Influence of the Environment on the Initiation of Precipitation in Tropical Cumuli over the Ocean[1, 2]

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Abstract

An analysis has been made of the day-to-day variation of the likelihood of precipitation in cumulus clouds observed over the ocean in the vicinity of Puerto Rico. It is shown that the probability of rain in a cloud having a particular height depends on environmental conditions, and that the principal factors governing precipitation initiation are stability, vertical wind shear and depth of the moist layer. On the west side of polar troughs moving into the tropics, these parameters have values which make precipitation likelihood small.

1. Introduction

During the University of Chicago flight operations over the ocean in the vicinity of Puerto Rico, observations were made of the dimensions of a large number of cumulus clouds. At the same time, the clouds were examined by a vertically scanning 3-cm radar to ascertain whether or not they contained a precipitation echo. From these data, a study has been made of the day-to-day changes of the ability of clouds to produce rain. For convenience the term "rainability" is used to designate the probability of precipitation in a cloud having a specified characteristic such as height or temperature.

2. Interdiurnal variability of cumulus cloud rainability

Studies of precipitation in cumulus clouds have shown that when rainability is plotted as a function of cloud top height, it has a distribution of the general form shown in Fig. 1. In clouds having tops at some low height it is zero, and in clouds with tops at some great height it approaches or becomes one. Studies of cumulus rainability have been made in various regions in the world. MASON (1954) and BATTAN and BRAHAM (1956) have summarized much of the available material. Because of the limited amount of data, little is known about the interdiurnal variation of the

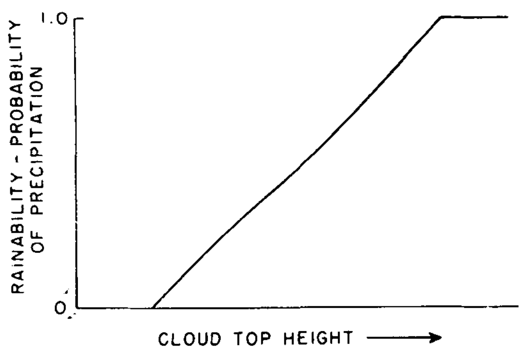

Fig. 1. Schematic representation of the probability of precipitation as a function of the cloud top height.

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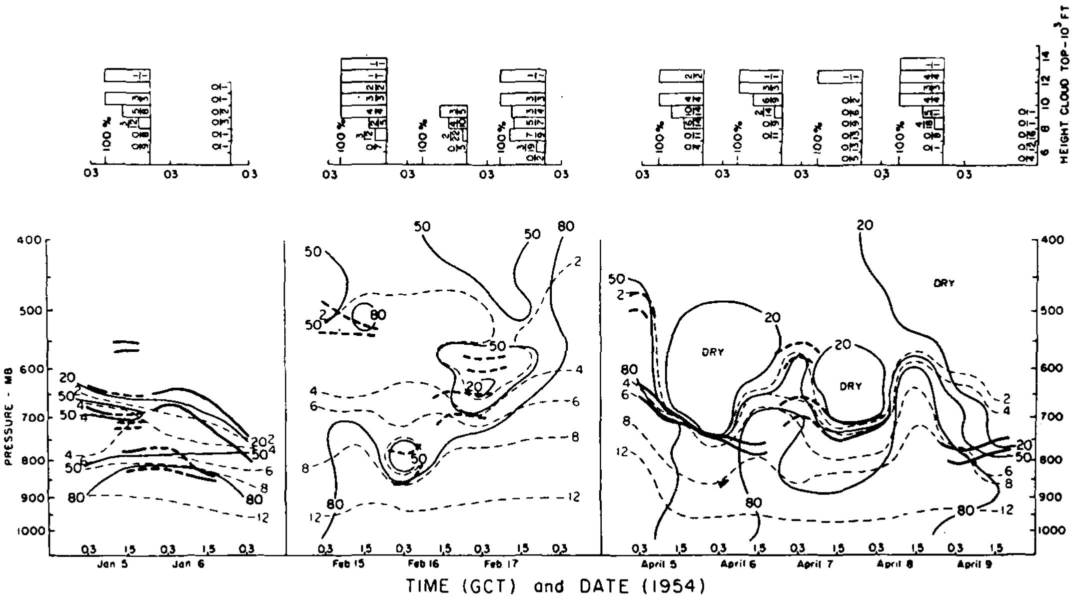

Fig. 2. Histograms of the fractions of clouds within 1000 ft height intervals which contained a precipitation echo (upper part of diagram). Vertical time sections for San Juan, P.R., showing positions of inversions (heavy solid lines), and stable layers (heavy dashed lines), relative humidity (light solid lines), and mixing ratio (light dashed lines).

rainability distribution. The cloud observations collected in the Caribbean area permit an examination of these changes and a study of the medium- and large-scale factors governing them. In the upper part of Fig. 2, histograms have been drawn showing the fraction of oceanic cumuli within certain height intervals which contained precipitation echoes. It can be seen that on January 6, April 7, and April 9, small cumuli did not contain precipitation. Although the number of clouds observed on these days is small, it seems reasonable to conclude that the rainability curve can be considered to be shifted to the right.

3. Environmental influence on precipitation formation

In examining the reasons for the observed day-to-day changes, Byers and Hall (1955) who used the same data presented here, plotted the smallest cloud which contained an echo as a function of the relative humidity at 650 mb and the thickness of the stable layer. They found that, in general, a shallow moist layer and a thick stable layer inhibited precipitation. To examine this relation in more detail, time cross sections showing the humidity distribution and stable layers were drawn for the periods on which cloud data were available for at least two consecutive days, Fig. 2. It can be seen that generally these cross sections support the

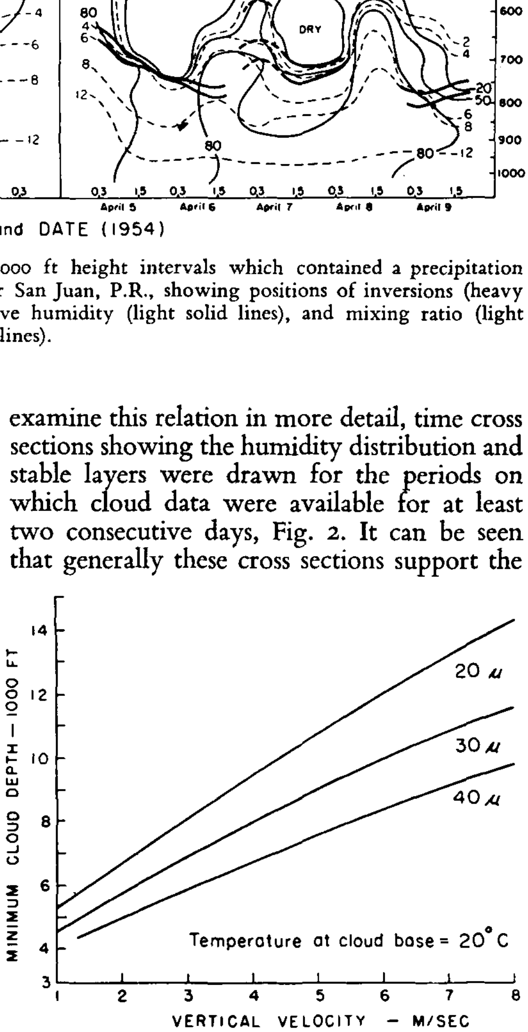

Fig. 3. Depth of cloud needed for the production of precipitation by coalescence as a function of updraft speed for clouds with drops of radii 20, 30 and 40 microns in the cloud base. (From Ludlam, 1951)

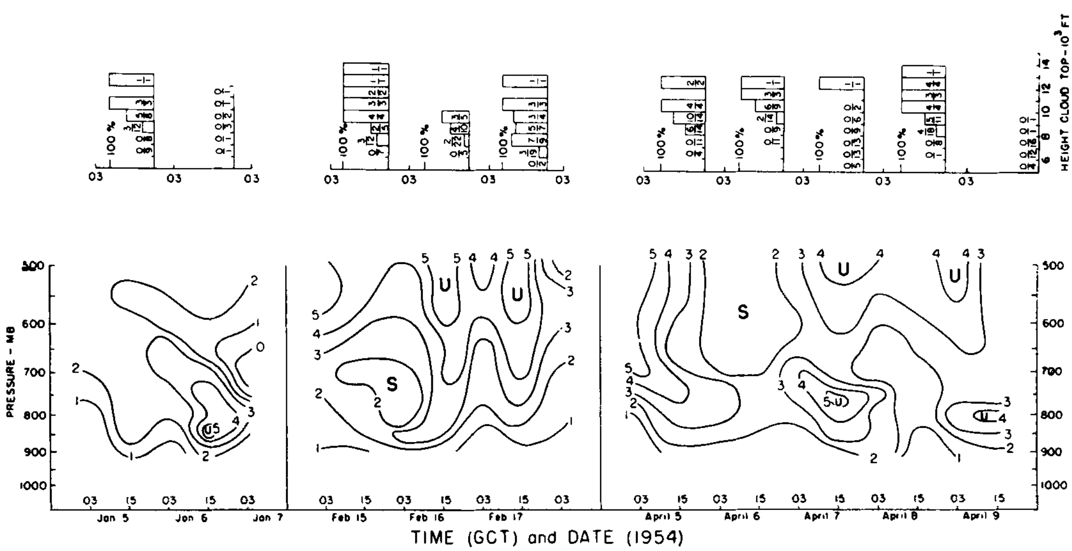

Fig. 4. Vertical time sections for San Juan, P.R., showing isopleths of ΔT, the temperature difference between moist adiabatically rising air and the environment air at the same level. Positive values mean the cloud is warmer than the environment.

conclusions drawn by Byers and Hall; however, there are exceptions. Also, since most of the clouds involved were below about 700 mb, there is some question as to whether the moisture and stable layer differences play the major role in causing the day-to-day variations.

LUDLAM (1951) studied the growth of rain by coalescence and presented the diagram shown in Fig. 3. The curves were calculated on the assumption that cloud bases were at a temperature of 20° C and the liquid water content averaged 2 g/m³. Both values seem reasonable for the cumuli considered here. It should also be recalled that the large concentration of large salt nuclei in this area are sufficient to produce, by condensation, an adequate number of drops in the range 20 to 40 microns radius to lead to precipitation (WOODCOCK, 1953; LODGE, 1955). It is evident that the strength of the updraft plays a major role in determining the depth of cloud needed for precipitation. Unfortunately updraft measurements in these clouds are not available. However, one can make estimates of their maximum values from the parcel-method theory of convection.

In order to calculate vertical velocities, it was assumed that the air moving through the cloud base had an upward speed of 1 m/sec. and was saturated at the temperature of the environment at the same level (2000 feet, 20° C). The parcel was then permitted to rise moist adiabatically. Temperature differences between cloud and environment air were measured from an adiabatic chart and the vertical distribution of vertical velocity was calculated starting from the well-known equation:

$$\frac{dw}{dt} = g\,\frac{(T\,\text{cloud} - T\,\text{environment})}{T\,\text{environment}}$$

The results of this analysis are shown in Figs. 4 and 5. It can be seen that on the three days of low rainability there were centers of instability (large ΔT) below 700 mb. In Fig. 5, these distributions of ΔT are reflected in the vertical velocities. It should be noted that the plotted values of w represent their upper limits because the parcel method neglects entrainment and vertical motions in the environment. Also, the liquid water in the clouds would reduce the vertical velocities. It appears that the maximum velocities are too great by a factor of about five.

When the average velocities in the layer from the cloud base to 700 mb are plotted (center of diagram), it can be seen that maximum values of $\bar{w}$ occurred on each of the three days of low precipitation likelihood. However,

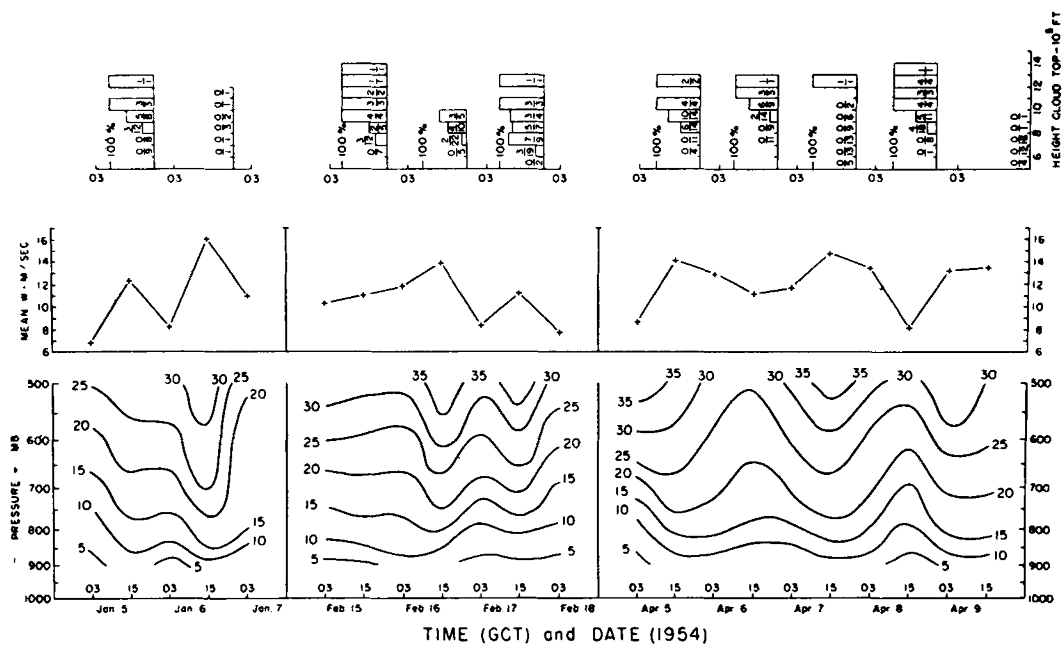

Fig. 5. Vertical time sections showing the distribution of calculated vertical velocity using values of ΔT shown in Fig. 4. Entrainment, environment motions and humidity differences not considered. Assumed velocity at cloud base of 1 m/sec. At center of diagram is a plot of the mean vertical velocity between the cloud base (2000 ft, $T = 20°$ C) and 700 mb.

maxima of w also occurred on several other days. It is therefore necessary to find other parameters to explain why on some days with large $\bar{w}$ small clouds did not contain precipitation while on others (*e. g.*, February 16 or April 5) some of the smaller clouds did contain precipitation.

It has long been recognized that vertical wind shear affects the growth of clouds and precipitation. MALKUS (1952), for example, has studied the action of strong vertical wind shear in inhibiting cloud growth. Also, ACKERMAN (1956) has shown that the ability of a particular tropical cloud to produce precipitation echoes is a function of the vertical wind shear. The vector differences of the wind velocities at 10,000 ft and 2,000 ft were obtained and the magnitudes of the differences were examined for the various days involved. From Fig. 6, it can be seen that the three days of low rainability can be isolated as days on which $\bar{w}$ and the vertical wind shear are high.

The relative effects of wind shear and moisture are shown in Fig. 7. From the displacement of the points representing January 6 and April 7 and 9, it is apparent that the depth of the moist layer is a relevant and important factor in governing the size of oceanic cumulus needed for precipitation.

If one compares the depth of the moist layer and the mean vertical velocities on particular days, it is found that on the three days with the shallowest moist layers, there were high values of the calculated vertical velocities. This result is a reflection of the fact that on these days the lapse rate below 700 mb was very unstable. Thus, those conditions which inhibit the development of rain in small cumulus clouds are a shallow moist layer, strong instability and strong vertical wind shear in the layer from the cloud base to 700 mb.

In view of this discussion, it is evident that the environment within which the clouds develop governs the overall ability of clouds to produce rain, *i.e.*, it governs the shift of the rainability curve. One might suppose that the microphysical properties of the clouds govern the shape of the curve.

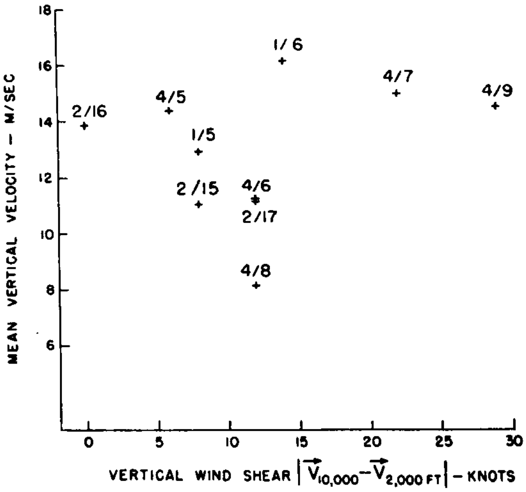

Fig. 6. The mean vertical velocity $\bar{w}$ and the magnitude of the vector difference between the winds at 2000 ft and 10,000 ft.

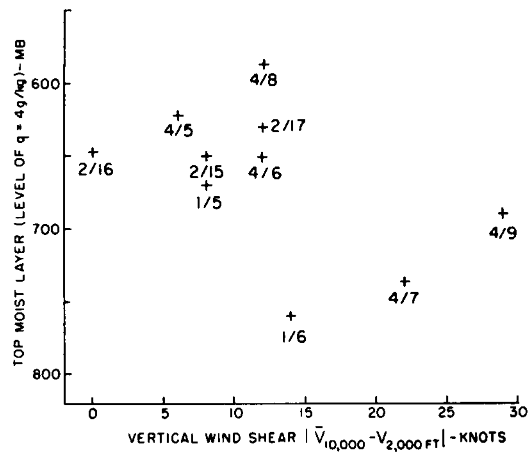

Fig. 7. The pressure level of the isopleth of mixing ratio equal to 4 g/kg and the magnitude of the vector difference between the winds at 2000 ft and 10,000 ft.

4. Large-scale flow pattern in the trades affecting the rainability

It has been shown that on days with large instability and wind shear in the lower 10,000 ft of the tropical atmosphere and a shallow moist layer, only large clouds or no clouds contained precipitation. The relationship between these conditions and the flow pattern over the tropics deserves attention. RIEHL (1954) has reported that in the winter and early spring, polar troughs aloft move into the tropical region and that on the west side of the troughs there is a general diminution of rain activity. Fig. 8 shows a vertical time section drawn for San Juan showing the upper winds.

It is evident that the reduction of rainability

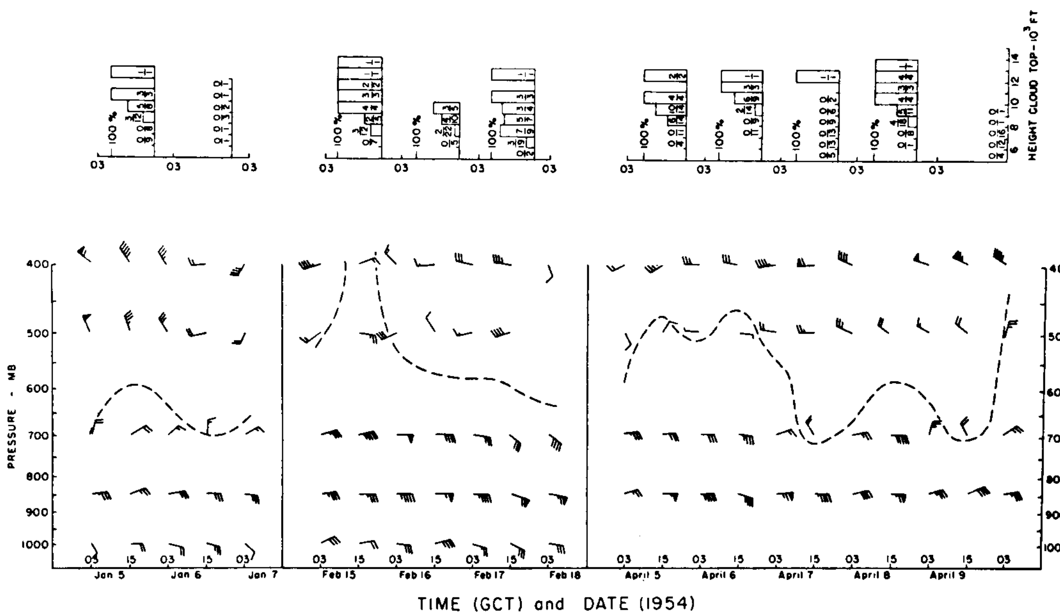

Fig. 8. Vertical time section showing winds aloft. Dashed line separates lower easterlies and upper westerlies.

on January 6, April 7 and 9 can indeed be attributed to the movement of polar troughs over the area involved. On each of the three days the winds at 700 mb and above shifted from the normal easterlies to the north and west. From a comparison of this diagram with Fig. 2, it can be seen that the polar troughs are accompanied by an inversion and a lowering of the moisture isopleths. Riehl has shown that as the air flows through polar troughs the horizontal shear and curvature effects lead to low level divergence and upper level convergence on the west side of the trough. The wind shift leads to an increase of the vertical wind shear and the divergence distribution accounts for a reduction of the depth of the moist layer, and an increase of the strength of the inversion. Also cooling aloft results in an increase of the lapse rate below the inversion leading to greater instability. The combination of these factors, as shown earlier, lead to clouds which are incapable of producing precipitation unless they reach large dimensions. Because of the strong stable layer, dry air aloft and strong vertical wind shear, relatively few clouds will succeed in reaching the necessary heights and thus, relatively few, if any, clouds produce precipitation.

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