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4.2.1 A COMPARISON OF THUNDERSTORM REFLECTIVITIES MEASURED AT VHF AND UHF

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INTRODUCTION

In this paper, we compare observations of thunderstorms made with two radars operating at different wavelengths of 70 cm and 5.67 m. The first set of observations was made with the UHF radar at the Arecibo Observatory in Puerto Rico, and the second set was made with the Max-Planck-Institut fur Aeronomie VHF radar in the Harz Mountains in West Germany. Both sets of observations show large echo strengths in the convective region above the -10°C isotherm. At UHF, precipitation echoes dominate. At VHF, there appears to be a contribution from both the precipitation echoes and the normal echoes due to scatter from turbulent variations in the refractive index.

A number of simple theories can be used to calculate the relative contributions of radar scatter from "clear air" and from precipitation in a cloudy atmosphere as a function of frequency (see, e.g., BATTAN, 1973). The theoretical predictions indicate a wavelength to the -4 power law dependence for scatter from raindrops. GOSSARD and STRAUCH (1981) have labeled this "incoherent scatter", and the scatter from turbulent variations in the refractive index has been called coherent Bragg scatter. The latter is expected to vary as the wavelength to the 1/3 power. Additionally, strong Fresnel scatter or reflection due to refractive index stratification has been found at VHF (e.g., ROTTGER, 1980b). However, the exact wavelength dependence of the reflective process is not known. The few detailed studies of the scatter from clouds at lower frequencies such as UHF and VHF have shown the echo strengths to be larger than expected, based on the theoretical predictions. Examples of such observations are given by SMITH (1964), NAITO and ATLAS (1966), CHERNIKOV (1968), GAGE et al. (1978), and GREEN et al. (1978). The most detailed discussion of the problem has been given by GOSSARD (1979) and GOSSARD and STRAUCH (1981).

Some of the earlier explanations of the enhanced reflectivities dealt with a possible organization of the precipitation on a scale comparable to half the radar wavelength due to turbulent motions within the cloud. Thus, the reflected radar signal would have both a coherent and an incoherent component. GOSSARD (1979) used results from a numerical cloud model developed by CLARK and HALL (1979) to improve the estimates of the dielectric fluctuations caused by water vapor and raindrop spectrum variations within the cloud. He concluded that, for reasonable values of the various parameters, organization of the precipitation by turbulent motions could not account for the observations. However, the variations of the thermodynamic variables and the coupling to the water vapor densities through nonlinear dynamics could produce significantly

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enhanced cloud reflectivities, although the calculated enhancements were still too small to explain the observations.

GOSSARD and STRAUCH (1981) used experimental data from an FM-CW radar to study the contributions from "incoherent scatter" and "Bragg scatter" in winter clouds in Colorado. Their results showed no significant departure from the classical predictions, but they could not conclude anything about the stronger summertime convective storms. Also, they suggested that some of the enhancements in reflectivity that have been reported in the literature could be associated with entrainment and mixing of dry air near the edges of the cloud.

So little data exists and, with the exception of the work by GOSSARD (1979), little has been done to improve the theory of scattering from clouds at long wavelengths. Since the theory of scattering from clouds at long wavelengths is uncertain, it is particularly important to have as much observational data as possible taken with different instruments. In this article, we will present data from two separate thunderstorm observations made in the Summer of 1978 and in the Fall of 1979. The first experiment was carried out with the SOUSY VHF radar located in the Harz Mountains in West Germany and operating at a frequency of 53.5 MHz. The second experiment was carried out with the 430-MHz Arecibo Observatory radar located in Puerto Rico. Although the observations were made in different parts of the world, in different climates, with different radars operating at different frequencies, there are significant similarities. Also, this comparison of the scatter at wavelengths of 70 cm and 5.67 m from cumulus clouds is the only such comparison of which we are aware.

THE SOUSY VHF RADAR OBSERVATIONS

The SOUSY VHF radar is operated by the Max-Planck-Institut fur Aeronomie and is located in the Harz Mountains near Bad Lauterberg. The radar frequency corresponds to a wavelength of 5.67 m, and the nominal height resolution is 150 m (see, e.g., ROTTGER, 1980a). The radar was operated during the early part of June 1978, when the flow over western Europe was characterized by a stable, anticyclonic air mass. On June 1 and 2, air mass thunderstorms developed, and some were reported near the radar site. In the evening of June 2, 1978, data were obtained after 1851 GMT, and, for almost two hours, a thunderstorm was immediately over or near the radar's location. ROTTGER (1980a,b) has described the experiment in greater detail.

The vertical velocities measured by the vertically pointing radar for the period from 1851 GMT until 2040 GMT on June 2, 1978, are summarized in Figure 1 (local Middle European Time is GMT minus one hour). The shaded areas indicate upward velocities, and the contour intervals are 1 m/s. The dark, solid bars show the times and ranges at which radar echoes from lightning were detected. A detailed discussion of these echoes is outside the scope of this paper, but we assume that they are likely due to scattering from the ionized lightning channel, although Bragg scattering from acoustic waves may occur, too. The lower part of the figure shows the measured mean pressure changes at the site and a subjective estimate of the rainfall intensity as a function of time. The thunderstorm symbol indicates the presence of lightning, and the open circle shows a period of clear sky overhead.

In Figure 2 we show the mean quasi-vertical velocity w, the echo power P and the rms velocity fluctuations σ_w during the final period from 2011-2041 GMT. The effective reflectivity, due to scattering from turbulent refractivity variations and partial reflection from coherent discontinuities in the refractivity, is proportional to the power P multiplied by the square of the range. It is normally a measure of the temperature and humidity variations in the radar volume. Note that an uplift of the reflectivity pattern from
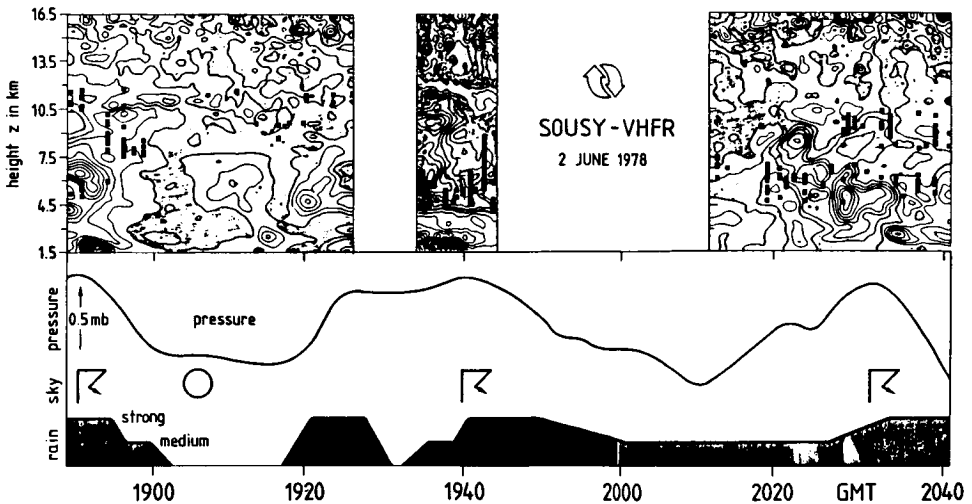
Figure 1.

about 7.5 to 10.5 km occurs within a 10-minute period at the beginning of the period shown in the figure. The reflectivity pattern then remains nearly stationary in height after about 2025 GMT. The behavior of the echoes is consistent with the vertical development of the thundercloud until it reached the height of the tropopause at 10.5 km, if we assume that the gray-shaded region represents the thundercloud region. Two indications support this assumption: (1) the high reflectivity band above 10.5 km at 2011 GMT presumably is the radar-detected tropopause (e.g., ROTTGER, 1980b), and (2) lightning echoes, which originate within the cloud, are detected only within the gray-shaded region. The final uplift of the high reflectivity regions in the tropopause level is connected with mean upward velocities of some meters per second. The strongest turbulence, viz., regions of large rms fluctuations in velocity, occurs in and above the regions of strong upward velocities.

A more detailed analysis of the Doppler spectra shows that, in addition to the relatively small upward velocities, sometimes large downward velocities occur simultaneously. Figure 3 shows 12 consecutive vertical velocity profiles obtained at 2-minute intervals with the SOUSY VHF radar. Actually, the figure represents gray-scale plots of the Doppler spectra as a function of range gate. The darker impressions indicate stronger signal strengths. The spectra for each range gate are normalized to their peak value. Thus, the extent to which the noise is suppressed is an indication of the signal-to-noise ratio.

Each profile shows a small fluctuating vertical wind component with an amplitude no greater than a few m/s over the altitude range from 3.0 to 12.0 km. However, before 1900 GMT, while the thunderstorm is above the radar, there are secondary peaks in the Doppler spectra between 2.5 and 9.0-km altitude. The secondary maxima have associated velocities between a few m/s at the upper end of the altitude range and 10-12 m/s at the lower end. The power associated with the secondary echoes has a maximum value of more than 10 dB above the noise level and is comparable in magnitude to the "clear air" or "small velocity" echoes which are seen to persist after the cloud has passed out of the radar beam. Around 7.5 km altitude at 1851 GMT, the secondary peak is even stronger than the small velocity part of the spectrum, as shown by its suppression resulting from the normalization. The height range where the secondary echoes occur is above the -20°C isotherm as determined from the
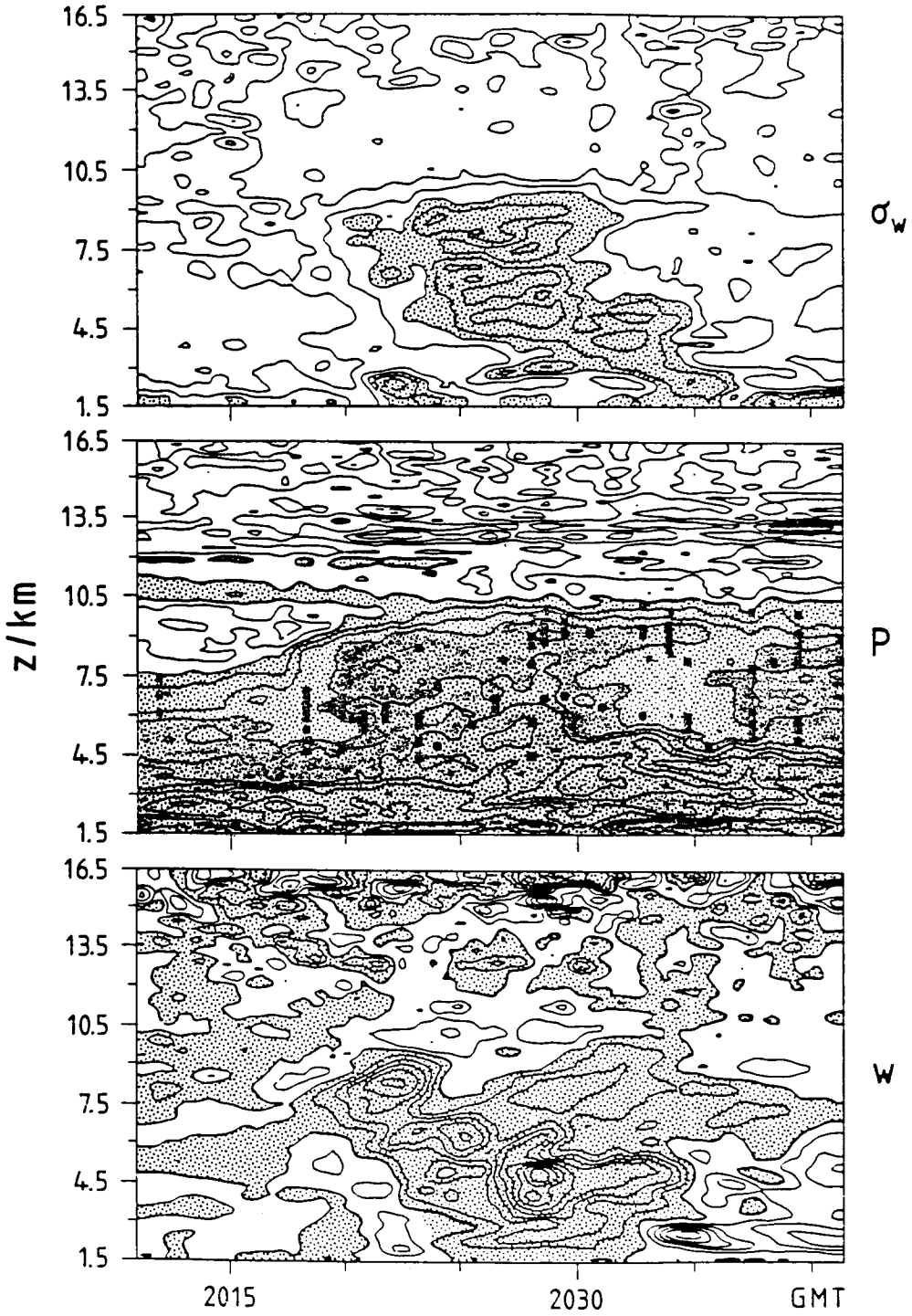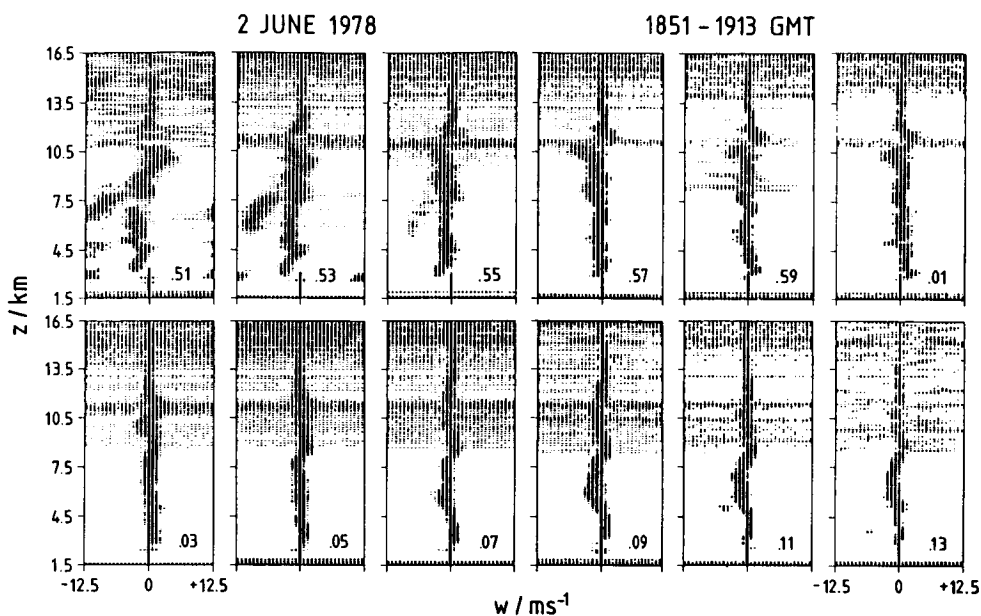
2 JUNE 1978

Figure 2.

Figure 3.

Hannover radiosonde data which were taken some 100 km northwest of the radar site at 1200 GMT.

Double peaked spectra of VHF radar echoes from a large cumulus cloud were also reported by GREEN et al. (1978). They found it difficult to interpret these double peaks, although they tentatively concluded that an updraft and a downdraft existed simultaneously within the radar volume. They interpreted the secondary echo as being from precipitation but found that the measured reflectivities were too large by an order of magnitude.

430-MHz THUNDERSTORM OBSERVATIONS AT ARECIBO

The experiment at Arecibo was carried out in September of 1979 using the 430-MHz radar at the Arecibo Observatory. The radar frequency corresponds to a wavelength of 70 cm. The radar is steerable within an angular range less than 20° off vertical, but during the experiment, the beam was pointed vertically during the entire observation period. At the beginning of the experiment, the intertropical convergence zone (ITCZ) was located unusually far north. A wave disturbance in the easterly flow passed over the island on September 13 and 14, 1979, and organized the convection that developed over the island due to the strong diurnal heating cycle. On September 14, there was thunderstorm activity over the radar from 1430 AST until 1750 AST. LARSEN et al. (1982) have described the experiment and some of the earlier results in greater detail.

The radar reflectivities are shown in Figure 4 for the period from 1430 to 1730 AST. No renormalization of the power for range-square dependence is necessary since the near-field (Fresnel region) for the Arecibo 430-MHz radar extends out to more than 100 km altitude. The Arecibo 430-MHz radar thus illuminates in the troposphere and stratosphere, a region with a horizontal diameter equal to the 305-m diameter of the dish antenna. As in Figure 2, Figure 4 clearly shows the cross section of a cumulus cloud, including the
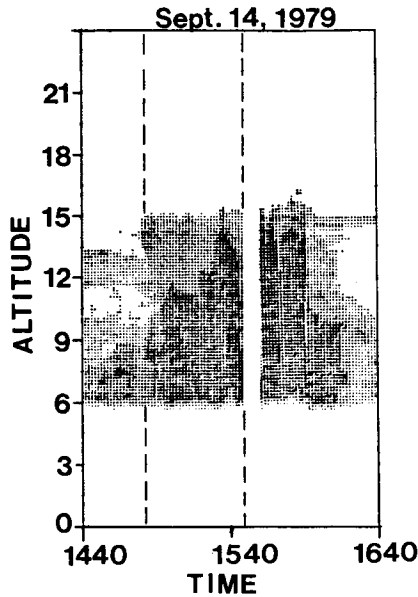
Figure 4.

anvil near the tropopause at the end of the afternoon. It is unusual to have such a long-lived thunderstorm, but in this case the combined effects of the easterly wave, the local topography, and the heating contrast between the land and the ocean must have produced favorable conditions for maintaining the cloud in a nearly stationary position. Care has to be taken in interpreting the data because the radar was not scanning during the experiment. Therefore, Figure 4 shows effects due to both advection of the cloud over the radar and the temporal evolution of the cloud in the course of the afternoon, just as in Figure 2.

Figure 5 shows a sample of five consecutive profiles of the vertical velocities measured with the radar. The vertical and horizontal axes are the same as in Figure 3, but the power is shown in contours rather than as a gray-scale plot. The contour interval is 3 dB. The echoes in the troposphere are very broad, and "x's" have been used to indicate the locations of the maxima in the power spectra. Typically, the echoes in the troposphere would have approximately the same width as the echoes seen in the region above the tropopause near 15 km.

The vertical velocity profiles observed at Arecibo once the cloud was overhead are very similar to the vertical profiles for the "precipitation" echoes observed with the SOUSY VHF radar. The echoes have small velocities near the tropopause and become more negative toward lower altitudes. In this case, the downward velocities attain magnitudes as large as 8 m/s. Note that around 7-8 km the measured Doppler shift is so large that the velocities become aliased and appear as large positive velocities. Data cannot be obtained below an altitude of 5.7 km due to the receiver protection system for the 430-MHz radar. Therefore, we do not know if the downward velocities become larger at lower altitudes.

In the Arecibo data set, there is no evidence of a "low velocity" signal from the "clear air", as there is in the SOUSY VHF radar data taken at a longer

Sept. 14, 1979

15:28:36   15:29:58   15:31:20   15:32:42   15:34:05
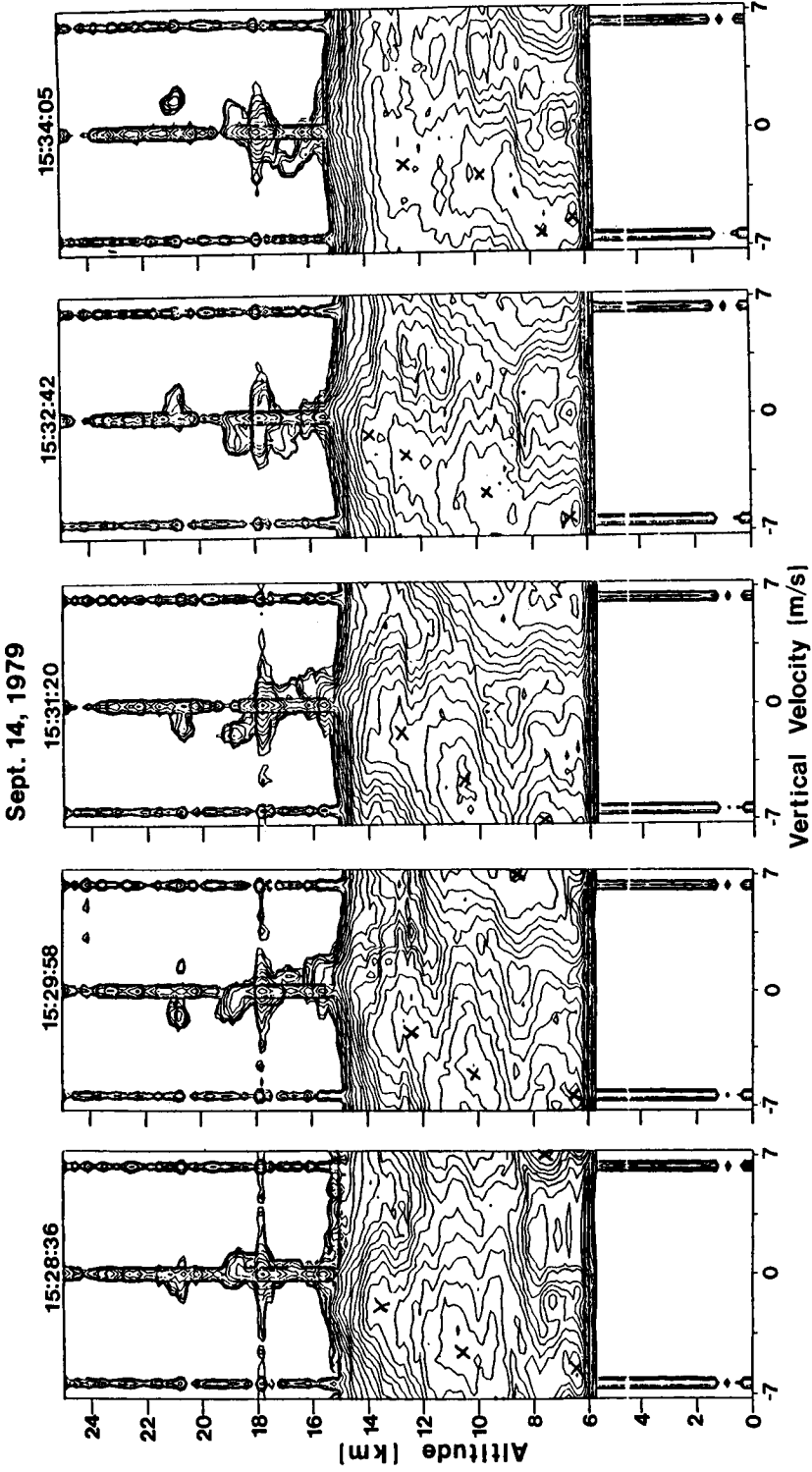
Altitude [km]

Vertical Velocity [m/s]

Figure 5.

wavelength. We have examined the Doppler spectra from the UHF radar in detail, and there is no evidence of a double peak. Of course, that may not be surprising since the echo strength of the signals shown in Figure 5 are of the order of 60 dB. The difference in the signal strength just above the tropopause near 15 km and the signals in the cloud just below the tropopause is approximately 30 dB at UHF but only 10 dB at VHF. The signal strength increases further by another 30 dB before it attains maximum values near 10-km altitude. The radiosonde ascent from San Juan, located 80 km east-northeast from the Arecibo radar, showed that the atmosphere was conditionally unstable from ground level to the height of the tropopause, and the lowest height where data were obtained with the radar corresponded to a temperature of −10°C. The temperature decreased further to −20°C at 400 mb or 7.6-km altitude. Therefore, we do not expect much liquid precipitation or liquid cloud droplets in the height range of the radar measurements.

Figure 4 shows that the echoes attain their largest magnitude near the center of the cloud and taper off at the edges. Therefore, the enhancements cannot be due to large refractivity gradients created by mixing of dry and cloudy air near the outside of the cloud. The largest magnitudes occur in what is typically the updraft region of the cloud, the right half of Figure 4, while somewhat less intense echoes occur in the region usually associated with downdrafts, the left half of Figure 4. The same is also true for the VHF observations as shown in the middle frame of Figure 2.

GRAVITY WAVES GENERATED BY THE STORMS

Both the SOUSY VHF radar observations and the Arecibo observations show that gravity waves were generated by the convection once the upward development reached the height of the transition from the unstable lapse rate in the troposphere to the stable lapse rates in the lower stratosphere (ROTTGER, 1980b; LARSEN et al., 1982). The gravity-wave motions are evident in the sample profiles shown in Figures 3 and 5. In Figure 5, the downward phase progression of the waves can be seen in the altitude range from 15 to 22 km. The downward phase progression implies upward group velocity for a packet of gravity waves. Figure 1 also shows some evidence of downward phase progression in the altitude range between 10 and 13 km as can be seen in the tilt of the height/time contours of the vertical velocities.

DISCUSSION

In all, there are a number of similarities between the two data sets in spite of the differences in the conditions and locations used for the observations. Both radars detect a "precipitation" echo that shows vertical velocities close to zero near the tropopause and increasing negative velocities at lower heights. The VHF radar also detects the clear-air component of the vertical motion. Finally, both sets of radar observations showed that gravity waves were generated in the lower stratosphere in connection with the cumulus convection.

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