RADAR OBSERVATIONS OF THE DEVELOPMENT OF TROPICAL THUNDERSTORMS AND CONVECTION CELLS USING THE ARECIBO RADAR

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1. INTRODUCTION

In the period from 13 Sept to 20 Sept 1979, the 430 MHz radar system at the Arecibo Observatory was used to study profiles of vertical velocity in developing and mature thunderstorms during the afternoon hours. During the eight day period, five days produced significant convective activity. The great sensitivity of the Arecibo radar facility allowed vertical velocities to be measured up to an altitude of 20 km. Since the tropopause over Puerto Rico is at an altitude of approximately 14 km at that time of year, the lower part of the stratosphere was also observed during the period of cloud development.

Many studies have been carried out using Doppler radars to probe the interior of convective cells (see Wilson and Miller, 1972 for an excellent review and bibliography; also Battan, 1973). This is particularly true of radars operating at shorter wavelengths of 3 or 10 cm which are more sensitive to reflections from precipitation within the clouds. The Arecibo radar, operating at a wavelength of 70 cm, receives echoes from variations in the index of refraction with a scale size of half the wavelength, or 35 cm. The fact that vertical velocities could be measured in both the troposphere and lower stratosphere is of particular interest in view of the theory that the upward flux of mass in the tropical branch of the Hadley cell is concentrated in the cumulus towers (Riehl and Malkus, 1958; Reiter, 1975). Puerto Rico, at approximately 18°N latitude, is in this branch of the Hadley cell. Therefore, the experiment is of interest both from the viewpoint of cumulus dynamics as well as the large scale circulation.

2. FORMAT OF THE EXPERIMENT

During each day of the experiment, the radar was pointed vertically during the entire period of observation which lasted from 1400 to 1730 LT. The movement of the antenna is extremely slow, particularly in relation to the rapidly changing conditions during strong convective activity. Therefore, no attempt was made to vary the look-angle. An IPP of 500 μsec was used with a pulse length of 2 μsec giving a height resolution of 300 m. Complete vertical profiles of the vertical velocity were obtained every 82 sec. The base height of the profile was limited to 5.7 km above MSL by internal constraints in the system's receiver cut-off. The highest altitude at which the signal remained above the noise level was near 20 km.

In support of the radar observations, the radiosonde data from Isla Verde Airport at San Juan, Puerto Rico was obtained on a daily basis. San Juan is 50 km from the Observatory site. Also, an all-sky camera was used to take pictures once every three minutes. This gave a pictorial record of the cloud cover above the radar during the data taking sessions. The 3 minute interval was chosen on the basis of the time that a particular cloud remained recognizable as it crossed the field of view. A tipping bucket rain gauge with a resolution of 0.01 inches was used to record the rainfall.

3. THE OBSERVATIONS

Figure 1 represents a series of five consecutive profiles during the period of maximum vertical extent of the cloud structures on 14 Sept. These particular profiles were chosen because they are to some extent representative of the conditions that were present on each of the five days when significant convective activity occurred. The individual profiles are contours of reflected power as a function of altitude and Doppler shift (velocity). The contour lines are at intervals of 3 dB. The rapid increase in the reflected power near 6 km is due to the receiver cut-off. The two vertical bars near +7 and -7 m/s are due to 60 cycle hum leaking into the signal processing equipment. The 60 cycle interference is evident at heights where the receiver is cut-off as well as at the higher altitudes where the reflected signal is significantly weaker.

The most noticeable feature of the profiles is the presence of very broad spectra between 5.7 and 14.5 km. Above 14.5 km, the

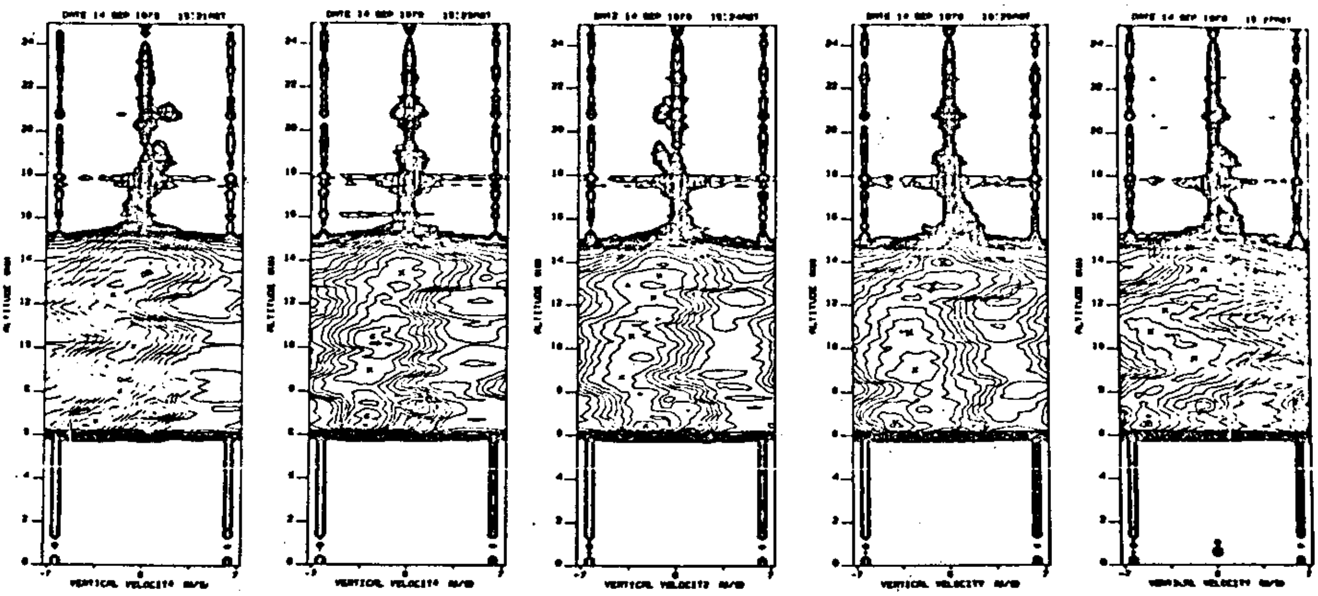

Figure 1. Five consecutive profiles of reflected power as a function of altitude and Doppler shift. The profiles are at 82 second intervals.

signal strength decreases rapidly by a factor of more than 30 dB. Also, the width of the spectra is greatly reduced. On each of the days when observations were made, radiosonde data was obtained from Isla Verde Airport in San Juan. The tropopause height indicated by the radiosonde was found to correspond very well with the highest altitude at which the broad spectra were observed. In fact, the entire region below 14.5 km, shown in Figure 1, is believed to be occupied by a cumulus cloud. On each afternoon, the cloud development could be observed by noting the increasing altitude range in which the broad spectra were present. At no time did the vertical "cloud" development extend above the tropopause boundary.

In the tropospheric altitude range, the spectral maxima are indicated by X's. It may be noted that negative vertical velocities predominate in the entire altitude range below the tropopause. The maximum downdraft in this case is 6 m/s at 1527 AST. Downdrafts in the region below 11 km were a persistent feature on all days once the clouds had developed into the upper troposphere. Vertical velocities between 11 and 14.5 km varied, sometimes being upward and sometimes downward as show in the figure. The maximum downdraft that was observed was 10 m/s, and the maximum updraft was 5 m/s.

In any vertical beam radar study, it is hoped that the series of profiles obtained will represent a vertical cross-section as the cloud passes overhead, and the succession of these cross-sections will be representative of the growth to maturity and decay of the cloud structures. This interpretation can often be misleading, especially if a strong directional shear with height exists in the background wind. This is the case with the profiles presented here. A review of the photographs taken during the experiment, coupled with the radiosonde wind profile data helped to clarify the situation. Figure 2 shows the San Juan radiosonde data for 00Z on 15 Sept (19 AST 14 Sept). It should be noted that the wind vector is turning with height from easterly below 3 km to southerly above 7 km. The effect of this background wind pattern was that in the early afternoon hours, low level clouds would develop directly over the radar, and these clouds would move from east to west. Near 1500 AST, large cumulus clouds, accompanied by lightning, would be evident to

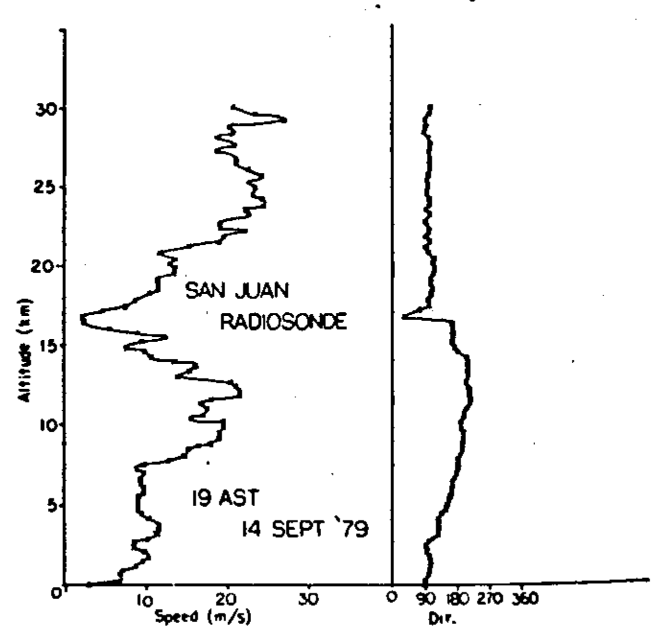

Figure 2. Radiosonde wind profile from Isla Verde Airport, San Juan, Puerto Rico for 1900 AST 14 Sept 1979. Direction is the azimuth that the wind is coming from.

the south of the radar site. As the clouds in the south became more fully developed and reached higher altitudes, they would move rapidly toward the radar. In effect then, the interior of the island was a region of much more active convection, although low level clouds would form over the radar. Our data from the early afternoon hours seem to be in agreement with this. The transition from shallow layers of enhanced reflectivity to the very deep layers shown in Figure 1 was very rapid, occurring over a period of 1 to 2 successive profiles (82 to 164 secs). Also, in the early afternoon hours, there was a trend toward small vertical velocities of 1/2 m/s but consistently upward between 6 and 12 km. The clouds which moved in from the south in the later afternoon hours were fully mature and accompanied by lightning and rain. For the mature clouds, updrafts were seen near the tropopause, but the region below 11 km was dominated by strong downdrafts.

4. GRAVITY WAVES IN THE STRATOSPHERE

Referring to Figure 1 again, it can be seen that there is an oscillation above the tropopause boundary with a vertical wavelength of approximately 6 km. Figure 1 represents half a cycle of this oscillation which therefore has a period of roughly 8.6 minutes. The Brunt-Vaisala period at this altitude was calculated to be 6.6 minutes. This type of oscillation was found to be present at all times when the clouds had reached the tropopause height. If this is a vertically propagating gravity wave, the vertical phase velocity should be 11.62 m/s and directed downward. This gives a vertical displacement of the phase front of 2.8 km over the interval of four consecutive profiles. There is indeed an indication of this which may be noted if particular attention is paid to the region between 18 and 21 km. The stratospheric oscillations in every case had periods close to the Brunt-Vaisala period calculated from the radiosonde data. Other examples exist in the data in which the vertical phase progression is much more distinct.

In general, the periods when gravity waves were present in the lower stratosphere were accompanied by a net positive upward mass flux across the tropopause. The direction of the vertical velocity just below the tropopause boundary was the same as the direction of the vertical velocity associated with the gravity wave just above the lower tropopause boundary. As Figure 1 indicates, the gravity wave's oscillations give both upward and downward vertical velocity components. If these were equal in amplitude, the net vertical mass flux would be zero. However, analysis of the data for 14 Sept shows that the amplitude of the downward component is slightly smaller than that of the upward component. The net upward component is 1/2 m/s. At the height of the tropopause boundary, the mass density is 0.252×10^3 kg/m^3. The upward mass flux is therefore 1.26×10^2 kg/m^2/s.

5. CONCLUSION

In this paper, we have made the initial presentation of vertical velocity data obtained during a period of active thunderstorms over Puerto Rico. In particular, the Arecibo radar has proven to be a powerful tool for studying the interaction between the troposphere and stratosphere during convective periods. Vertically propagating gravity waves were found to be generated at all times when the clouds were sufficiently deep to reach the tropopause. An initial estimate has been made of the vertical mass flux into the lower stratosphere resulting from the convective activity. However, a full analysis of the vertical mass movement on all five days when data was obtained will be carried out in the future.

Acknowledgements. The National Astronomy and Ionosphere Center (Arecibo Observatory) is operated by Cornell University under contract with the National Science Foundation.

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