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PRECIPITATION DEPENDENCE ON SYNOPTIC-SCALE CONDITIONS AND CLOUD SEEDING

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RESUMEN

Se analizó, mediante el uso de radar, la precipitación sobre el sur de la Florida para determinar su dependencia de las condiciones sinópticas y de la siembra de nubes. Los parámetros sinópticos que se usan son: el flujo predominante, la humedad, la estabilidad y el cizallamiento vertical del viento. Los resultados indican que la variación en las condiciones sinópticas es mucho más importante que la siembra múltiple de nubes en la determinación de la precipitación. Estos resultados también indican que aquellos experimentos de siembra de nubes en la Florida, que no toman en cuenta el efecto de las condiciones sinópticas, pueden conducir a conclusiones equivocadas.

ABSTRACT

Precipitation over South Florida, as indicated by radar, was analyzed in order to determine its dependence on synoptic-scale conditions and cloud seeding. The synoptic-scale parameters which are used are the prevailing flow, the humidity, the stability and the vertical wind shear. We found that the variation of synoptic-scale conditions is, by far, much more important than multiple cloud seeding in determining precipitation. This finding indicates that cloud seeding experiments in Florida which do not take into account the effect of the varying synoptic conditions, can lead to misleading conclusions.

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INTRODUCTION

This paper describes a study of the dependence of precipitation on synoptic scale conditions and multiple cloud seeding over South Florida. Our interest in this subject arose because, while investigating convergence-precipitation patterns for South Florida, we noted that the area covered by radar echoes was less on the days of multiple cloud seeding than on the control (unseeded) days. Multiple cloud seeding days are days during which about 10 to 20 clouds were seeded. Seeding was conducted by the NOAA Experimental Meteorology Laboratory. This was done by dropping repeatedly into the clouds silver iodide pyrotechnics from an aircraft flying slightly above the 20 000 ft. level. Control days are days without seeding; they are used as a standard for testing the seeding effect on seeded days. This implies the assumption that control days meet similar seeding conditions (determined by a numerical model) as the days with seeding.

In this paper we will use the percent of a selected area which is covered by radar echoes as an indication of precipitation or rainfall. For convenience, the term *rainfall* will be used hereafter interchangeably with the term percent of the selected area which is covered by radar echoes. The area selected (Fig. 1) is bounded by the polygon whose vertices are Miami (MIA)-Ft. Myers (FMY)-Vero Beach (VRB)-West Palm Beach (PBI)-Miami. The area of cloud seeding experiments by the NOAA Experimental Meteorology Laboratory is bounded by the dashed lines in Figure 1. Although the area of cloud seeding and the area of our rainfall studies do not coincide exactly, they overlap to a great extent.

Rainfall in the area of our study is estimated from the Miami WSR-57 radar, a 10-cm wavelength radar which normally operated at 0.5° antenna elevation angle during the period July-August 1973. On the basis of these estimates, the mean diurnal variation of rainfall for seeded and control days in July-August 1973 is constructed and shown in Figure 2. This figure shows clearly that much more rain occurred on control days than on seeded days. What is the explanation for the fact that less rainfall occurs on seeded days than on control days? There are two possible explanations. First, cloud seeding reduces rainfall. Second, the reduction in rainfall is merely due to differences in the synoptic conditions (humidity, prevailing wind, stability, wind shear) for both seeded and control days. These differences are indicated in Table 1. The differences are based upon the Miami soundings which are taken as representative of synoptic-scale conditions over the South Florida area. The large variability in the synoptic-scale conditions (associated with tropical and temperate-latitude weather systems) as indicated by Table 1 appears to justify the second explanation. This hypothesis is examined by assessing the relative importance of synoptic conditions and cloud seeding in controlling rainfall. The assessment is done by analyzing rainfall as a function of the varying synoptic conditions throughout the period July-August 1973.

RAINFALL AS A FUNCTION OF SYNOPTIC-SCALE CONDITIONS

The dependence of rainfall on the synoptic-scale conditions will be discussed in subsequent paragraphs. The synoptic-scale conditions will be specified in terms of the following parameters: a) prevailing flow, b) humidity, c) stability and d) vertical wind shear.

a) *Prevailing flow*

According to a previous study (Frank, Moore and Fisher, 1967), the prevailing flow has an important effect in determining precipitation patterns in Florida. This is confirmed by the graph in Figure 3. The graph illustrates the mean diurnal variation of rainfall for the easterly and the westerly regimes (a composite of 49 days) and for the N-S flow regime (a composite of 9 cases). The larger rainfall for the N-S flow regime is presumably due to more heating associated with the longer trajectories over heated land that for the easterly and westerly regimes. The larger rainfall under the N-S flow regime, which is parallel to the Florida peninsula, agrees with results obtained both theoretically and observationally by Bhumralkar (1973) in his study over the Grand Bahama Island.

For our purpose, the prevailing wind is defined as the averaged wind for the layer 1000-600 mb; this averaged wind is computed from the Miami morning soundings. The rainfall is defined by the maximum percent area for each day covered by radar echoes. A polar diagram is a convenient diagram for showing the relationship of the rainfall with the prevailing wind. For each day in July-August 1973, the rainfall is plotted at the end of the vector which represents the prevailing wind. Rainfall values are then smoothed by averaging, using overlapping sectors (40°-wind angle and 10-knot radial interval). This procedure gives the rainfall field shown in Figure 4. Note that the largest rainfall values are found along the N-S direction; the smallest values are found along the E-W direction. Note, in addition, that the larger the wind speed the smaller the rainfall.

b) *Humidity*

It is expected that a moist atmosphere is favorable for the occurrence of precipitation (see, e.g. Gentry, 1950). As a measure of moisture we use the mean mixing ratio from the Miami morning soundings. This is the average between the 1000 mb and the 600 mb levels. The importance of the humidity effect is illustrated by Figure 5 (top) which shows the mean diurnal variation of rainfall for two mean humidity categories. It may be seen that the larger the humidity, the larger the rainfall. The graph at the bottom of Figure 5 is a scatter diagram of mean humidity vs. the maximum rainfall for each day in July-August 1973. This graph shows also a positive correlation between mean humidity and maximum rainfall.

c) *Stability*

It is generally accepted that an unstable thermal stratification favors precipitation occurrence. In our study, the stability is specified in terms of the Showalter Index (S.I.) obtained from the Miami morning soundings. This index is defined by the temperature difference (in degress Celsius) between the observed temperature at 500 mb and the temperature which would result after lifting an air-parcel (dry adiabatically until condensation and the moist adiabatically) from the 850 mb level to the 500 mb level. The dependence of rainfall on stability is shown in Figure 6 (top). This dependence indicates that the less stable the conditions the larger the rainfall and viceversa. The bottom graph in Figure 6 is a scatter diagram of the stability vs. the maximum rainfall for each day in July-August 1973. This latter graph also indicates a negative correlation between stability and maximum rainfall.

d) *Vertical wind shear*

It has been found that a large vertical wind shear favors the formation of thunderstorms and related disturbances in middle latitudes. We have, therefore, attempted to determine the effect of wind shear on rainfall in Florida. As shown by the graphs in Figure 7, we found no correlation between the vertical wind shear (850-200 mb) and maximum rainfall.

e) *Combined effect of stability, humidity and prevailing flow*

So far, we have considered only the separate effects of the different meteorological parameters. In the actual atmosphere, all these effects are simultaneously present. Therefore, it is necessary to consider the combined effect of these parameters. The method of combining the simultaneous influence of the stability, humidity and prevailing wind is accomplished by means of the diagrams shown in Figure 8. In these diagrams, the maximum rainfall is expressed in terms of two Cartesian coordinates (stability and humidity) and one *implicit* coordinate (direction of the prevailing flow). In constructing these diagrams, the maximum rainfall for each day is entered at the location whose coordinates are the stability and the humidity for the day, if and only if the direction of the prevailing wind lies within prescribed sectors. The sectors which are chosen for the diagrams at the top and at the bottom of Figure 8 are defined by a 30° angle on either side of the lines 080°-260° and 140°-320°, respectively. These sectors are selected in order to include the prevailing wind direction for most seeded and control days in July-August 1973. Maximum rainfall values are then smoothed by an averaging procedure over overlapping squares (1 g/kg interval for humidity and 2°C interval for the Showalter Index). This averaging procedure generates the diagrams in Figure 8. The effect of wind speed is not incorporated in these rainfall fields. It is, therefore, necessary to modify the rainfall specification from the diagrams in Figure 8 by applying a correction which is obtained from Figure 9. In this figure we have plotted the maximum rainfall vs. the wind speed along the lines bisecting the sectors in Figure 8. This correction corresponds to deviations from 9 kt, which is the mean speed for the days that are entered on each diagram in Figure 8. The correction is positive for cases of wind speed less than 9 kt, and negative otherwise.

It should be noted that in constructing Figures 8 and 9 both seeded days (7) and unseeded days (55) in July-August 1973 are used. Ideally, these figures should be constructed only with data on unseeded days. However, the inclusion of the small number of seeded days does not affect significantly the content of the diagrams.

RAINFALL RESULTS

The motivation for preparing the diagrams in Figures 8 and 9 is to assess the relative importance of synoptic-scale conditions and cloud seeding in controlling rainfall. This assessment is done with the aid of a set of control and seeded days in July-August 1973. Because no seeding was done on control days, the rainfall for these days should agree closely, in the mean, with what is expected from the diagrams in Section 2, Item e). On the other hand, the cloud seeding effect, if present, should produce a departure in the actually observed rainfall (for seeded days) with respect to the rainfall expected from the diagrams. As a first step in obtaining these departures, we have located on the diagrams in Figure 8 points which correspond to the synoptic conditions for each seeded day; beside the points the actually observed rainfall is indicated. The location of each point on the diagrams enables us to determine the expected rainfall by interpolation. This expected rainfall is shown in column 2, Table 2. The expected rainfall still does not incorporate the effect of wind speed. Therefore, a correction due to wind speed is estimated from Figure 9 and then applied to column 2 to produce the corrected expected rainfall in column 3. The last column gives the difference between the actually observed rainfall and the corrected expected rainfall. This column gives a measure of the effectiveness of the seeding. It can be seen that the effect is, in the mean, small. The negative result indicates that multiple cloud seeding appears to decrease the area of precipitation.

The same procedures were applied to the control days and the results are shown in the lower half of Table 2. In the mean, the difference between actually observed rainfall and the corrected expected rainfall is nearly zero. This is to be expected since cloud seeding was not done on control days.

The results above indicate that the variation in synoptic-scale conditions is, by far, much more important than cloud seeding in determining rainfall for the seeded and control days in July-August 1973. In order to confirm these results, we have undertaken the same type of analysis, using another set of seeded and control days in 1970-1971. This analysis uses also the diagrams in Figures 8 and 9. The synoptic conditions for the days in 1970-1971 are summarized in Table 3. The results of the analysis for these days are shown in Table 4. Again, it may be seen that multiple cloud seeding does not increase rainfall in the mean. Corresponding difference (in the mean) between actually observed and corrected expected rainfall for the 1970-1971 control days is the same as that of the seeded days.

RAIN VOLUME ANALYSIS

So far, our study has used the maximum area covered by radar echoes as a quantity related to precipitation. A more precise indicator of the precipitation amount is the rain volume as measured by radar. Therefore, we have attempted to establish a relationship between the maximum area covered by radar echoes and the volume. The volume is derived from a time integration of the echo contour area and an appropriate Z-R relationship.

Figure 10 is a scatter diagram which shows the rain volume for seeded and control days in July-August 1973 in the abscissa against the corresponding maximum area covered by radar echoes in the ordinate. The maximum area covered by radar echoes is taken from column 1, Table 2. The rain volumes are obtained from graphs published by Woodley *et al.* (1974); they are calculated for the area limited by the dashed lines in Figure 1 and for the six-hour interval after the starting time of the real or simulated seeding operation on seeded and control days. These rain volumes are derived by radar, after adjustment for raingauge measurements at the ground. The rain volumes which are used are those inferred directly from radar films.

Figure 10 shows that, in general, there is a good correlation between the rain volume and the maximum area covered by radar echoes. A line of best fit is drawn by eye in the figure; this line allows us to transform the corrected expected rainfall (max echo % area) from column 3, Table 2 into corrected expected rain volume which is the rain volume to be expected under the prevailing synoptic conditions. Actually observed rain volumes (from Woodley *et al.*, 1974) and corrected expected rain volumes for seeded and control days in July-August 1973 are presented in Table 5. The difference between actually observed and corrected expected rain volumes is, in the mean, very small for both seeded and control days. This indicates that the rain volume is basically determined by synoptic-scale conditions. The effect of multiple cloud seeding shows to be negligible and, in fact, no increase in rain volume due to cloud seeding is detected.

The set of seed and control days in 1970-1971 is also studied following the same procedure described in the preceding paragraphs. Figure 11 is based upon rain volume information for the 1970-1971 cases (as given by Simpson *et al.*, 1973) and maximum area covered by radar echoes from column 1, Table 4. Note that, for the 1970-1971 set, there is also a good correlation between the rain volume and the maximum area covered by radar echoes. The line of best fit in Figure 11 allows us to derive corrected expected rain volumes from the corrected expected rainfall in column 3, Table 4. Actually observed rain volumes (after Simpson *et al.*, 1973) and corrected expected rain volumes for the 1970-1971 set are presented in Table 6. The difference between actually observed and corrected expected rain volumes is again small, in the mean, for both seeded and control days. Thus, the 1970-1971 set gives additional evidence of the fact that the rain volume is basically determined by synoptic-scale conditions and that effect of multiple cloud seeding is negligible.

SUMMARY AND CONCLUSIONS

In this study we have analyzed precipitation during multiple cloud seeding experiments over South Florida. Based upon the analysis, we formulated a method for eliminating the effect of the synoptic-scale conditions on the precipitation variability. This method was applied to two sets of observations (July-August 1973 and 1970-1971 seeded and control days) and found that the multiple cloud seeding effect is much smaller than the effect of the synoptic-scale conditions in controlling the rain volume and the areal extent of precipitation. This finding is important due to its implication on the design of experiments for evaluating the effect of multiple cloud seeding in Florida. The implication is: Experiments (e.g. Simpson *et al.*, 1973; Simpson and Woodley, 1974) which, in their design and evaluation, do not take into account the effect of the varying synoptic conditions on precipitation can lead to misleading results. This is because the multiple cloud seeding effect is small; therefore, it is dominated and masked by the effects of synoptic conditions. If the effects of the varying synoptic scale conditions are to be eliminated, the errors in this elimination could still be comparable to the multiple cloud seeding effect. Thus, it would be impractical to evaluate the effectiveness of multiple cloud seeding.

Table 1
Synoptic conditions for seeded and control days, July-August 1973.
Seeded days

Date	Stability (S.I.)	Wind Shear (850-200mb) (kt)	Mean Hum (g/kg)	Mean Wind (1 000-600mb) (deg, kt)
7/7	1	17	10.0	28007
7/20	1	13	9.3	11007
7/25	1	35	11.0	08010
8/22	1	64	7.0	26006
8/25	0	40	11.0	14005
8/27	1	11	9.1	08010
8/28	1	20	8.4	06014
AVG	.9	28.6	9.4	08004

Control days

Date	Stability (S.I.)	Wind Shear (850-200mb) (kt)	Mean Hum (g/kg)	Mean Wind (1 000-600mb) (deg, kt)
7/9	2	20	9.3	33003
7/16	1	28	9.7	13003
7/17	3	27	9.8	11007
7/26	2	26	9.1	03005
8/6	2	22	9.9	13005
8/9	0	33	11.0	09003
8/11	1	17	10.0	16015
8/14	– 1	29	10.0	15007
8/26	0	17	8.0	12011
AVG	1.1	24.3	9.7	13005

Table 2

Rainfall for seeded and control days, July-August 1973

Seeded days

Date	(1) Act. obs. Rainfall	(2) Expected Rainfall (Max. echo % area)	(3) Corrected Expected Rainfall	Difference (1-3)
7/7	21	23	26	– 5
7/20	12	19	22	– 10
7/25	11	21	20	– 9
8/22	22	2	7	15
8/25	29	33	39	– 10
8/27	5	16	15	– 10
8/28	8	8	3	5
AVG	15.4			– 3.4

Control Days

Date	(1) Act. obs. Rainfall	(2) Expected Rainfall (Max. echo % area)	(3) Corrected Expected Rainfall	Difference (1-3)
7/9	23	15	26	– 3
7/16	39	31	42	– 3
7/17	24	13	16	8
7/26	23	26	33	– 10
8/6	22	18	25	– 3
8/9	40	28	43	– 3
8/11	16	32	27	– 11
8/14	70	41	44	26
8/26	13	22	20	– 7
	30.0			– 0.7

Table 3
Synoptic conditions for seeded and control days, 1970-1971.
Seeded days

Date	Stability (S.I.)	Wind Shear (850-200mb) (kt)	Mean Hum (g/kg)	Mean Wind (1 000-600mb) (deg, kt)
6/29/70	2	9	8.1	27006
7/2/70	2	16	8.5	08004
7/8/70	1	16	10.0	09001
7/18/70	5	43	7.8	16002
6/16/71	5	12	7.6	25011
7/13/71	1	44	6.3	10007
7/14/71	1	52	8.2	12002
AVG	2.4	27.4	8.1	20001

Control Days

Date	Stability (S.I.)	Wind Shear (850-200 mb) (kt)	Mean Hum (g/kg)	Mean Wind (1 000-600mb) (deg, kt)
6/30/70	2	13	9.3	30004
7/7/70	3	21	8.9	33003
7/17/70	3	17	8.3	03003
7/1/71	9	7	7.0	10009
7/12/71	0	19	9.0	11004
7/15/71	6	40	6.2	14007
7/16/71	3	16	8.3	19004
AVG	3.7	19.0	8.1	11002

Table 4
Rainfall for seeded and control days, 1970-1971.
Seeded days

Date	(1) Act. Obs. Rainfall	(2) Expected Rainfall (Max. echo % area)	(3) Corrected Expected Rainfall	Difference (1-3)
6/29/70	17	7	12	5
7/2/70	15	9	19	– 4
7/8/70	47	23	45	2
7/18/70	15	15	27	– 12
6/16/71	8	5	3	5
7/13/71	11	1	4	7
7/14/71	14	18	30	– 16
AVG	18.1			– 1.9

Control Days

Date	(1) Act. Obs. Rainfall	(2) Expected Rainfall (Max. echo % area)	(3) Correted Expected Rainfall	Diference (1-3)
6/30/70	21	26	34	– 13
7/7/70	30	15	25	5
7/17/70	14	8	21	– 7
7/1/71	13	1	1	12
7/12/71	30	20	30	0
7/15/71	7	7	9	– 2
7/16/71	20	20	28	– 8
AVG	19.3			– 1.9

Table 5

Rain volume for seeded and control days, July-August 1973

Unit: $M^3 \times 10^7$

Seeded days

Date	(1) Actually Observed	(2) Corrected Expected	Difference (1-2)
7/7	3.7	4.1	– 0.4
7/20	10.2	3.6	6.6*
7/25	1.8	3.1	– 1.3
8/22	4.3	1.2	3.1
8/25	4.7	6.1	– 1.4
8/27	0.7	2.4	– 1.7
8/28	0.9	0.5	0.4
		Average:	– 0.2

Control days

Date	(1) Actually Observed	(2) Corrected Expected	Difference (1-2)
7/9	5.5	4.1	1.4
7/16	4.2	6.6	– 2.4
7/17	3.9	1.5	2.4
7/26	3.6	5.1	– 1.5
8/6	14.5	3.9	10.6*
8/9	3.5	6.7	– 3.2
8/11	2.4	4.2	– 1.8
8/14	10.0	6.9	3.1
8/26	5.5	3.1	2.4
		Average:	+ 0.1

* Excluded from average because the value departs by a large amount from the best fit line in Fig. 10

Table 6

Rain volume for seeded and control days, 1970-1971

Unit: $M^3 \times 10^7$

Seeded days

Date	(1) Actually Observed	(2) Corrected Expected	Difference (1-2)
6/29/70	4.0	4.0	0.0
7/2/70	2.4	6.3	– 3.9
7/8/70	14.6	15.0	– 0.4
7/18/70	10.3	9.0	1.3
6/16/71	0.3	1.0	– 0.7
7/13/71	3.7	1.3	2.4
7/14/71	6.0	10.0	– 4.0
		Average:	– 0.8

Control Days

Date	(1) Actually Observed	(2) Corrected Expected	Difference (1-2)
6/30/70	8.5	11.3	– 2.8
7/7/70	9.3	8.3	1.0
7/17/70	5.7	7.0	– 1.3
7/1/71	1.9	0.3	1.6
7/12/71	9.3	10.0	– 0.7
7/15/71	2.3	3.0	– 0.7
7/16/71	8.6	9.3	– 0.7
		Average:	– 0.5

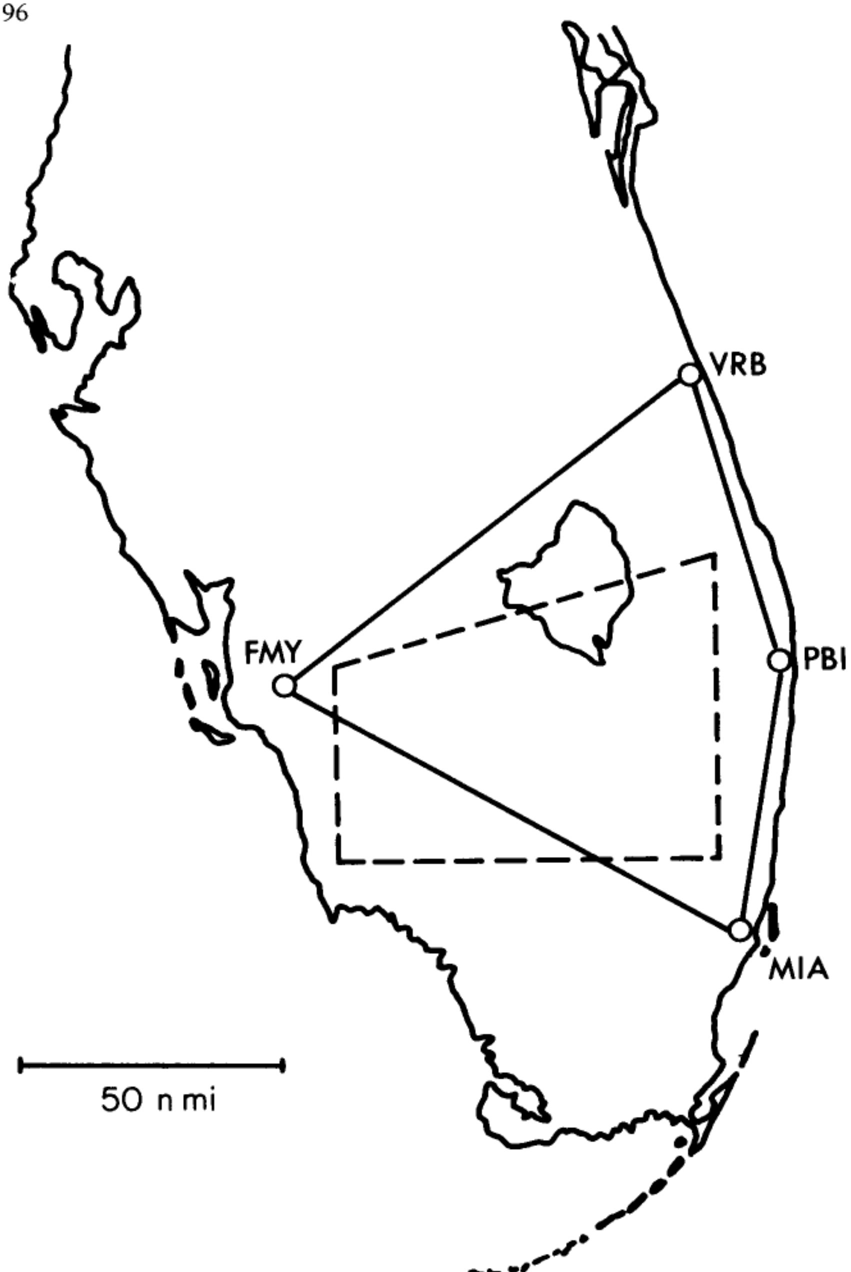


Figure 1. Map showing the areas of rainfall studies and multiple cloud seeding.

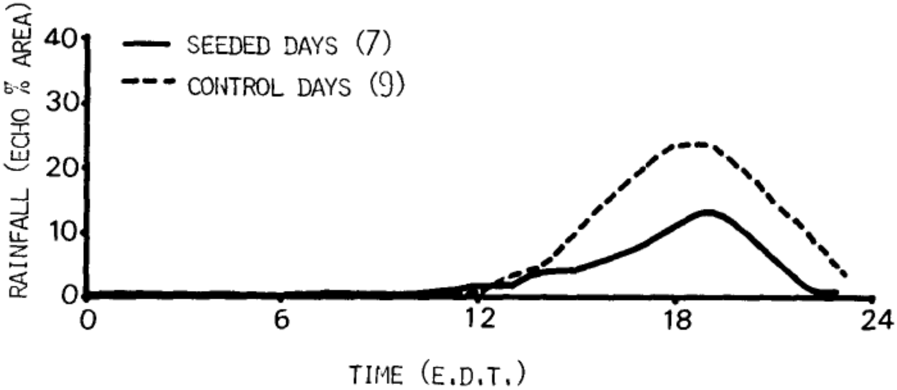


Figure 2. Mean diurnal variation of rainfall for seeded and control days in July-August 1973.

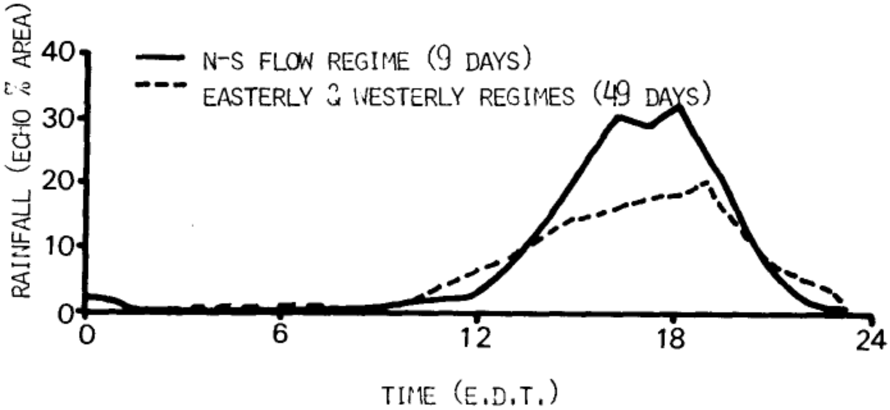


Figure 3. Graph showing the dependence of rainfall on the prevailing wind direction.

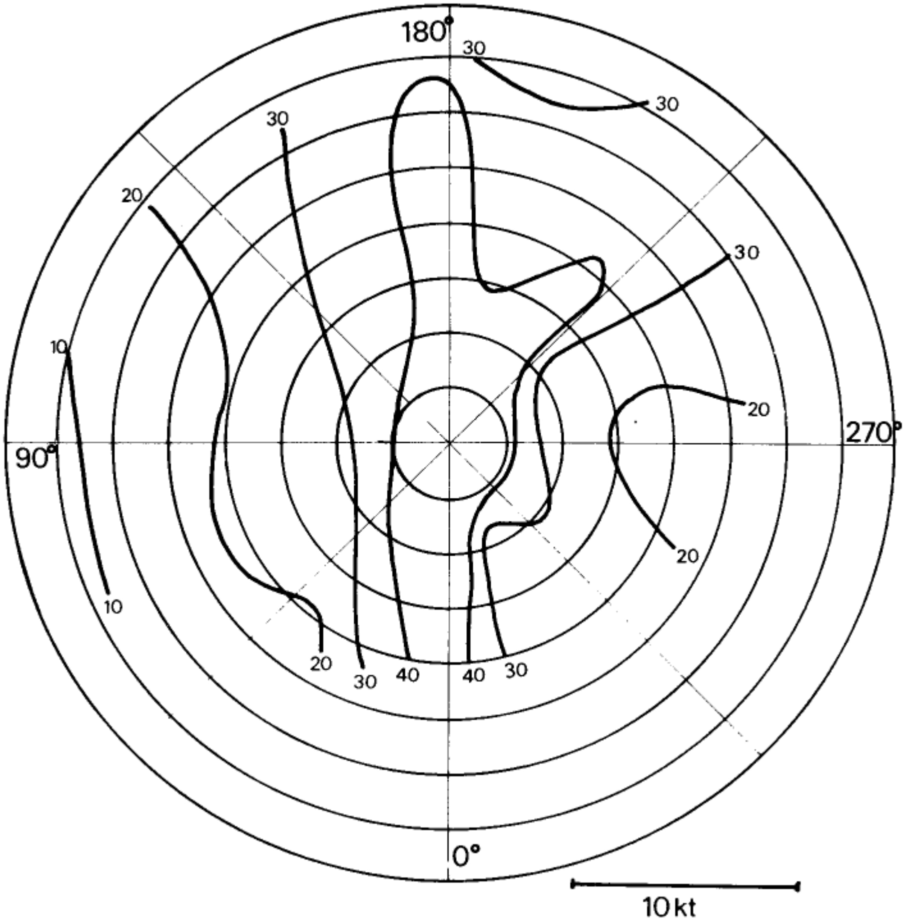


Figure 4. Maximum rainfall as a function of the mean wind.

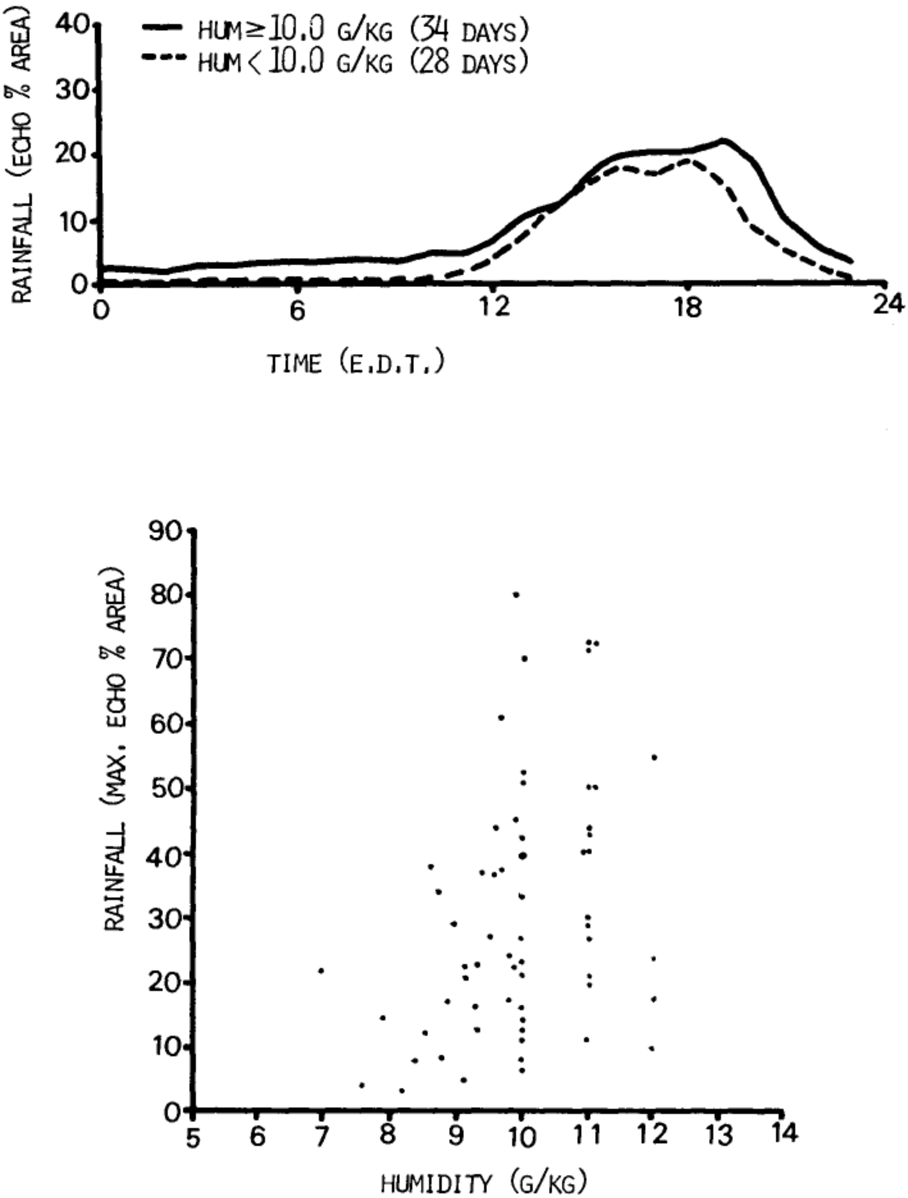


Figure 5. Graphs showing the dependence of rainfall on humidity.

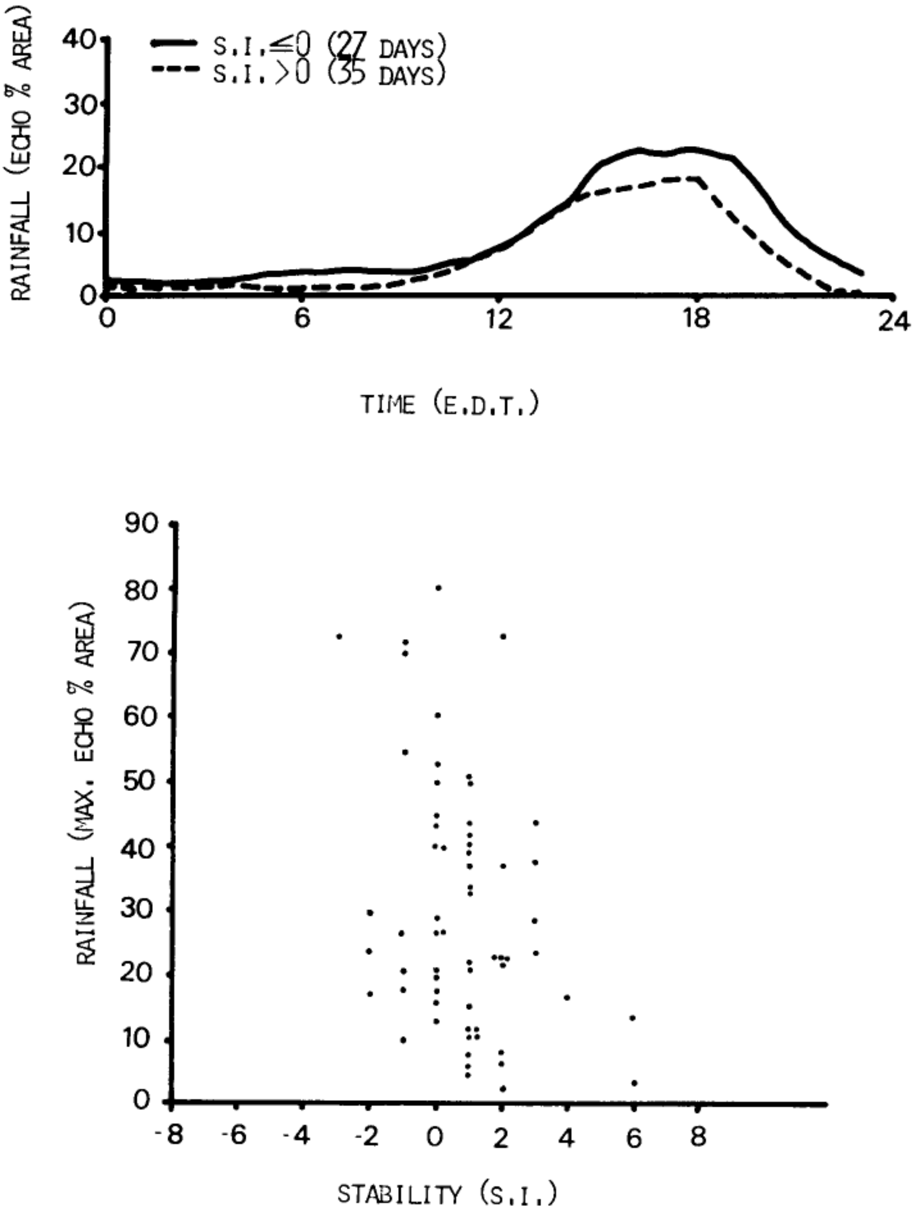


Figure 6. Graphs showing the dependence of rainfall on stability.

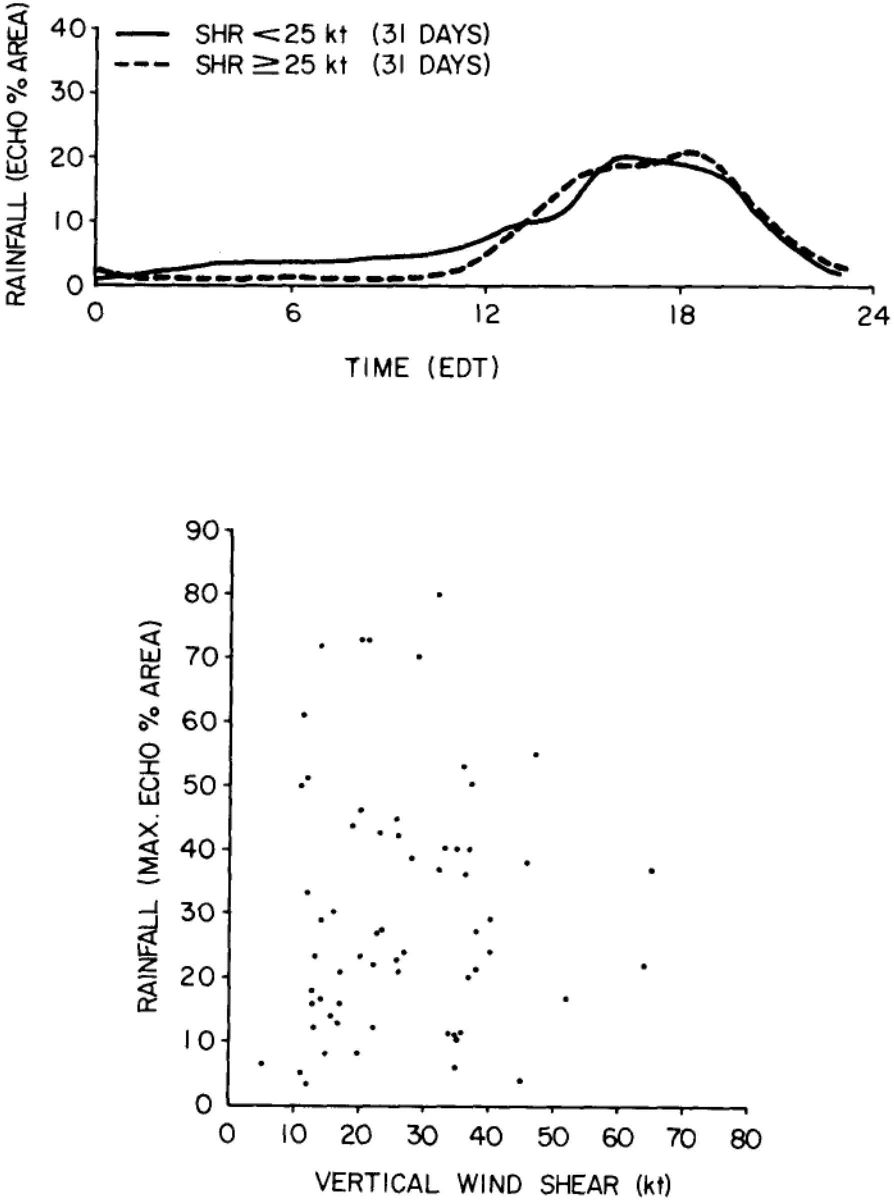
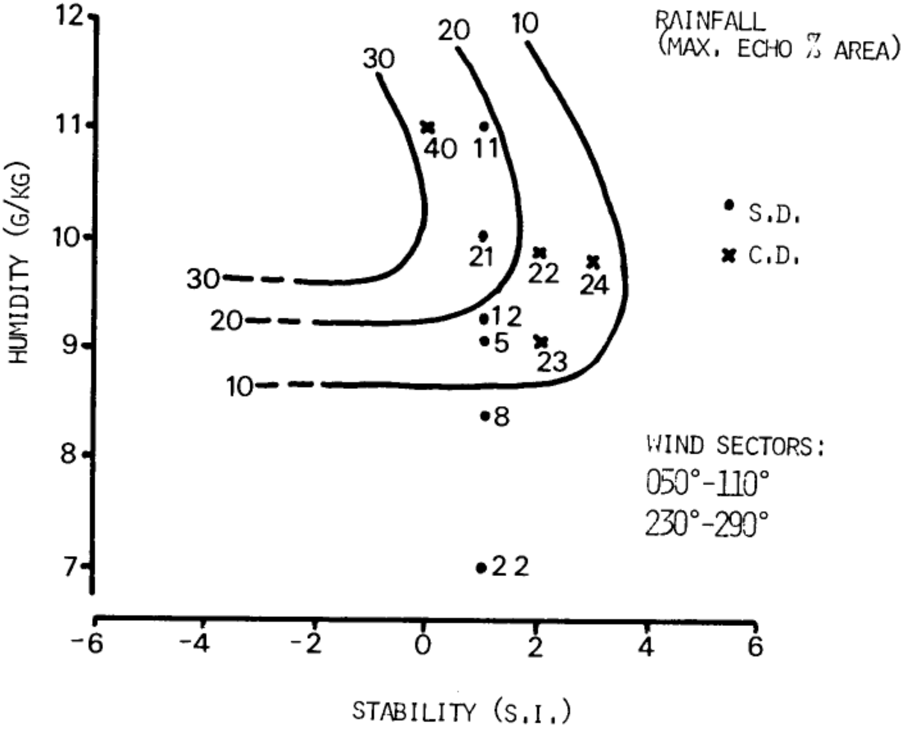


Figure 7. Graphs showing that there is no dependence of rainfall on vertical wind shear.



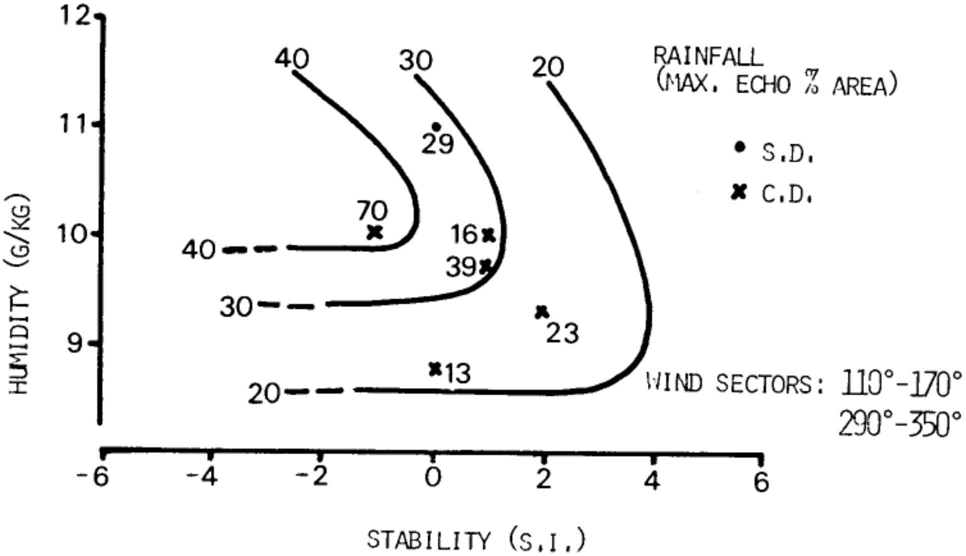


Figure 8. Diagrams showing maximum rainfall as a function of stability, humidity, and the direction of the prevailing glow. The location of seeded and control days in July-August 1973 is superimposed on the diagrams. Seeded days are indicated by •; control days are indicated by X. Numbers beside the location of seeded and control days indicate actually observed maximum rainfall.

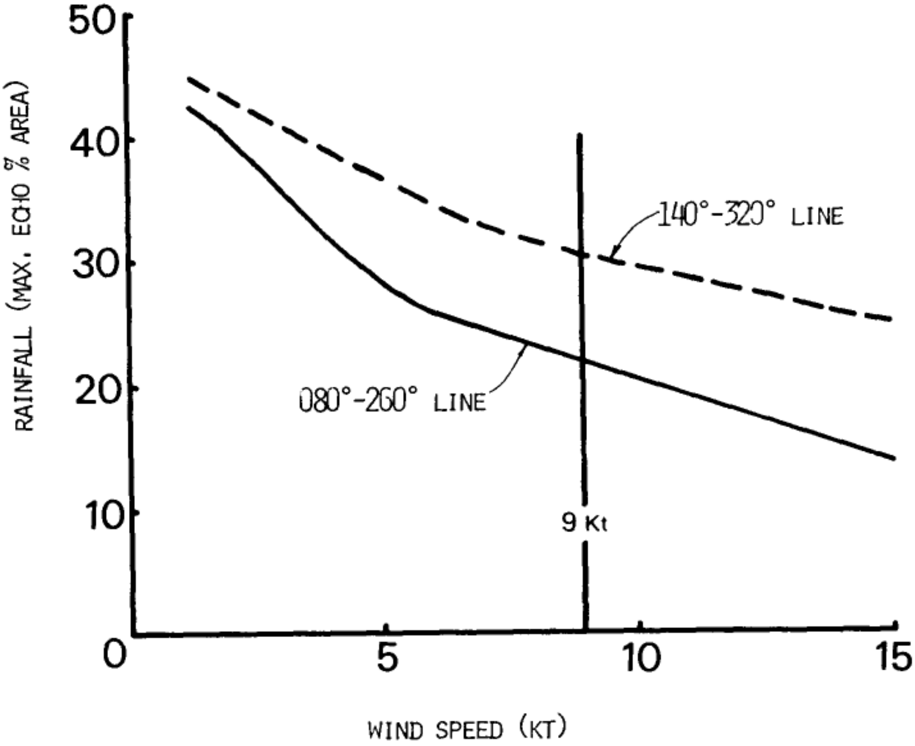


Figure 9. Profiles of maximum rainfall vs. wind speed along the lines 080°-260° and 140°-320°. These profiles are based upon information in Figure 4. The 9-kt mark indicates the mean wind speed for each diagram in Figure 8.

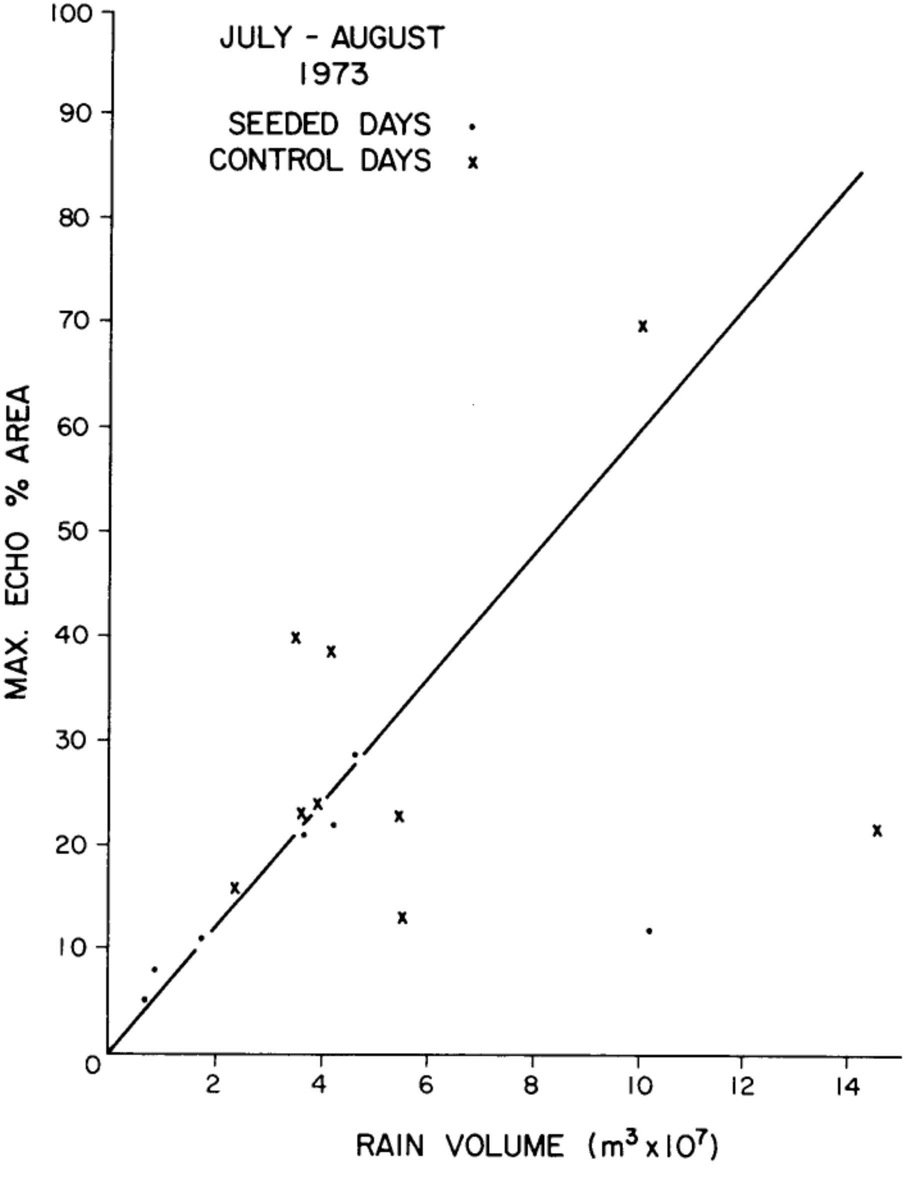


Figure 10. Graph showing the relationship between rain volume and maximum area covered by radar echoes for seeded and control days in July-August 1973.

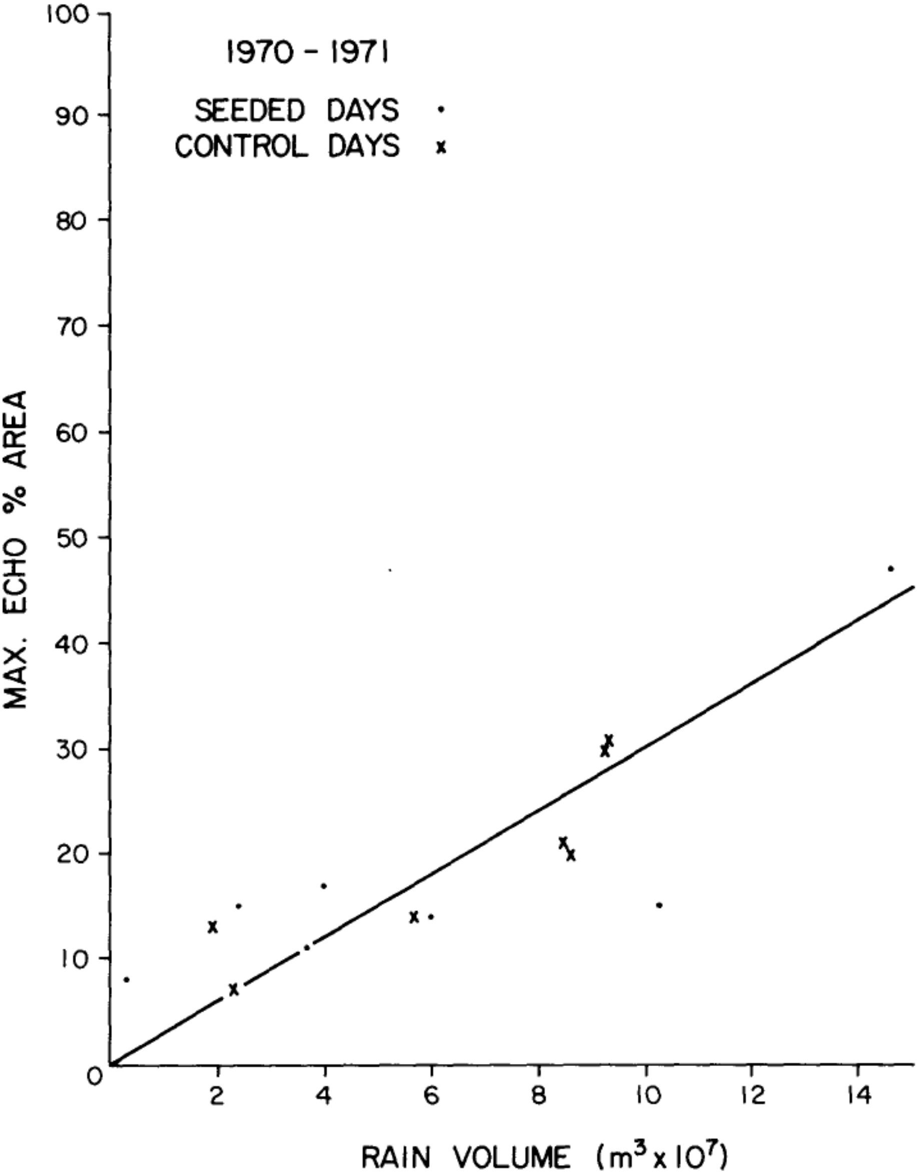


Figure 11. Graph showing the relationship between rain volume and maximum area covered by radar echoes for the set of 1970-1971 seeded and control days.

ACKNOWLEDGMENTS

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