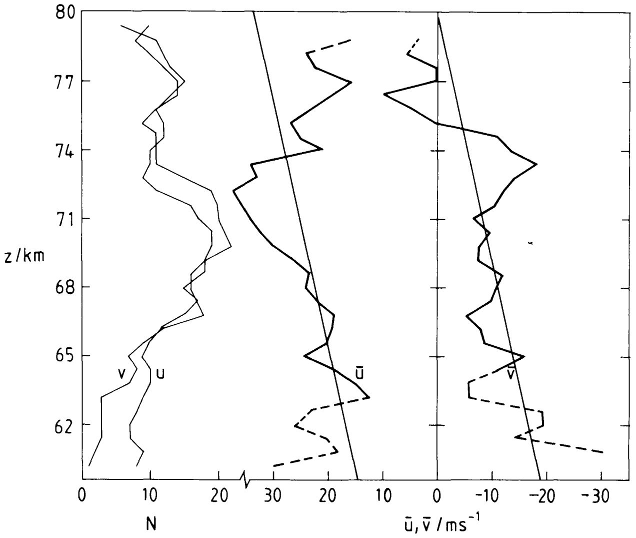

Fig. 4. Average zonal (ū) and meridional (v̄) velocity components measured between 13 and 15 AST on 32 days during the December 1980/January 1981 campaign. The straight lines indicate the supposed mean background wind profile. Dashed parts of the velocity curves indicate marginal significance. On the left-hand side the height distribution of the number N of days (out of the 32 days of radar operation) is shown when evaluable echoes were detected

assumed that other factors such as electron density gradients, lapse rate changes due to the tide or planetary waves, or gravity waves superimposed on tidal or planetary wave shear also play a role in generating these echo structures.

In Figs. 3a and 3b zonal and meridional velocities are shown for four consecutive days in December 1980. These diagrams show velocities deduced from hourly averages of Doppler spectra; the antenna pointed at 5° zenith angle. The zonal velocity was obtained from 13–14 AST and the meridional from 14–15 AST. During these times sufficient signal power was mostly found in the two height regions around $z = 70$ km and 78 km, which was mentioned earlier. The zonal velocity u had peak values of 70 m s^{-1} around $z = 70$ km and exhibited strong shears of about 0.01 s^{-1} below 70 km. The day-to-day variation of the zonal component was smaller than that of the meridional component. The latter one changed from southerly to northerly direction within one day. It is assumed that the consistent westerly velocity u is due to a pronounced prevailing wind, on which tidal and planetary wave disturbances were superimposed. This assumption can be checked by the following evaluations.

When averaging height profiles of wind velocities over several weeks, one expects to smooth out variations due to transient planetary waves. The averaged height profiles should consist of a superposition of the prevailing wind and tidal variations if all the observations are performed during the same time of the day, and it can be assumed that stationary planetary waves have a small amplitude. A result of average wind profiles, obtained for the period 10 December 1980 to 18 January 1981, is shown in Fig. 4. This period of 40 days appears to be sufficiently longer than typical periods of observed waves which were at about 6 days and 20 days. It therefore can be assumed that the averaging over 40 days attenuated these planetary wave oscillations. The height profiles of average velocity in Fig. 4 indicate a quasi-wavelike pattern superimposed on a steady change of background wind with height. This wavelike pattern has a vertical wavelength of about 12 km and indicates that the velocity vector superimposed on the background wind rotated clockwise with increasing height. The amplitude of the wave increased from about 5 m s^{-1} at 66 km to 8 m s^{-1} at 72 km and 10 m s^{-1} at 78 km. These values are slightly smaller than tidal amplitudes in these height regions, measured by Groves (1975) with grenade experiments at 5.9° S. We presume that our observations are consistent with the propagating diurnal tide, but more detailed investigations of these data have to be carried out. Our presumption, however, is supported by continuous measurements during four days in November 1981 which clearly indicate a diurnal variation. These observations, which simultaneously were carried out with measurements by Aso and colleagues at the Jicamarca Observatory in Peru on the opposite side of the equator, and at other locations of the globe, will be described elsewhere. Incoherent scatter observations also showed the diurnal tide over Arecibo (e.g. Mathews, 1976; Fukuyama, 1981).

On the left-hand side of Fig. 4 also the number N of days is plotted at which the received echo power exceeded a given level sufficient for estimating velocity data. One again surmises the two echo maxima around 70 km and 78 km. It is not discernible that these regions coincide with regions of maximum wind shear, which supports our earlier suggestion that other factors, such as electron density or temperature variations or shears by gravity waves, have to be regarded as well to explain the mesospheric radar echoes.

Our analyses of the tidal structure were performed under the assumption that the prevailing wind, i.e. the meanflow due to global circulation, changed linearly with height and can be described by the straight lines in Fig. 4. This may not generally be justified (e.g. Groves, 1980), but it is the only approach we can take since continuous wind observations during 24 h a day during the full campaign could not be achieved at all.

Fig. 5 shows that the prevailing wind in the mesosphere had a rather persistent component to the east. The arrows in this diagram represent speed and direction of the 2-hour averages of the mesospheric winds. At some heights and times only one wind component could be deduced because of too low signal-to-noise ratios or restricted radar operation. These instances are identified by single dots in Fig. 5. It is seen that the westerly winds were strongest during the first part but seem to reverse towards the end of the campaign. The day-to-day variability indicates some oscillating pattern over periods of several days (particularly during the first part of the campaign). The echo minimum around 74 km seems to change slightly its height during the observation period, which will be discussed further in subsequent reports.

Search for Planetary Waves (Tropical Wave Disturbances)

To obtain a clearer picture of the day-to-day variations depicted in the previous section we have plotted in Fig. 6 the time series of velocity deviations u′ and v′ from the mean velocities ū und v̄. The profiles of mean velocities, which are averages over the entire campaign from 10 December 1980 to 18 January 1981, are plotted in Fig. 7. Since it was not possible to operate the radar on every day be-

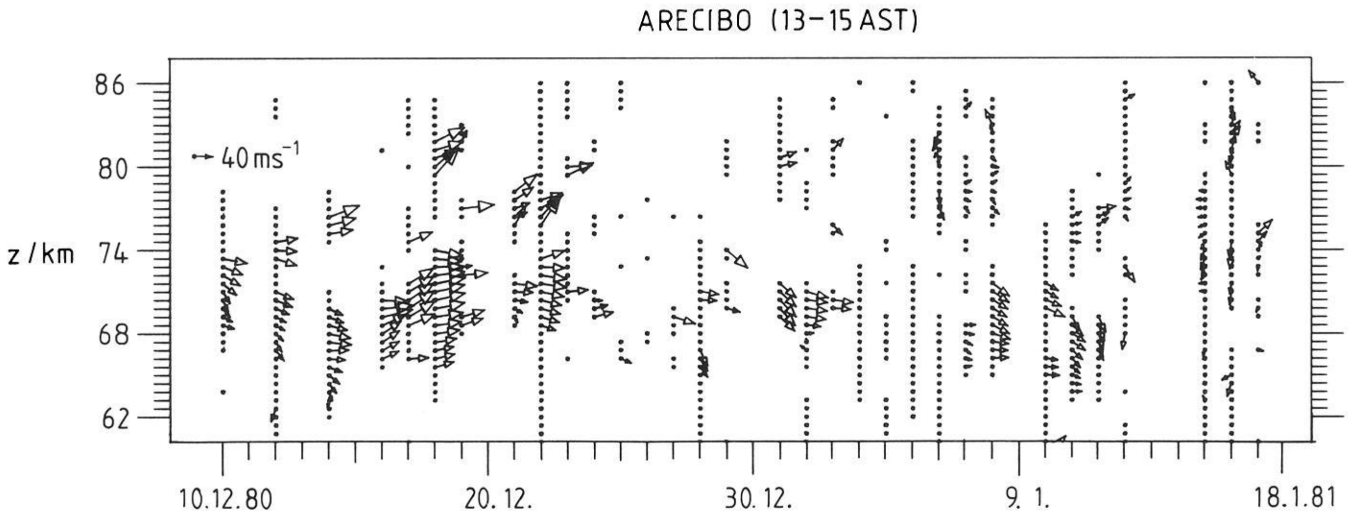

Fig. 5. Wind velocities in the mesosphere. The arrows indicate magnitude and direction of the wind. The dots indicate cases where radar signals were sufficiently strong, but only one velocity component could be determined

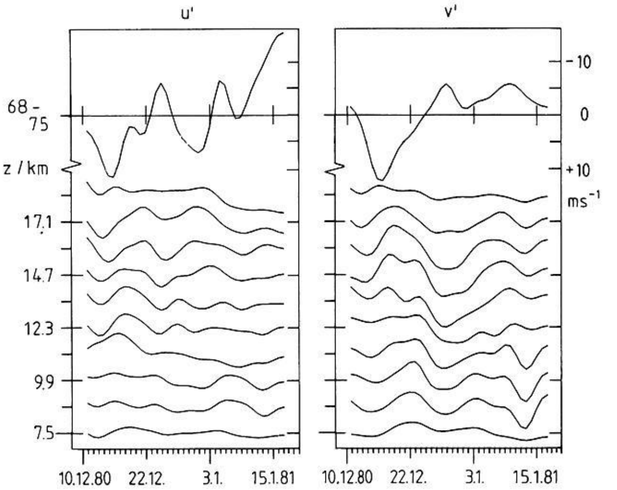

Fig. 6. Deviations u′ and v′ from the average zonal (ū) and meridional (v̄) velocities (see Fig. 7). Missing days were linearly interpolated, and the time series were filtered with a 3-point Hamming filter

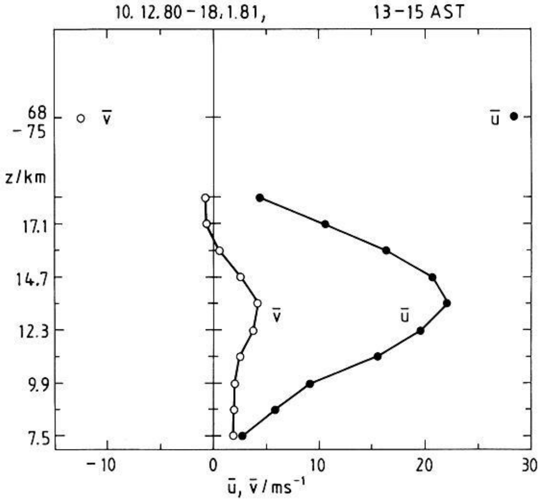

Fig. 7. Average velocities ū and v̄ measured between 13 and 15 AST in the period 10 December 1980 to 18 January 1981

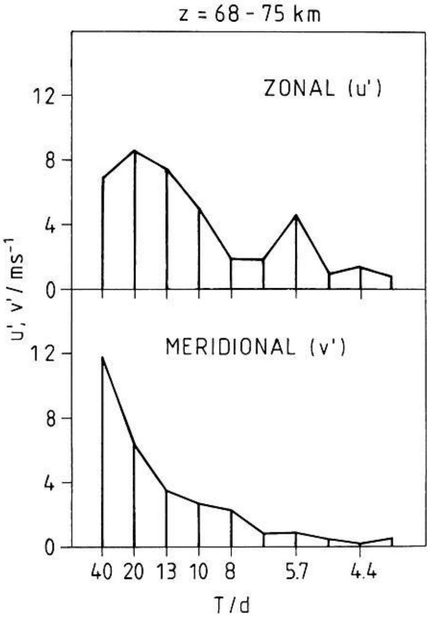

Fig. 8. Amplitude spectrum of linearly detrended zonal u′, and meridional wind component v′ for the mesospheric height range 68–75 km

cause of restrictions due to the observatory schedule, a continuous time series of velocities was not achieved. The interruptions, however, were not longer than 2 days, and these gaps were filled by linear interpolation, followed by smoothing the data series with a 3-point Hamming filter. This procedure is adequate when investigating time changes which are longer than 3–4 days. The mesospheric velocities still had some gaps because of insufficient SNR (Chap. 2.b) and therefore were height averaged over 68–75 km, which is roughly the centre height range from which mesospheric echoes were received. Tropospheric velocities, which could be deduced up to heights around the tropopause, are also included in Fig. 6 to search for tropical disturbances in the lower atmosphere. The average velocities have pronounced maxima in the troposphere around $z = 13.5$ km, which are due to the subtropical jetstream. The velocity deviations u′ and v′ show some quasi-wavelike disturbances with periods between 5 and 20 days. These, however, are mostly confined to height ranges of a couple of kilometers, i.e. they do not appear to propagate vertically. The spectral analysis of the zonal (u′) and meridional (v′) component does not indicate significant amplitudes at the same period over more than a few kilometers altitude range.

In the mesosphere the zonal component has a significant maximum of $4\,\mathrm{m\,s^{-1}}$ amplitude at a period of about 6 days, as can clearly be seen in the spectra shown in Fig. 8. This period of 6 days was also found by earlier meteor radar observations in Puerto Rico (Massebeuf et al., 1981). The 6-days period may point to mixed Rossby gravity waves. However, this oscillation is not at all found in the meridional component, which is a signature of a Kelvin wave (e.g. Wallace, 1973). On the other hand, a 6-days period is not a typical feature of a Kelvin wave. A longer period, such as 15–20 days, is more typical for Kelvin waves, and one may assume that this period is also present in the observed zonal component (see Fig. 8). Hirota (1978) suggested that tropical wave disturbances, such as Kelvin waves, can propagate into the mesosphere where they supply westerly momentum to the zonal mean flow. It cannot be concluded from our presented preliminary observations if the wave disturbances we observed had propagated from the lower atmosphere to the mesosphere. Although the energy source of tropical wave disturbances lies in the troposphere, they most prominently can be detected in the stratosphere. Since our depicted VHF radar observations do not yet cover the stratosphere (due to moderate radar power and sea-clutter problems), analyses of radiosonde data of stratospheric winds have to be included for following investigations. Oscillations with 5–6 and 12–18 days period are also prominent in the stratosphere and mesosphere at middle latitudes and could well generate wind oscillations with small meridional amplitudes at low latitudes (Madden, 1979). We consequently cannot clearly decide from our single-location observations which type of wave we had observed.

Summary

We have described some features of VHF radar observations which were carried out at the Arecibo Observatory during December 1980 and January 1981. We conclude from our preliminary data interpretation that mesospheric signals are strongly controlled by the background electron density profile. This evidence leads to some limitations for continuous recordings of turbulence and winds in the mesosphere. During daylight hours mesospheric winds could essentially be determined in the height range between 65 and 80 km. Average profiles measured during a nearly 6-weeks campaign from 10 December 1980 until 18 January 1981 indicate velocity variations due to the diurnal tide. Wind oscillations with a period of 6 days showing a typical feature of a Kelvin wave, namely a negligible meridional velocity component, are found in the mesospheric wind profiles.

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