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## HIGH LEVEL VERTICAL MOTION IN RELATION TO TROPICAL RAINFALL

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### ABSTRACT

A single-station technique is used to compute vertical velocities over San Juan, P. R., at standard constant pressure levels from 850 to 100 mb. Periods of strong upward motion are observed to occur rather frequently within the layer 400 to 100 mb. and these are discussed in relation to subsequent precipitation patterns.

### INTRODUCTION

During recent years, forecasting techniques in tropical and subtropical latitudes have been vastly improved, largely due to the efforts of Dunn [1], Riehl [2], and others too numerous to mention, who have developed and applied what Palmer [3] calls the perturbation method to low latitude disturbances. The identification and forecasting of the motion of easterly waves, polar troughs, shear lines, and other tropical phenomena often results in satisfactory forecasts of the accompanying weather. But frequently, identifiable changes in the wind, temperature, or pressure fields (including the isallobaric pattern) occur almost simultaneously with the onset of precipitation so that no adequate forecast can be issued.

The present study began as an effort to discover some element that would enable the forecaster to determine at least 24 hours in advance whether or not an approaching disturbance would yield significant precipitation over Puerto Rico. Conversely, it was desired to forecast accurately periods of no precipitation which might be expected to last 2 or more days.

Puerto Rico lies just within the tropical zone, and its climate is a combination of the tropical and subtropical. Showers normally occur on more than 200 days per year, so the usual forecast of partly cloudy with a few scattered showers has a better than even chance of verifying every day of the year. But such a forecast is of little value to the recipient. There are periods of prolonged shower activity which may go on for as long as 2 or 3 days with excessive rainfall amounts being recorded. There are also

periods during which the sky remains almost cloudless and no showers occur for several days. Advance warning of such periods of unusual weather would be of value to the public as well as to agriculture and industry.

Since weather changes, regardless of the latitude, are intimately connected with vertical motion in the atmosphere, an attempt was made to measure this quantity and to correlate its values with subsequent weather patterns.

### METHODS

The single-station technique as developed by Panofsky [4] was used to compute the vertical motion. He derived the relationship

$$\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T + w(\Gamma - \gamma) = 0 \quad (1)$$

where  $T$  is temperature,  $t$  is time,  $\mathbf{V}$  is horizontal velocity,  $\nabla$  is the horizontal vector differential operator,  $w$  is the vertical velocity,  $\Gamma$  is the dry adiabatic lapse rate, and  $\gamma$  the prevailing lapse rate (the average between two successive constant pressure surfaces).  $\frac{\partial T}{\partial t}$  was evaluated by determining the 24-hour local temperature changes at each level. A 12-hour change would have been better, but the diurnal variations were so large that obviously incorrect values resulted, and not enough data were available to establish the normal diurnal changes. However, it would seem desirable to determine such normals if further research along this line is pursued. To find  $\mathbf{V} \cdot \nabla T$  from the winds aloft (radio winds are available at

San Juan so that the computations are not restricted to good weather) use was made of the relationship (see Panofsky [5])

$$\mathbf{V} \cdot \nabla T = \frac{2fT}{g} \frac{\partial A}{\partial z}, \quad (2)$$

where  $f$  is the Coriolis parameter,  $g$  is the acceleration of gravity,  $\partial A$  is the area enclosed by the vectors  $\mathbf{V}$ ,  $\mathbf{V} + d\mathbf{V}$  and  $d\mathbf{V}$  on a hodograph of observed winds, and  $z$  is the vertical coordinate. The right side of (2) was evaluated by taking the wind shear between adjacent levels, i. e., 1000–850 mb., 850–700, 700–500, etc. No corrections were made for the variations of the heights of the constant pressure surface when  $\frac{\partial T}{\partial t}$  was determined. However, these variations were usually small, in most cases less than 25 meters, and so only small errors were introduced. Application of this technique to more northerly latitudes where the changes in the constant pressure heights are significant would necessitate the correction of the local temperature changes for this factor.

As pointed out by Panofsky, the above method has two sources of inherent error. First, nonadiabatic processes are at work in the atmosphere, and these result in some errors in the computed vertical motion, particularly in the lower levels after precipitation starts. Second, the theory of advection from the hodograph is based on the assumption of geostrophic wind flow. This is a more serious objection than the first when the method is applied to a southerly latitude such as Puerto Rico, where it is usually assumed that the geostrophic relationship frequently does not apply. For this latter reason, the present study was undertaken with serious misgivings, and the expectations of failure were high. Actually, there were cases in which apparently supergradient winds, strong anticyclonic curvature, and cross-contour flow resulted in some computed values of vertical motion which seemed to be incorrect, but on the whole results were better than expected. The correlation between the vertical velocities and the weather changes was generally satisfactory, although the values were usually smaller, level for level, than those computed by Miller [6] and others at New York University for temperate latitudes.

The value of the Coriolis parameter at 20° N. latitude is  $0.497 \times 10^{-4} \text{ sec.}^{-1}$ , or about one-half that for a latitude of 43°, and this value is not a negligible factor by any means. It appears possible that the deviation from the geostrophic balance is less at the latitude of Puerto Rico than is normally supposed. The results of the present study at a low latitude do not always agree with those made in the middle latitudes, a possibility suggested by Panofsky [7], but whether this apparent difference is real or a fault of the method of computation is questionable at this time.

## RESULTS

Vertical velocities were computed at seven isobaric levels twice daily for the periods November 20–December 10, 1951; December 27, 1951–January 6, 1952; and Janu-

ary 27–February 14, 1952. Discussion here will be limited to the winter months, when the level of the westerly winds over Puerto Rico is relatively low. Some studies were carried out during the summer season, under conditions of predominantly deep easterly flow, but the results will not be treated at this time.

The computed vertical motions in the lower levels (850–500 mb.) were in most cases in fairly good agreement with the observed weather. That is, rising air was usually associated with increase in cloudiness, precipitation, and a steepening of the lapse rate, while descending air was accompanied by the opposite effects. However, the values of the vertical velocities were small, in most cases less than 1.0 cm. sec.<sup>-1</sup>. The absolute average at the 700-mb. level was 0.4 cm. sec.<sup>-1</sup> for 117 cases. Miller [6] reported a mean absolute value of 1.4 cm. sec.<sup>-1</sup> at 700 mb., this value being based on 455 cases at selected points within the United States, ranging from 35° to 45° N. latitude. It is to be expected that the magnitude of the vertical motion in the Tropics or subtropics would be somewhat less than that in the middle latitudes. In addition, Miller's results were computed for 12-hour periods, while the present study is based on 24-hour intervals.

Much larger values were observed to occur in the upper layers, 400 mb. and above. The maximum was usually reached at 200 mb., where the absolute average was 3.0 cm. sec.<sup>-1</sup> for 112 cases. The remainder of this discussion will be confined to the high level values.

Rather large positive values of vertical velocity occurred frequently within the layer 400–100 mb. In some cases, the vertical motion was damped out after a single appearance, but the usual pattern was for the positive values to persist for several days at a time. Whenever such continuity did occur, moderate to heavy rainfall was usually observed at San Juan within 60 hours or less after the initial appearance of the upward motion in the higher levels.

In an attempt to use these upper level periods of maximum vertical velocity as a forecast tool, it was first necessary to separate the minor fluctuations from the significant centers. The following rule was therefore adopted. No value was considered significant unless it was, first, at least 1.5 cm. sec.<sup>-1</sup>, and second, observed to occur twice in succession, but not necessarily at the same level, since there was a marked tendency for the levels of maximum vertical velocity to rise and fall. However, the two successive positive values were required to be connected, i. e. occur at adjacent levels (or at the same level if the center did not change elevation). For example, a positive value might be observed at 200 mb. and 12 hours later lower to 300 mb., a fairly frequent occurrence. There were also a few cases under which the level of maximum positive vertical motion rose with time.

After the relationship between upward motion at high levels and later shower periods became evident, it was necessary to define "significant precipitation." As previously stated, showers occur approximately 2 days out of 3 in the vicinity of San Juan, with the predominating

fall being light and of short duration. For the purpose of this study it was desired to differentiate between the "normal" and the unusual rainfall regimes, and consequently "significant rainfall" was arbitrarily defined as at least 0.50 inch in 24 hours, with the shower period lasting at least 12 hours, i. e. with rainfall being measured in at least two consecutive 6-hour periods. The average rainfall for San Juan is about 55 inches per year, so the value of 0.50 inch per day is over three times the normal daily rainfall.

Table 1 shows a summary of the cases meeting the above stipulations. Ten cases were observed. Nine of the ten cases were accompanied by significant rainfall. In the other case, that of November 25, the positive values of the vertical velocity were restricted to the 300-mb. level only, with large negative values being present at both 400 and 200 mb. throughout. The case was atypical, and appears to be an instance in which the method of computing the vertical velocities failed. The situation was marked by strong winds, apparently supergradient, and decided veering from the 400-mb. to the 300-mb. level. This resulted in apparent positive values, but they were possibly nonexistent.

In 8 of the 9 cases accompanied by precipitation, there was an appreciable time lag after the second positive value of 1.5 cm. sec.<sup>-1</sup> or more was observed before the rain began. In 6 of the 8 cases this time lag was 21 to 57 hours, and in the other 2 it was only 9 hours. The average lag was 30 hours; the value of such a time factor as a forecast tool is obvious.

TABLE 1.—Relationship between high level vertical velocity patterns and subsequent rainfall at San Juan, P. R., November-February 1951-52

Date and time 2d positive value of $w \geq 1.5$ cm/sec occurred	Level of 1st occurrence of positive value of $w \geq 1.5$ cm/sec	Maximum value of $w$ observed during period	6-hour period of beginning of significant rainfall	Time lag rain began after positive value of $w$ observed 2d time	Duration of positive values of $w$ at level 100-400 mb ( $w \geq 1.5$ cm/sec)	Duration of significant rainfall	Total rain all during period
GMT	mb.	cm/sec	GMT	hr.	hr.	hr.	in.
1500 Nov. 20	200	5.4	0600 Nov. 22	39	84	72	3.05
1500 Nov. 25	300	4.1	Nil	-----	36	Nil	Nil
0300 Dec. 1	100	4.1	1200 Dec. 3	57	48	24	4.90
0300 Dec. 6	300	5.3	1200 Dec. 6	9	60	48	3.39
0300 Jan. 5	400	2.8	0000 Jan. 6	21	24	12	.91
1500 Jan. 7	200	4.2	0600 Jan. 9	39	84	18	1.35
0300 Jan. 12	400	3.1	0000 Jan. 12	0	24	18	.67
1500 Jan. 27	100	4.6	1800 Jan. 29	51	60	12	.84
0300 Feb. 9	300	7.4	0600 Feb. 11	51	60	24	1.83
1500 Feb. 12	300	1.6	0000 Feb. 13	9	24	36	1.86

In only one case (January 12) was rainfall observed to occur without there first having been present upward motion at some high level over the station. A single positive value was present at 400 mb. before rain began, but such occurrences cannot be considered significant until they are observed at least twice in succession. Consequently the appearance of the center of maximum positive vertical velocity over the station and the onset of precipitation must be considered approximately simultaneous.

It should also be noted that there were no cases of significant rainfall which failed either to follow closely or occur simultaneously with a period of high level upward motion.

Figures 1-3 show some typical examples. They are time cross sections over San Juan, depicting isopleths of vertical motion at intervals of 1 cm. sec.<sup>-1</sup>, winds aloft at standard isobaric surfaces, and the rainfall measured at the 6-hourly observations.

While these figures show computations of vertical velocity only, levels of divergence and convergence may be identified from the vertical changes in the vertical motion patterns. For example, the centers of maximum positive vertical velocity are levels of zero divergence; below this level, where the vertical velocity is increasing upward, horizontal velocity convergence is taking place. Above this level of zero divergence, the vertical velocity is decreasing upward, and horizontal velocity divergence is occurring. The negative centers are likewise levels of zero divergence, with convergence above and divergence below these centers. However, the method of computation in neither case is sufficiently accurate to locate precisely, or even closely, the actual level of nondivergence.

In figure 1, the initial positive value of vertical velocity was observed at 0300 GMT, November 20, 12 hours before the time of beginning of the cross section. The value was 3.9 cm. sec.<sup>-1</sup> and it occurred at 200 mb. At the time of the second appearance of positive values, the maximum had lowered to 300 mb. where it was observed to be 2.2 cm. sec.<sup>-1</sup>. Twelve hours later the maximum was again at 200 mb. where it remained until 0300 GMT, November 24, when negative values were present at this level. Significant rainfall began about 0600 GMT, November 22, (0.28 inch was measured at 1230 GMT on that date), about 39 hours after the time the maximum was observed for the second time. Showers lasted for about 72 hours, with a total accumulation of 3.05 inches.

Figure 2 reveals a similar pattern, but in this case the initial upward motion is found at 100 mb., and there is a marked tendency for the level of maximum positive vertical velocity to lower with the passage of time. This feature is also noticeable to a lesser degree in figures 1 and 3, and it should be mentioned here that this seemed to be the usual pattern. As long as the center of maximum positive vertical velocity remained at a constant high level, precipitation did not occur. But as soon as the center lowered, or small offshoots from the high level

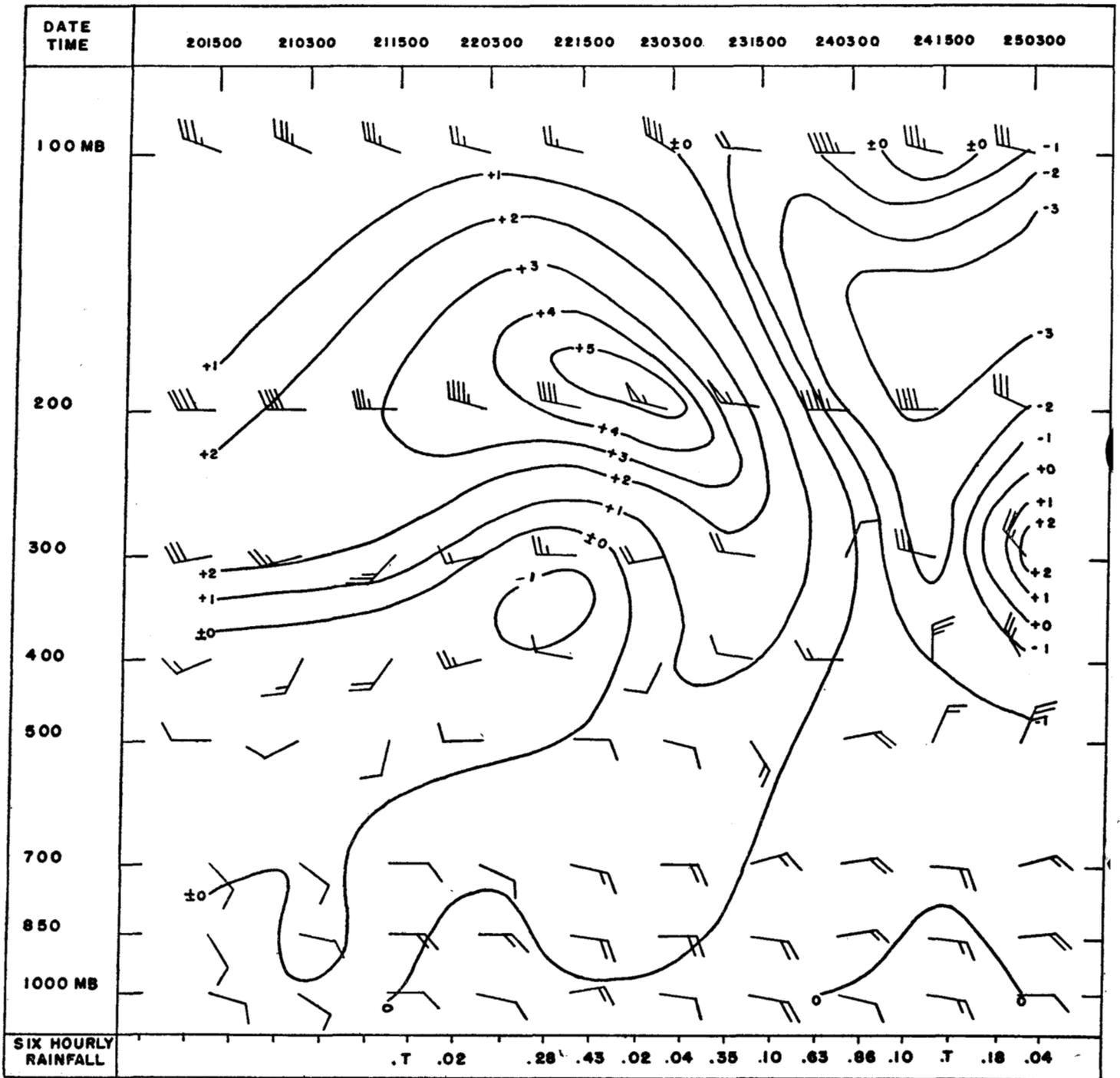


FIGURE 1.—Time cross section over San Juan, Puerto Rico, 1500 GMT November 20 to 0300 GMT November 25, 1951. Isopleths of vertical motion are indicated in cm. sec.<sup>-1</sup>. Rainfall amounts are in inches, and wind speeds in knots.

center extended into the lower levels, early rainfall was in prospect.

In figure 3, the rising air is first in evidence at 300 mb., and throughout the history of this case a strong divergent flow persisted immediately above the upward motion. The fact that the upward motion appears at a lower level at this time of year (February 8-14) than it did earlier in the winter is perhaps a reflection of the well known tendency for the dominant features of the general circulation to appear at lower levels during the winter season.

Another interesting feature of this cross section is the reappearance of a small, secondary center of positive vertical velocity at 0300 GMT, February 12. This is almost immediately followed by heavy rain on the 13th. Perhaps during a rainy regime, less violent activity is required to cause an already existing disturbance to regenerate than would normally be required.

A comparison with the work of Graves [8] is interesting. He correlated the variations in the heights of a secondary tropopause over San Juan with the incidence of strong

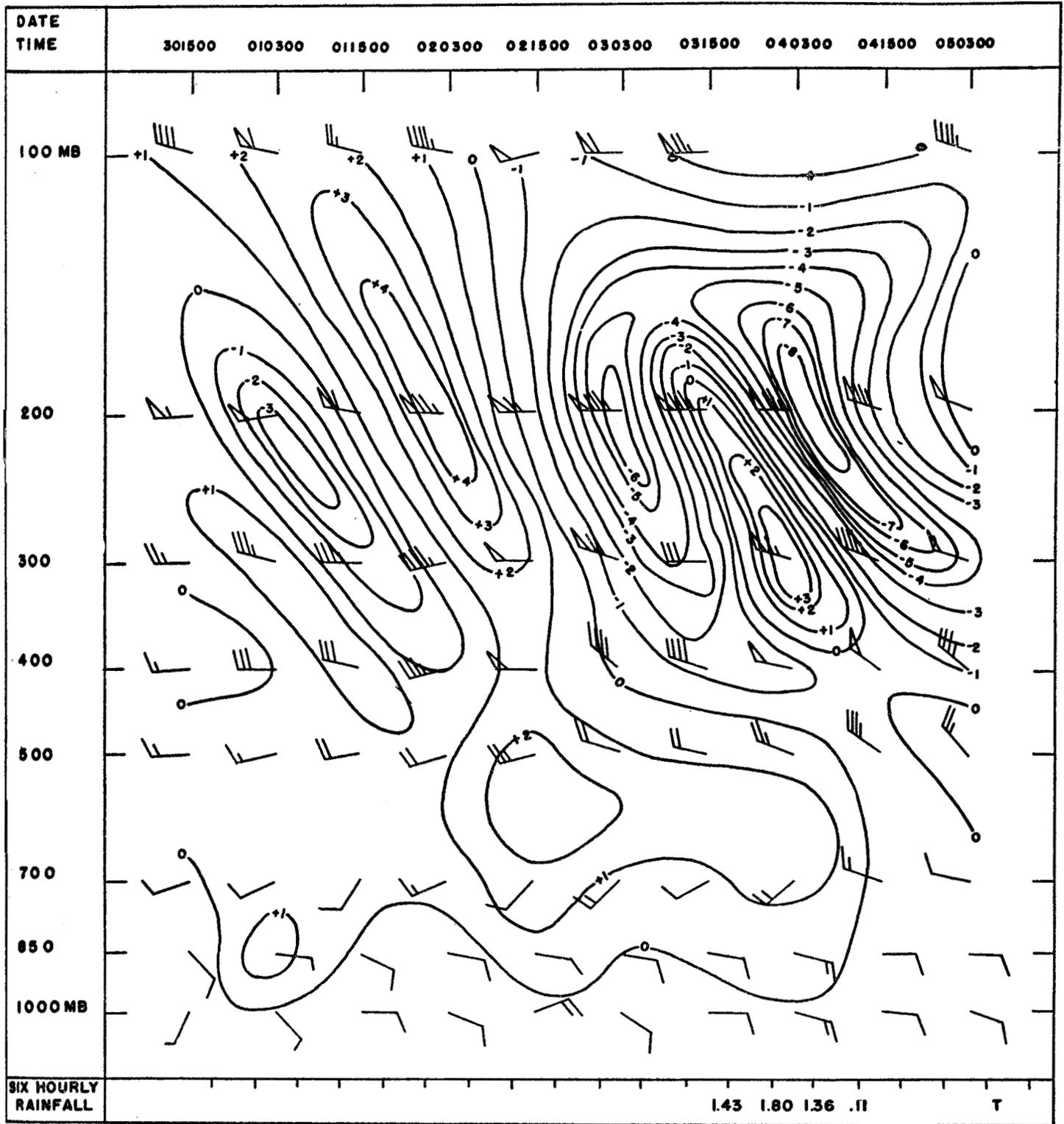


FIGURE 2.—Time cross section over San Juan, Puerto Rico, 1500 GMT November 30 to 0300 GMT December 5, 1951. Isopleths of vertical velocity are indicated in cm. sec.<sup>-1</sup>. Rainfall amounts are in inches and wind speeds in knots.

convective activity over Puerto Rico. He found that the existence of a rising secondary indicated that severe convection was unlikely within 48 hours, and that a lowering secondary favored its occurrence.

At first glance, it might appear that the present study contradicts Graves' results, since rising air in the level of the secondary tropopause (300–150 mb.) could be expected

to cause the tropopause to lift. However, as Miller [6] pointed out, two factors, vertical velocity and advection combine to change the height of the tropopause, and the signs of the vertical motion and the change in the height of the tropopause are not necessarily the same. Figure 3 shows a case in which strongly descending air at 200 mb. is superimposed on rising air at 300 mb. It is suggested that

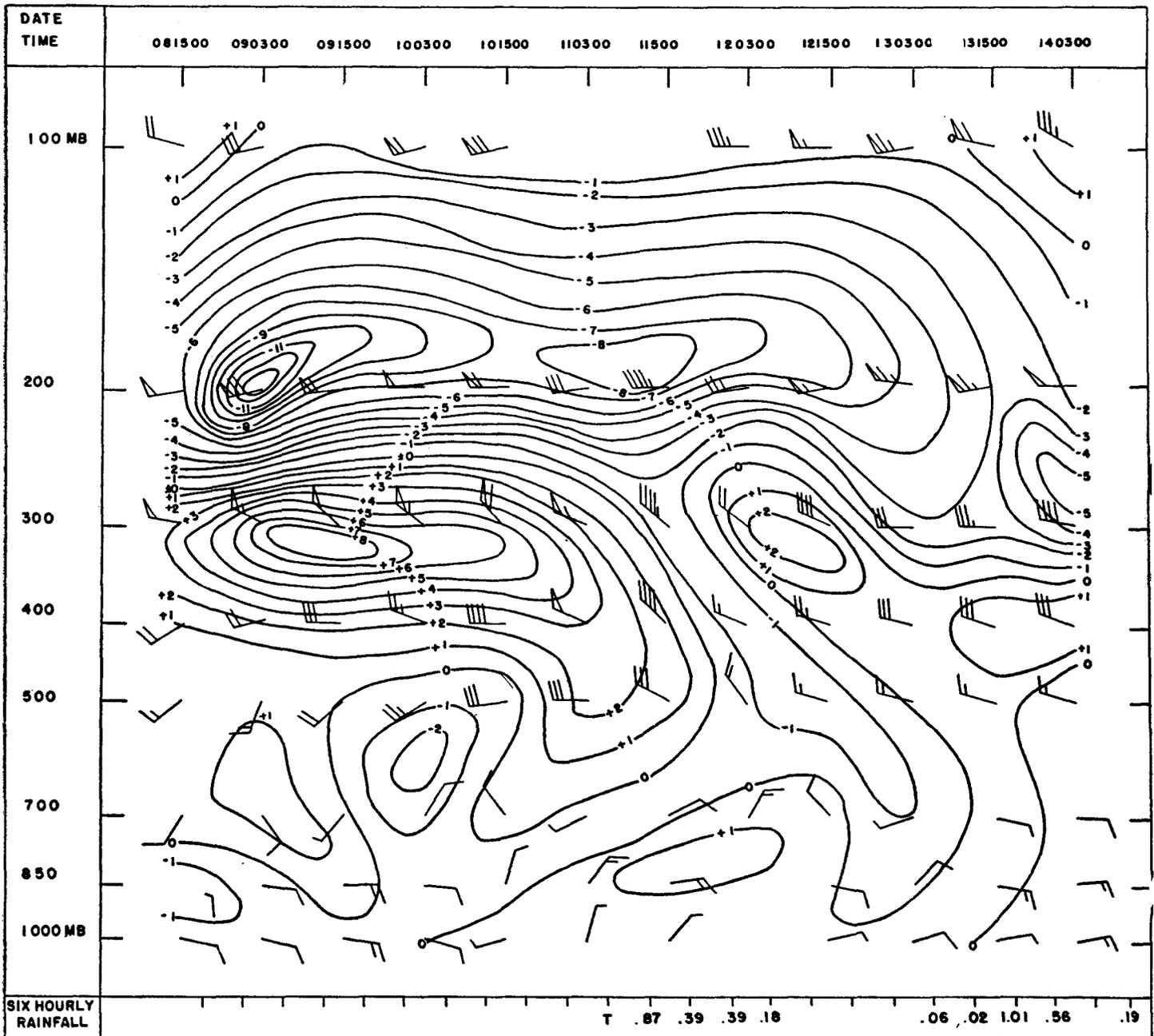


FIGURE 3.—Time cross section over San Juan, Puerto Rico, 1500 GMT February 8 to 0300 GMT February 14, 1952. Isopleths of vertical motion are indicated in cm. sec.<sup>-1</sup>. Rainfall amounts are in inches and wind speeds in knots.

this is a possible mechanism for the production and maintenance of the secondary tropopause as observed by Graves, by steepening the lapse rate from below and stabilizing it from above. It seems logical that the break in the lapse rate thus produced (identified by Graves as a secondary tropopause) might be expected to lower whenever the center of maximum positive vertical velocity begins to migrate to a lower level, which as stated above was observed to occur just before precipitation began.

Finally, an effort was made to discover some element highly correlated with vertical motion at the latitude of Puerto Rico. Miller [6], for example, found a good correlation between the vertical motion in the temperate latitudes and the meridional flow, but this relationship did

not appear to exist in the Tropics. Vertical motion computations as carried out by the method used in this investigation are very time consuming, and if some other element could be used instead, the value of vertical motion as a forecast tool would be increased.

Three linear correlations were computed, using the vertical motion at 200 mb. and (1) the 24-hour thickness change for the layer 300 to 200 mb., (2) the 24-hour temperature changes at 200 mb., and (3) the wind shear term for the 300- to 200-mb. layer. The value of the first was negligible, 0.05. In interpreting the other two correlation coefficients it should be remembered that both the 24-hour temperature change and the wind shear were used in computing the vertical motions with which they

are correlated. The only thing they reveal is the relative importance of the linear contribution of the two terms used in the computations. The correlation between vertical velocity and 24-hour temperature changes was  $-0.03$ , and that for vertical velocity and wind shear was  $-0.96$ . This shows that the wind shear term was the predominant factor in determining the sign and magnitude of the vertical motion. This was obvious throughout the course of the investigation. The use of wind shear alone would give values almost as good as the relationship actually used. However, this would not greatly simplify the method, since the 24-hour temperature changes are relatively simple to obtain. Also, it should be pointed out that the use of the wind shear term alone would probably not prove satisfactory in computing vertical velocity in temperate latitudes, due to stronger temperature gradients and the resulting greater temperature advection.

#### SUMMARY

The appearance of strong upward motion within the layer 400 to 100 mb. indicated that moderate to heavy rainfall was likely within 60 hours, the average time being 30 hours. The absence of such a period of rising air indicated that above normal rainfall was improbable. This is suggested as a possible forecast tool in tropical and subtropical latitudes. The equation of continuity requires that upward motion in the region of the upper troposphere be compensated by low level horizontal convergence, and it is probable that it is this convergence which causes the prolonged shower activity found to be associated with the periods of positive vertical motion in the higher levels. Figures 1-3 actually show in some cases this low level convergence and their failure to show it more definitely is probably due to shortcomings in the method used to compute the vertical motion. The presence of the upper level ascending motion could be detected in advance whenever associated with a disturbance approaching Puerto Rico from the west. These were polar troughs, shear lines, and the rare cold front which penetrated to this latitude. Such ascending motion could not be detected in the case of disturbances with deep easterly flow, viz easterly waves and related phenomena.

A mechanism for the production and maintenance of

the secondary tropopause in the Tropics is suggested. It consists of the superimposition of a strongly divergent flow on a layer of air undergoing horizontal convergence, which steepens the lapse rate from below and stabilizes it from above. This process appears to be a frequent occurrence in the Tropics.

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