Venezuelan Rainstorms as Seen by Radar

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ABSTRACT

The underlying premise of the research is that a contribution can be made to understanding the interrelation between mesoscale cumulonimbus systems and synoptic disturbances as well as the general circulation by following individual cloud histories in detail. During a mesoscale experiment carried out in eastern Venezuela in 1969, 232 such histories were obtained. At first the statistical properties of the sample are explored with respect to maximum height attained by clouds; maximum area; duration of cumulonimbus systems and radar index; correlations between maximum height, maximum area and duration; symmetry of time histories; vertical motion of echoes; diurnal effects; echo displacement in relation to tropospheric winds; and merger or separation of echoes.

In the second part it is shown that the observed outflow profiles of mass in the upper troposphere from synoptic disturbances or poleward from the tropics as a whole can be parameterized largely by erosion of the buoyant energy of cumulonimbus towers through entrainment of mid-tropospheric air at the fractional rate of 0.6 for the layer 850–400 mb.

1. Introduction

The actual injection of mass and energy into the middle and upper troposphere by means of cumulonimbus “hot towers” takes place in only about 1% of the area in the tropics (Riehl and Malkus, 1958). As a corollary, the time scale of the active phase of such clouds also has the magnitude of 1/1000 (Riehl et al., 1972). Conventional radiosondes, for many reasons, hardly ever penetrate into the hot towers; thus, these are not represented on synoptic charts nor do they appear in climatic statistics. Yet they are of primary importance for synoptic weather disturbances and the general circulation of the atmosphere.

In recent years various investigators, well aware of these problems, have proposed models for parametric inclusion of cumulus and cumulonimbus convection in energy balance and in prognostic equations. In contrast, special data collections that would aid in formulating adequate expressions for hot towers and their environment have remained very limited. For instance, a synoptic view on a cumulonimbus sky always reveals a variety of cloud top heights. Are these heights all parts of a single cloud history, seen at different stages of growth and decay? Or do we observe different cloud histories, where individual clouds vary in greatest height and area attained? If so, will different modes of cloud histories occur in different synoptic structures?

The answers to these questions should help to shed light on interpreting the role of cumulonimbus in relation to their broader setting. Assuming spatially constant temperature and moisture in the surface layer, the anvils of completely protected hot tower cores rising through the troposphere should all be found at approximately the same height, near the equilibrium level of undilute parcel convection. If the anvils occur at different heights, however, some mechanism must exist whereby the energy of ascending towers is eroded during ascent similar to cumulus clouds, or that cloud tops that have “overshot” the equilibrium level do not return to it. Then the outflow at high levels from the tropics to higher latitudes also must have a profile spread over some finite thickness, whereas with single undilute cloud histories all outflow would occur in a very narrow layer centered on the parcel ascent equilibrium height.

Questions of this character led to the Venezuela Meteorological and Hydrological Experiment (VIMHEX), conducted June to September, 1969, in northeastern Venezuela (Fig. 1). A main objective of this project was the determination of complete cloud histories using special radar and rawinsonde observations. In this paper certain results of the experiment are presented, especially the description of cloud histories and their impact on meridional circulation profiles. Betts (1972) has discussed the mesoscale interaction between the clouds and their environment, while Riehl et al. (1972) consider cumulonimbus in relation to synoptic systems.

2. Material for study

During VIMHEX I a combined radar-rawinsonde installation was located at Anaco (Fig. 1). The radar
was a modified M-33 type, with the following characteristics:

- Wavelength: 10 cm
- Horizontal beam width: 1.25°
- Vertical beam width: 4°
- Rotation speeds: 10, 20, 30 rpm
- Minimum detectable signal: −105 dBm
- Pulse repetition frequency: 1000 Hz
- Pulse width: 1.3 μsec
- Effective radius: 80–100 km

The sky was monitored daily after the morning convective lull. When evidence of active convection began to appear, 35-mm photographs were taken with the following routine. Beginning at 18° antenna elevation (the highest possible), the antenna was tilted at 2° intervals down to 2° yielding nine photos which constituted one observation. During particularly interesting cases the gain-setting also was adjusted by −6, −12 and −18 dB, the latter corresponding to about 1% of full energy received. The complete observation then consisted of 36 pictures and the time consumed by one observation was about 10 min. Successive observations were made at 15-min intervals until convective activity died down. About 70,000 photographs were taken during the project.

3. Methods of analysis

a. Procedure

Film strips taken from the radar scope were projected on a Recordak microfilm screen and enlarged, so that 1 cm on the screen corresponded to 10 km in nature. At first, using only the frames taken at 2° antenna tilt and at zero attenuation of the radar beam, contours of the individual echoes were drawn every 10–15 min depending on the frequency of observations. Fig. 2 is a sketch of such an observational sequence. Next, at each position in space, certain parameters were measured after a selection of echoes for analysis was made. Only cumulonimbus clouds (echoes extending beyond 5 km height) were considered. At maturity, echoes had to have an area of at least 400 km², following the definition of mesosystems of Riehl and Malkus (1958); this criterion was later modified to include some smaller clouds. Finally, the echo was required to be located within 80 km from the radar site, in order to avoid boundary errors in the accuracy of radar reflectivity.

b. Parameters

1) The position of a whole cloud echo at a given time was defined by the position of the highest echo portion observed.

2) The echo top was taken as the greatest height of the minimum detectable echo; this height was calculated from the radial distance and the elevation angle. Two instrumental effects are important. The radar beam width of 4° means an uncertainty in height of ±2 km at a range of 60 km. The true cloud height also differs from the radar height and this difference may depend on the radar reflectivity of the storm.

3) The echo area was determined using a 10 cm × 10 cm transparent overlay grid; the number of 1-cm squares covered by the echo was counted. The measurement of these parameters was carried out for each observation, until the echo went out of range or dissipated.

c. Summary

A total of 232 separate cloud histories was obtained. For each case, time-development of area and height of each echo was plotted as in Fig. 3, yielding smoothed time profiles and also maximum height, maximum area and storm duration.

Trajectories for each echo were constructed and smoothed as indicated in Fig. 2. The mean track was defined as the straight line parallel to the line connecting the first and last points but passing through the trajectory so that areas on both sides were equalized.

The mean echo speed was calculated by dividing the length of the mean track by its duration. For strongly
4. Statistical properties of echo histories

a. Maximum height

Fig. 4 shows the percent frequency distribution of maximum height \(H_{\text{max}}\) attained by the 232 echoes studied, in class intervals of 2 km altitude. Median height was 9.7 km; most tops occurred between 6 and 14 km. This diagram suggests the existence of a variety of individual cloud histories. It is not thought that different cloud reflectivities are primarily responsible for this variability in echo height, and the error due to radar beam width is likely to be systematic (and difficult to assess). It will be suggested that the variability can be accounted for in terms of changing energy content of the surface layer (diurnal and day to day) and entrainment into rising towers (Fig. 14).

b. Maximum area

The frequency distribution of maximum area \(A_{\text{max}}\) for all cases finally selected for analysis is given in

![Graph](image)

Fig. 4. Percent frequency distribution of \(H_{\text{max}}\) of 232 echoes analyzed.

Fig. 5. One-half of the cases lie between 400 and 1000 km² in a highly skewed distribution. From the individual graphs, \(\bar{A} = 3/4 A_{\text{max}}\) approximately, where \(\bar{A}\) is the average area over the echo duration. Then the average \(\bar{A} = 500\) km² with radius of 12.5 km. This is the size of the model cloud adopted by Betts (1972).

c. Duration

The majority of the echoes lasted 1–3 hr. The average was slightly less than 2 hr for the whole sample (232 storms, Fig. 6), and 2.2 hr for the subset for which the complete life cycle was observed. Duration is thus comparable to that of summer thunderstorms in the United States, but a few cases persisted for 4–7 hr, suggesting the time scale of squall lines of the western United States plains.

A radar index value was determined for each day by finding the product of \(\bar{A}\) and duration for each echo and then summing over all echoes on a given day. The

![Graph](image)

Fig. 6. Percent frequency distribution of duration of 232 echoes analyzed. Dashed line indicates median duration.
resulting value is expressed in percent of the maximum index \( H_{\text{max}} = 1.1 \times 10^7 \text{ km}^2 \text{ min} \) defined for the total area under the radar screen and a duration of 6 hr, the normal daily length of the convective activity in northeastern Venezuela on days with active clouds. As would be expected, the frequency distribution is highly skewed (Fig. 7), with the average index near 5%; occasionally much larger values occur indicative of major synoptic disturbances.

d. Correlations

A close relation between \( H_{\text{max}} \) and \( A_{\text{max}} \) was expected; however, the correlation coefficient turned out very low, namely 0.08, a subject examined by Riehl et al. (1972). Correlation between \( H_{\text{max}} \) and duration also proved to be zero, whereas the coefficient between \( A_{\text{max}} \) and duration was 0.5 (Fig. 8). Thus, large clouds have a long life but by no means necessarily a great height.

Fig. 8 also contains an average curve for \( A_{\text{max}} \) times duration which, when normalized to \( A \), is one of the most important indices in computing interaction between convective clouds and their environment. The weighting is heavily in favor of large clouds. Thus, ten clouds with \( A_{\text{max}} \) of 1000 km\(^2\) only have the weight of two clouds with 2000 km\(^2\).

This relation may find its explanation in the fact that the circumference/area relation of cumuli, \( 2\pi r / (\pi r^2) = 2/r \), i.e., larger clouds tend to be protected more than small clouds from turbulent entrainment at their boundary (Riehl, 1954).

e. Time histories

An interesting feature encountered in plotting the time histories of individual clouds was the fact that most curves presented a single peak for area and height, in spite of the lack of correlation between \( H_{\text{max}} \) and \( A_{\text{max}} \), and that the curves were quite symmetrical with respect to the peak. The majority of clouds started to decrease shortly after attaining their peak value, though in the case of the largest clouds, several peaks were reached with some higher and some lower, or a merger of two or more echoes occurred.

For a quantitative expression testing the symmetry of the life cycle we set \( t = \Delta t / \bar{t} \), where \( t \) is total time of the life cycle of a cloud and \( \Delta t = t_{\text{max}} - t_0 \), the time between starting point of an echo and the time of its maximum development. For a completely symmetrical storm \( t = 0.5 \) with these definitions. Fig. 9 shows the frequency distribution of \( t \); it indeed turns out that nearly 60% of all echoes had a nearly symmetrical time history, while in one-third of the sample ascending phase was more rapid than the descending phase which might have been expected to be the prevailing mode. Since some life cycles may still be incomplete, this asymmetry is not thought to be significant.

Another interesting comparison is afforded by frequency distributions of echo mean vertical velocities during ascending and descending phases, as determined over each phase of each individual echo. Table 1 shows the result. We see that little difference exists between the rates of growth and decay of echoes.

f. Diurnal variation

As already indicated, one reason for the observed spectrum of \( H_{\text{max}} \) (Fig. 4) could lie in a diurnal variation.

![Fig. 7](image)

**Fig. 7.** Percent frequency distribution of radar index, expressed in percent of maximum index for a convective period of 6 hr.

![Fig. 8](image)

**Fig. 8.** Scatter diagram of \( A_{\text{max}} \) vs duration, linear regression line (estimated), and curve giving the product of area and duration.

![Fig. 9](image)

**Fig. 9.** Percent frequency distribution of the time \( t \) needed by echoes to attain \( H_{\text{max}} \), where \( t \) is the fraction of total lifetime of an echo.
TABLE 1. Percent frequency distribution of radar echo mean vertical motions (m sec\(^{-1}\)).

<table>
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<tr>
<th></th>
<th>0-1</th>
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<th>2-3</th>
<th>3-4</th>
<th>4-5</th>
<th>5-6</th>
<th>6-7</th>
<th>7-8</th>
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<td>14</td>
<td>11</td>
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<td>0</td>
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<td>5</td>
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<tr>
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<td>33</td>
<td>14</td>
<td>8</td>
<td>12</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE 2. Percent frequency distribution of time of occurrence of radar echoes and of the onset of precipitation at Anaco. See text for definition of precipitation.

<table>
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<th>Time of echo occurrence</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hour (local standard) beginning at</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
</tr>
</tbody>
</table>

of the energy of the surface layer resulting from accumulation of solar energy received (René, 1970). Fig. 10 shows some indication of a variation of maximum height with time of day, with greatest height in late afternoon. A good correlation also exists between the time of onset of precipitation (yielding more than 0.02 inch at Anaco) and the frequency distribution of time of occurrence of echoes (defined as their time of maximum height), i.e., essentially between the number of clouds and local time (Table 2).

g. Echo motion

A major point of interest lies in the relation between echo motion and the tropospheric wind field at low and middle levels which may be expected to act as a steering current. The success of satellite-derived winds, for instance, depends on the existence of a high correlation.

After many different tries in the course of this study, the 700-mb level and the 850–400 mb direction and speed were selected for correlation. For direction the difference was small, so that Fig. 11 serves to illustrate the situation both for 700-mb level wind and for the 850–400 mb layer wind. We see that there is a bias of echo motion to the right of the 700-mb wind; 50% of the echoes moved between 0° and 30° to the right. However, 76% moved within 30° to right or left with a correlation coefficient of 0.7. It is seen that echo motion can be predicted from wind soundings generally within 20° accuracy and that satellite winds derived from tracking the movement of large (~500 km²) convective clouds may be accepted as correct within 30° over three-quarters of the cases. This result has marginal application potential since the significant variation of wind direction in tradewind synoptic disturbances normally is no more than 30° in the low troposphere.

Fig. 12 shows the correlation between echo and 700-mb speed. Evidently the relation is rather good, although the correlation coefficient is only 0.5. Regression equations for both 700 mb and the 850–400 mb layer follow \( (V, \text{ m sec}^{-1}) \):

\[
V_{\text{echo}} = 4.9 + 0.4V_{700}
\]

\[
V_{\text{echo}} = 3.7 + 0.6V_{850-400}
\]

These relations are quite similar. It should be pointed out that the wind used is that of Anaco whereas the
individual echoes were up to 80 km distant. Further, the Anaco wind represents the mean overall ascents made in the course of a daily convective period, usually 4–5 soundings, for stabilization of the wind profile.

5. High-tropospheric mass outflow profiles

If line integrals are taken around the boundary of an area containing mesoscale cumulonimbus systems, or even around whole latitude circles, one always finds a mass outflow profile roughly between 500 and 100 mb, with largest values near 200 mb. As pointed out initially, the existence of such a wide altitude range of profiles can be due to three factors: variable energy content of the sub-cloud layer, different atmospheric temperatures in the middle atmosphere, and entrainment into cumulonimbus towers. As Fig. 10 indicates, there is a diurnal variation of the maximum height reached by the echoes. However, the spread of $H_{\text{max}}$ at any time of day is so great that influences other than a diurnal energy cycle must be found to explain most of the variance.

Fig. 13 shows the distribution of echo tops with respect to a classical mean parcel ascent determined separately for each day. Evidently, any outflow profile is hardly affected by overshooting cumuli. An area of uncertainty is indicated for $H_{\text{max}}$ within 2 km of the parcel height, due partly to sensitivity of the calculation to errors in cloud-base $\theta_a$ and due to the fact that the radar has a wide beam width ($4^\circ$); this latter factor may also enable it to see an $H_{\text{max}}$ which lies below the real cloud top (see Section 3). An attempt to determine cloud top temperatures and heights from Nimbus satellite data failed, because Nimbus did not pass over Venezuela during the afternoon convective period. There can be no doubt, however, that the bulk of the echoes terminate their growth well below classical parcel height; the latter ranged from 320 to 140 mb, with a median of 190 mb. Clearly, entrainment seems quantitatively significant.

In order to test the entrainment hypothesis, the following calculation (suggested by Prof. Betts) was performed on each day:

1) A quantity $\theta_a$ was determined at cloud base, using the average Anaco sounding from the ascents made during the principal convective period on a given day. Following Ooyama (1969), $\theta_a$ is defined as the equivalent potential temperature that corresponds to radiosonde temperature at saturation. For instance, if $T=24^\circ \mathrm{C}$ at $p=950$ mb, $\theta_a = 360^\circ \mathrm{K}$. The closely analogous saturation wet-bulb potential temperature has been used for some time (e.g., Browning and Ludlam, 1962).

2) An average value of $\bar{\theta}_a$, the actual equivalent potential temperature, was calculated for the layer 850–400 mb, where entrainment is thermodynamically most significant, using radiosonde values at 850, 700, 600, 500 and 400 mb.

3) A value of $\theta_a$ for a rising cumulonimbus tower was calculated at 400 mb, using the relation

$$\theta_a(400 \text{ mb}) = \frac{\theta_a(\text{cloud base}) + f \bar{\theta}_a}{1 + f},$$

where $f = \Delta M/M_0$, a fractional entrainment. Various values of $f$ were used, from 0.4 to 0.8.
The cumulonimbus $\theta_a$ at both cloud base and 400 mb adequately defines the ascent curve for an entraining parcel. A height $H_E$ was determined from the intersection of the entraining parcel curve (extrapolated where necessary) and the daily mean sounding for each assumed value of entrainment rate.

5) On each day an average value of $H_E$ vs $\bar{H}$ (mean height of echoes ending below parcel ascent height) was established for several entrainment rates, using scatter diagrams plotted from $f=0.4$ to $f=0.8$. Of these, Fig. 14 shows the best fit at $f=0.6$, i.e., a correlation coefficient of 0.75. Malkus and Williams (1963) suggested that $(1/M)dM/ds \approx 1/r$, where $M$ is the vertical mass flow at a given level and $r$ the tower radius of the cloud. From this one might calculate a cloud tower radius of 2 km, a reasonable result.

It is suggested that the previous calculation adequately explains the observed spectrum of $H_{\max}$. A fractional entrainment has been deduced, of importance to some parametric models of deep convection (Ooyama, 1969; Arakawa, 1969). The wide variation of $H_E$ depends on the relation of the surface energy ($\theta_a$) which determines parcel $\theta_a$ at cloud base, and the mid-level atmospheric $\theta_a$. These clearly differ greatly from one day to another, as indicated by the scatter along the line in Fig. 14, and need further study. The scatter across the mean line is not unexpected as the entrainment coefficient can only be a mean value. There will be a range of cloud sizes, and entrainment may differ from cloud to cloud. Betts (1972) finds approximate energy balance for a model cloud by assuming ascent in 5K “tubes” of air with conservation of $\theta_a$. However, the wet day composite sounding of Riehl et al. (1972) shows that the difference in actual $\theta_a$ between the subcloud layer average and the 850–400 mb average is only about 7K so that, with an entrainment rate of 0.6, the $\theta_a$ of any rising tower would only be reduced by 3K, well within the class limits used by Betts. Thus, these two methods of analysis are not inconsistent.

Fig. 15 shows the frequency distribution of maximum radar echo tops ($H_{\max}$) in Venezuela in comparison with the outflow profile from the equatorial trough zone of Riehl and Malkus (1958). Broadly, the correlation is very good, considering that information from such different sources has been put together. The somewhat lower peak of the Venezuela data can have various causes. There may not be a precise correspondence between $H_{\max}$ and mass flow; the radar probably underestimated cloud tops; and finally the surface energy over Venezuela is somewhat lower than over the continental belt of Africa and Asia and over the western Pacific. It is suggested, however, that Fig. 15 illustrates the principle mainly responsible for the existence of broad outflow profiles in the upper troposphere above 500 mb in synoptic systems and in the general circulation exchange between low and high latitudes. Also, the natural variation of cumulonimbus heights may be used to study variations of the level of tropical mass outflow.

6. Summary

By means of the data collected in VIMHEX I, conducted in northeastern Venezuela during July–September, 1969, several questions have been answered concerning the interrelations between mesoscale cumulonimbus systems and synoptic disturbances as well as the general circulation.

By studying the histories of 232 echoes, statistical
properties for the sample were established. The results can be summarized as:

The height of the echoes ranged between 7 and 14 km with a mean of 9.7 km. This confirms the existence of a large variety of cloud histories. One-half of the cases had areas between 400 and 1000 km², the average of the distribution being 500 km², which gives a mean radius for the echoes of 12.5 km. The duration of the life cycle was 2 hr on the average, a value comparable to that of summer thunderstorms in the United States. On the average, during the convective activity periods, a radar index of 5% was determined. Low correlation was found between \( A_{\text{max}} \) and \( H_{\text{max}} \) as well as between \( H_{\text{max}} \) and duration. However, the correlation coefficient between \( A_{\text{max}} \) and duration came out to be 0.5. From those correlations it can be concluded that large clouds have long life but by no means necessarily a great height. Very symmetric curves were found in plotting the time histories. Convection was found with maximum activity during the period of maximum accumulation of solar radiation in the ground. In regard to the movement of echoes, it was found that the best correlation is with the 700-mb wind speed, while the direction was within 30° to right or left of the wind direction at the same level. Hence, it seems that echo motion can be predicted from wind soundings generally within 20° accuracy. In relation to the high-tropospheric mass outflow profiles it was found that those profiles can be accounted largely by the thermodynamic calculation of cumulonimbus parcel heights with entrainment. Variation in atmospheric structure and low-level equivalent potential temperature give rise to the spreading of the mass outflow profile from the tropics. From calculations made with different rates of entrainment it turned out that the best correlation between observed and calculated tops is for a fractional entrainment \( f = \Delta M/M_0 \) of 0.6 for the layer 850–400 mb.

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