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ENGINEERING RESEARCH
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# DISCUSSION

OF

R. H. Douglas'

# RECENT HAILSTORM RESEARCH - A REVIEW

by

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## TABLE OF SYMBOLS

$\Delta V / \Delta Z$ — Wind shear as measured by the difference in wind velocity component between 12 and 35 thousand feet msl, knots per thousand feet. (Wind components were measured along the mean wind direction from the surface to the tropopause.)



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# RECENT HAILSTORM RESEARCH - A REVIEW

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## ABSTRACT

Research on hailstorms is hampered by the fact that quantitative climatological data on hail events are limited. Recent research studies have developed new techniques to obtain such quantitative data, including use of passive recorders for recording characteristics of hailfalls. Through use of such equipment in Colorado hail studies, it was found that while hailstorms with large stones are spectacular, they are relatively rare. Most of the crop damage from hail in Colorado probably results from hailstones smaller than 1.5 cm diameter.

Hailstone crystal structure from Colorado hailstones suggests an average process by which the stones form at warm temperatures, then grow to radii of 2 to 3 cm in a "dry" environment, and finally grow to radii in excess of 3 cm in a "wet" environment. It was found that successively larger fractions of the total volume of hail were formed in a "wet" environment as the season progressed from May to July.

It was found that conventional hail forecasting techniques suffer an inability to distinguish clearly between severe hail and heavy rain. The occurrence of strong winds aloft was found to be associated with severe hail.

## 1. INTRODUCTION

Dr. Douglas has given a comprehensive review of recent hailstorm research. Rather than to attempt to discuss all facets of his paper, this discussion will be confined to the parts of his paper concerning hailstorm characterization, hailstone structure, and the synoptic environment. The discussion will draw heavily on experience from studies of hail in Colorado.

## 2. HAILSTORM CHARACTERIZATION

One of the first tasks of a researcher is to quantify the event of concern. In the case of a hailstorm this is a difficult task, as evidenced by the fact that most researchers on hail have felt it necessary to establish special networks and reporting procedures in order to obtain more precise information on hail occurrences. [2; 4; 7; 8; 22; 26]*

With the exception of data from such special studies, quantitative data on hailstorms are meager. One quantitative measure which can be obtained from existing climatological data is the "number of days" with hail, which is being used as the variable for evaluation in one experiment in hail suppression [19; 27]. This method of characterization, however, makes no distinction as to intensity of hail. Current reports of hail in published climatological data [25] in the United States, in addition to location and date, give an estimate of dollar damage from hailstorms. Since these reports are frequently compiled from press clippings, their accuracy is open to question, and in addition, the reports are subject to a bias, since severe storms in heavily populated areas will receive wider press coverage than in uninhabited regions. Summaries of these data, such as given by Flora [11], suffer the same limitations.

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* Numbers refer to appended references.

Post-storm reconnaissance has provided in recent years a number of case-history studies of hail events, including details of time and space distribution of hailfall, and details of the structure of individual stones [3; 15; 17; 20].

None of these techniques alone, however provides a reliable quantitative measure of hail occurrence and intensity.

The use of passive recorders made of aluminum foil and styrofoam was being developed at about the same time in Oregon by Decker, in Illinois by Stout, and in Colorado by Schleusener and Jennings. Characterization of hailfalls in terms of estimated impact energy from passive hail recorders in the Colorado hail studies provides a method for such quantitative estimates of hail size and intensity, and therewith a method for comparison of intensity of hail among hail events [21]. Examination of the data obtained in 1960-1961 from passive recorders from the Colorado State University network [22] provides an insight into the differences that can exist between successive hail seasons, and the relations between quantity of hail, impact energy, and crop damage over a wide region. Table 1 shows a comparison of the volume of ice ($in^3/in^2$) and impact energy ($ft\text{-}lb/ft^2$) for 1960-1961, obtained from the hail indicators exposed in the Colorado State University hail network.

Table 1 shows that most of the volume of ice, and most of the hail impact energy, came from stones of 1/2-inch diameter or smaller. Further, while 1960 had a higher fraction of volume and impact energy in the largest stone size class, the <u>total</u> volume and <u>total</u> impact energy were substantially higher in 1961.

It is of interest to compare these data with records of sugar beet damage from the same geographic region. Table 2 shows such a comparison.

TABLE 1.

Volume of ice ($in^3/in^2$) and estimated impact energy ($ft\text{-}lb/ft^2$) by hail size class for 1960-1961. Data from hail indicators were obtained from the from the Colorado State University hail network.

| Size Class Median Diameter Inches | 1960 | | | | 1961 | | | |
|---|---|---|---|---|---|---|---|---|
| | VOLUME | | ENERGY | | VOLUME | | ENERGY | |
| | $\frac{in^3}{in^2}$ | Per-cent | $\frac{ft\text{-}lb}{ft^2}$ | Per-cent | $\frac{in^3}{in^2}$ | Per-cent | $\frac{ft\text{-}lb}{ft^2}$ | Per-cent |
| 1/8 | .0046 | 23 | 0.0# | 0 | .0029 | 6 | 0.0# | 0 |
| 1/4 | .0057 | 30 | 1.6 | 22 | .0122 | 23 | 3.4 | 13 |
| 1/2 | .0044 | 22 | 2.4 | 32 | .0215 | 40 | 12.0 | 47 |
| 3/4 | .0017 | 9 | 1.0 | 14 | .0145 | 27 | 8.6 | 34 |
| ≥ 1-1/8 | .0032 | 16 | 2.4 | 32 | .0020 | 4 | 1.5 | 6 |
| Total | .0196 | 100 | 7.4 | 100 | .0531 | 100 | 25.5 | 100 |

#Stones of this size do not dent the hail indicators.

TABLE 2.

Comparison of total volume of hail and total impact energy from hail with area of sugar beets damaged from hail, 1960-1961.

| Year | Volume of Hail $\frac{in^3}{in^2}$ (Table 1) | Impact Energy $\frac{ft\text{-}lb}{ft^2}$ (Table 1) | Total Acres of Beets Damaged by Hail # |
|---|---|---|---|
| 1960 | .020 | 7.4 | 41,428 |
| 1961 | .053 | 25.5 | 124,634 |
| Ratio $\frac{1961}{1960}$ | 2.65:1 | 3.45:1 | 3.0:1 |

#Mr. Lymon H. Andrews, Southern District Manager of Great Western

Sugar Company, writes as follows:

"In response to your inquiry. . . . , I have asked our statistician to compile the following figures, which give in total the number of acres of beets that were hailed in the past three years, which includes all of Northern and Eastern Colorado, some acreage in Nebraska East of Julesburg, and in the Holdrege, Nebraska area:

| | |
|---|---|
| 1961 | 124,634 Acres |
| 1960 | 41,428 Acres |
| 1959 | 37,958 Acres |

You will note that this checks very closely with your observations that three times as much total ice fell in Northeastern Colorado in 1961 as fell in 1960. 124,634 acres hailed, which includes acreage that was hailed more than once, is the largest damage suffered from hail in this district in many years."

From the preceding data, one may conclude that there is room for improvement in our ability to characterize hailstorms in a quantitative manner. Further, one should be cautious in characterizing the severity of a hail season by the number of cases of large hail. While hailstorms with large stones are spectacular, it appears from the foregoing limited sample that crop damage is more closely related to the total volume of ice, or total impact energy, than to the occurrence of large stones.

## 3. HAILSTONE STRUCTURE

The structure of hailstones has been the subject of study for many years. Construction of laboratory facilities by the Swiss [13] for growth of artificial stones has given new interest to such studies. Early hopes for unique interpretation of hailstone growth rings do not seem justified.

List [14] concludes that current results are somewhat discouraging that "the type of ice in each different layer of hailstone may be interpreted on a theoretical basis," since the various types of ice in hailstones might be formed in several ways. However, there seems to be general agreement on the fact that formation of small crystals is indicative of hailstone growth in an environment composed predominately of ice crystals and larger crystals indicate growth in a wet environment, predominately of liquid water drops [14; 28].

Hailstones collected in the Colorado State University hail network were analyzed to determine the relative amounts of ice in the stones composed of large and small crystals, which presumably are indicative of the relative volumes of hail grown in "wet" and "dry" environments, respectively.

Photographs were made of sections of hailstones viewed under ordinary light to obtain air bubble structure, and then photographed under polarized light to get crystal structure [9].

The various layers within the stone were then categorized as having predominantly "Large", "Medium", or "Small" crystals, using 3 mm and 1 mm as the dimensions of crystals separating the three categories.

If one considers the "medium" class of crystal as being uncertain as to environment during growth, then the relative amounts of "large" and "small" crystals can give some indication of the volumes of ice grown in a predominantly "wet" and "dry" environment, respectively.

Figure 1 shows the average hailstone crystal structure for stones from the storm of 29 June 1960. Figure 1 shows a greater average volume of large than small crystals for stones of 0.5 cm radius. There is a greater average volume of small than large crystals for radii 1.0 - 2.2 cm. For stones larger than 2.2 cm, large crystals again predominate. For the largest radius (4.0 cm), large crystals made up 82 per cent of the total volume, and small crystals made up 12 per cent of the total volume.

It should be emphasized that the data of Figure 1 are for the average structure for the number of stones within each size class. Specific stones, of course, may depart significantly from the average values. As an example, some stones of radius 0.5 to 1.0 cm were composed entirely of small crystals.

The data of Figure 1 suggest a process by which the hailstone formed in the lower ("wet") portion of the cloud, grew to intermediate size in the upper ("dry") portion of the cloud, and grew to large size as they fell through the lower ( "wet") portion of the cloud.

Figure 2 shows the average hailstone crystal structure for all stones analyzed in 1960 and 1961. The average crystal structure is such that large crystals predominate for stones of all radii.

Figure 3 shows the fractional part of the total volume of the stones composed of large and small crystals, based on the data from Figure 2 . Figure 3 also shows the same trend noted in Figure 1 , i.e., an increase in the volume of small crystals for intermediate stone sizes.

The average fraction of the total volume of the stone composed of large crystals for each of the months of May, June, and July, is shown in Figure 4. From Figure 4 it may be seen that the average fraction of total volume of hailstones composed of large crystals increases as the season progresses. One possible explanation for this difference could be that the $0^{0}$C melting level rises from May to July, with a resultant increase in depth of liquid cloud.

It is of interest to note that the average structure shown for Colorado hailstones in Figures 1 - 4 is in general agreement with the structure that would result from the trajectories computed by Douglas.

## 4. THE SYNOPTIC ENVIRONMENT

Success in forecasting hail occurrences requires the ability to identify a given set of synoptic conditions as those which can produce hail. Procedures for forecasts of hail are closely related to those for forecasts of tornadoes, and generally are patterned after those developed by Fawbush and Miller [1; 10]. A refinement of this technique, based on physical reasoning, has been suggested by Foster and Bates [12].

Additional evidence for a close relation between the small-scale phenomenon of hail and the broad-scale circulation is provided by recent studies by the writer [23], which show consistent relationships between hail occurrences in the lee of the Rocky Mountains (in Colorado and Alberta) and the latitude and strength of the 500 mb west wind measured along $110^0$ west longitude. Such studies indicate the importance of the broad-scale synoptic environment, even when the event of interest is as localized as hail.

Additional studies by the writer have indicated an inability of present forecast procedures to differentiate between cases of heavy rain and cases of heavy hail. In addition, the importance of strong winds aloft for formation of severe hail is confirmed. These studies are described below.

The storms of 20 June, 29 June, and 3 July 1960 as observed in the Colorado State University hail network provide two cases of severe hail and one of heavy rain for comparative purposes. Table 3 gives some of the pertinent characteristics of each storm.

Examination of some of the conventional synoptic parameters presented in Figures 5 to 8 show little difference between the one heavy rain case (3 July) and the two severe hail days (20 and 29 June).

Figure 9 shows the maximum hailstone size forecast by the Fawbush-Miller technique [10], based on soundings taken at 1700 MST. Comparison with Table 3 indicates that the forecast size was smaller than observed for each day. In addition, although larger sizes of stones are indicated for the two severe hail days (20 and 29 June) than for the heavy rain day (3 July), the difference would probably not be considered sufficiently large to distinguish between the two categories of severe weather.

TABLE 3.

Characteristics of three storms in the Colorado State University hail network, 1960.

| Date | 20 June | 29 June | 3 July |
|---|---|---|---|
| Number of reports of hail received | 38 | 36 | 9 |
| Maximum stone size reported | 3"+ | 3"+ | 1-3/4" |
| Maximum depth of precipitation, inches | 2.0 | 2.5 | 4.5 |
| Impact energy, ft-lb/ft$^2$# | 5 greater than 100 | 9 greater than 100 | 1 greater than 10 |
| Hail classification | severe | severe | mild |
| Precipitation classification | mild | mild | heavy |

#Estimated from observer reports.

In a further search for parameters which might explain the difference between the rain and hail cases, the environmental wind field from 1700 MST for Denver, (DEN) North Platte, (LBF) and Goodland (GLD) were analyzed. The mean wind from the surface to the tropopause was determined from a hodograph, and the wind shear along the mean wind direction was measured by the difference in speed between 35,000 and 12,000 feet (the approximate top and base of cumulonimbus, respectively). The results of the analysis are shown in Table 4.

TABLE 4.

Wind shear (along the mean wind direction) between 12,000 and 35,000 ft, knots per thousand feet.

| Date | Station | ΔV/ΔZ | Average |
|---|---|---|---|
| 20 June, 1960 (Severe Hail) | DEN | 3.26 | |
| | LBF | 2.78 | 3.01 |
| | GLD | 3.00 | |
| 29 June, 1960 (Severe Hail) | DEN | 2.65 | |
| | LBF | MSG | 2.24 |
| | GLD | 1.83 | |
| 3 July , 1960 (Heavy Rain) | DEN | 1.22 | |
| | LBF | 2.30 | 1.69 |
| | GLD | 1.57 | |

From the foregoing analyses it appears that synoptic parameters of moisture content, stability, and height of wet-bulb zero suffer an inability to distinguish between cases of severe hail and heavy rain. The high values of wind shear shown in Table 4 for the severe hail cases give an indication of a possible significant parameter for making such a distinction.

As a further test of the ability of this parameter to distinguish severe hail cases, 18 cases from 1961 were analyzed. Six cases were for days of severe hail occurrence; six cases were for days of light hail occurrence; and six cases were for days with no hail. The average wind from the surface to the tropopause was determined for Denver (DEN), Lander (LND), Scottsbluff (BFF), North Platte (LBF), and Goodland (GLD), and the wind component along the mean direction was determined for each station. Average profiles for all stations were then prepared for each category of hail occurrence: severe, light, or none. The results are shown in Figure 10.

The foregoing data indicate higher wind speeds aloft for days with severe hail. The data from Figure 10 tend to support the findings of Dessens [5; 6], who found a relation between severe hail and strong winds aloft, in contrast to those of Ratner [18], who concluded that Dessens' theories do not apply to the United States.

## 5. SUMMARY AND CONCLUSIONS

a. There is need for improvement in the techniques for observing and reporting climatological data on hail, since little quantitative data can be obtained from present reports.

b. While structural damage to aircraft and property damage are probably closely related to maximum hailstone size, crop damage appears to be more closely related to the total volume of ice that falls per unit area, or to the impact energy per unit area from a hailstorm.

c. The average structure of about 150 stones collected in Colorado suggests an average process of formation involving formation in a "wet" environment, growth at intermediate hailstone radii of 2 - 3 cm in a "dry" environment, and growth to radii in excess of 3 cm in a "wet" environment.

d. Consideration of conventional synoptic parameters of moisture content, stability, and height of the wet-bulb zero frequently is inadequate to distinguish between severe hail cases and heavy rain cases.

e. Strong winds aloft have been found to be closely correlated with the occurrence of severe hail.

## 6. RELATION TO OTHER AREAS OF STUDY

It is the opinion of the writer that there are three major categories in which studies of hail overlap into other areas of investigation:

a. The synoptic environment: the present status of knowledge concerning the relation of hail to the environment should not be considered a pinnacle of progress that can not be improved upon, but rather a base upon which further progress can be made.

b. The crystal structure of hailstones as an index of the local environment during growth of hailstones: additional laboratory investigations are necessary to improve our interpretation of the observed crystal structure of hailstone. These studies are of particular interest as indicators of changes that might take place as a result of cloud seeding for attempts at hail modification.

c. Radar reflectivity - hailstorm intensity studies: although not discussed in detail here, this area of study presents the possibility of characterizing hailstorms quantitatively, and should be continued.

## 7. OUTLOOK

The writer hopes that current research work, and work to be accomplished in the reasonably near future, might make possible the following:

a. Reporting of climatological data on hail in quantitative terms.

b. Quantitative information on extent and intensity of hail occurrence on an operational basis from radar data.

c. A better understanding of the interaction between broad-scale and local circulations that produce hail.

d. Beneficial modifications of hailstorms to reduce crop and property damage.

## ACKNOWLEDGEMENTS

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## REFERENCES

1. Air Weather Service Manual 105-37, Severe weather forecasting. Hq., Air Weather Service, 1956.

2. Beckwith, W. B., 1960. Analysis of hailstorms in the Denver network, 1949-1958. In Physics of Precipitation, Amer. Geophys. Union, Monograph No. 5, p. 348-353.

3. Browning, K. A., and F. H. Ludlam, 1960. Radar analysis of a hailstorm. Tech. note No. 5, Contract No. AF 61 (052)-254, Imperial College of Science and Technology, Dept. of Meteor., London.

4. Decker, Fred W., and Lyle D. Calvin, 1961. Hailfall of 10 September, 1959 near Medford, Oregon, Bul. Amer Meteor. Soc. 42(7): 475-480.

5. Dessens, H., 1961. Comments on "Do high speed winds aloft influence the occurrence of hail?", Bul. Amer. Meteor. Soc. 42(7): 513.

6. Dessens, H., 1960. Severe hailstorms are associated with very strong winds between 6,000 and 12,000 meters. In Physics of Precipitation, Amer. Geophys. Union, Monograph No. 5, p. 333-338.

7. Donaldson, R. J., Jr., A. C. Chemla, and C. R. Shackford, 1960. Some behavior patterns of New England hailstorms. In Physics of Precipitation, Amer. Geophys. Union, Monograph No. 5, p. 354-368.

8. Douglas, R. H., 1960. Size distributions, ice contents, and radar reflectivities of hail in Alberta, Nubila 3(1): 5-11.

9. Eaton, Larry, 1961. Hailstone structure studies, Colorado State University. Unpublished report.

10. Fawbush, E. J., and R. C. Miller, 1953. A method for forecasting hailstone size at the earth's surface, Bul. Amer. Meteor. Soc. 34(6): 235-244.

11. Flora, S. D., 1956. Hailstorms of the United States, Norman, Oklahoma, Univ. of Okla. Press.

12. Foster, Donald S., and F. C. Bates, 1956. A hail size forecasting technique, Bul. Amer. Meteor. Soc. 37(4): 135-141.

13. List, R. J., 1960. Design and operation of the Swiss hail tunnel, In Physics of Precipitation, Amer. Geophys. Union, Monograph No. 5, p. 310-316.

14. List, R. J., 1961. On the growth of hailstones, Nubila 4(1): 29-38.

15. Ludlam, F. H., and W. C. Macklin, 1959. Some aspects of a severe storm in S. E. England, Nubila 2(1): 38-50.

16. Macklin, W. C., E. Strauch, and F. H. Ludlam, 1960. The density of hailstones collected from a summer storm, Nubila 3(1): 12-17.

17. Mossop, S. C., A. E. Carte, and J. J. LeRoux, 1961. Hailstorm at Johannesburg on 9 November, 1959, Nubila 4(1): 68-86.

18. Ratner, B., 1961. Do high-speed winds aloft influence the occurrence of hail? Bul. Amer. Meteor. Soc., 42(7): 443-446.

19. Sanger, R., 1957. Third large-scale experiment to prevent hail in Tessin, Switzerland, In Final Report of the President's Advisory Committee for Weather Control, Vol. 2, p. 268-272.

20. Schaefer, V. J., 1960. Hailstorms and hailstones of the Western Great Plains, Nubila 3(1): 18-29.

21. Schleusener, Richard A., and P. C. Jennings, 1960. An energy method for relative estimates of hail intensity, Amer. Meteor. Soc. Bul. 41(7): 372-376.

22. Schleusener, Richard A., and Lewis O. Grant, 1961. Characteristics of hailstorms in the Colorado State University Network, 1960-1961, Proc. Ninth Wea. Radar Conf.

23. Schleusener, Richard A., 1962. On the relation of the latitude and strength of the 500-millibar west wind along 110 degrees west longitude and the occurrence of hail in the lee of the Rocky Mountains, Prepared for Amer. Meteor. Soc. Severe Storms Conference, Norman, Oklahoma.

24. Showalter, A. K., 1953. A stability index for thunderstorm forecasting, Bul. Amer. Metero. Soc., 34(6): 250-252.

25. Storm data, published by U. S. Weather Bureau.

26. Stout, Glenn, R. H., Blackner, and K. E. Wilk, 1960. Hail studies in Illinois relating to cloud physics, In Physics of Precipitation, Amer. Geophys. Union, Monograph No. 5, p. 369-383.

27. Thom, H. C. S., 1957. A method for evaluation of hail suppression, In Final Report of the President's Advisory Committee for Weather Control, Vol. 2, p. 55-69.

28. Weickmann, H., 1960. The language of hailstones, Paper presented at Verona hail conference.

LIST OF FIGURES

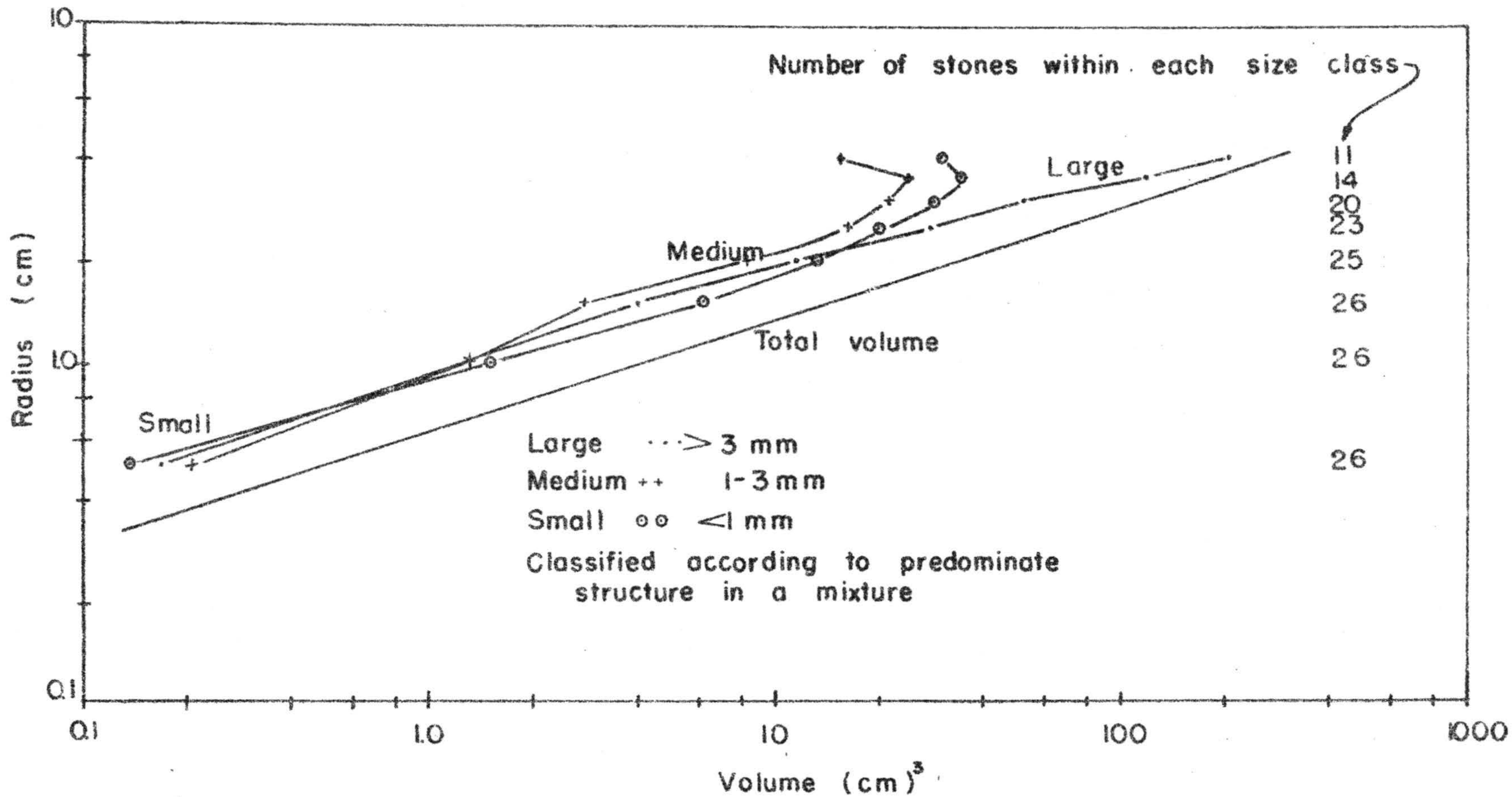


Fig. 1. Average hailstone crystal structure, 29 June 1960.

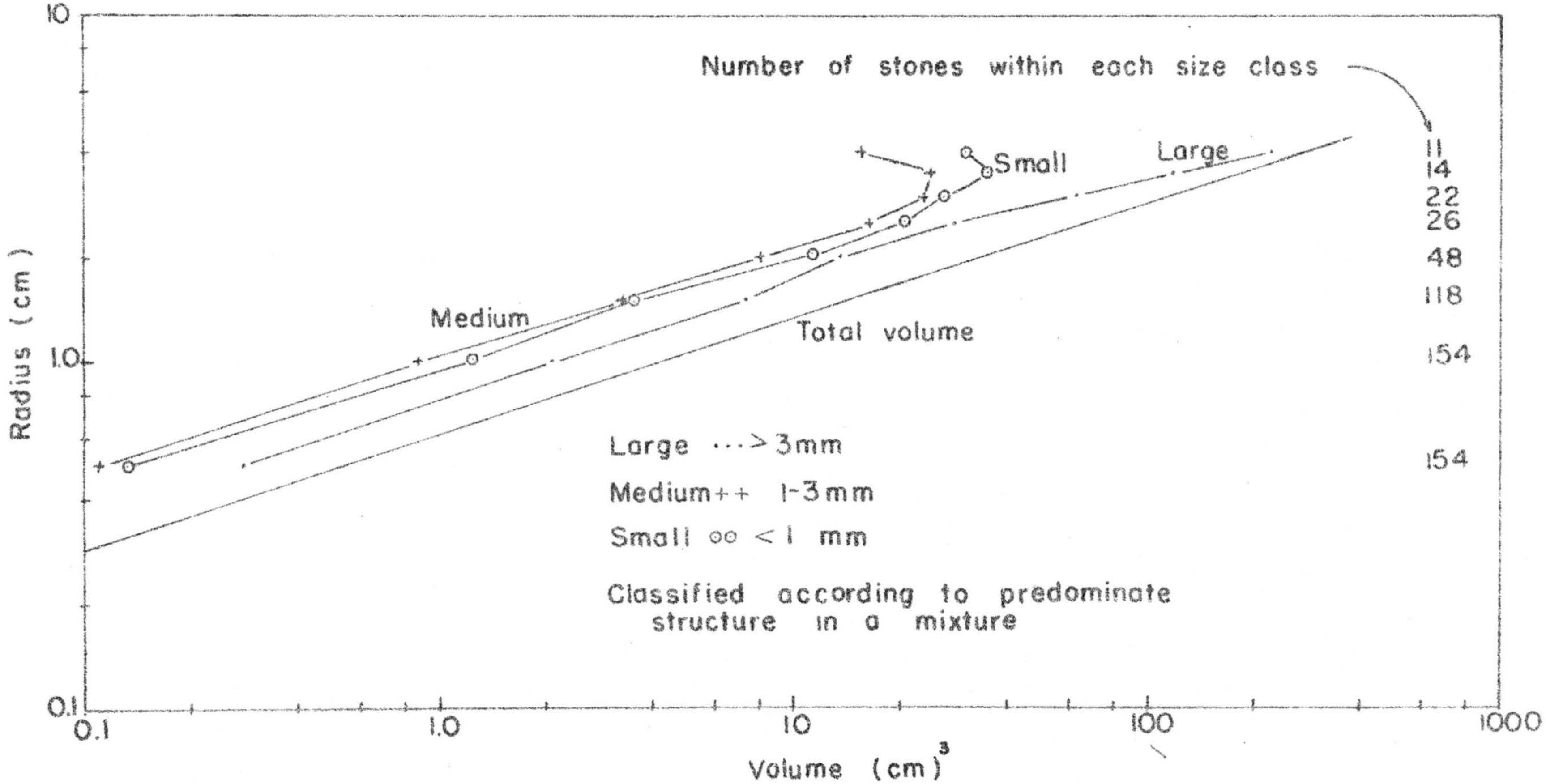


Fig. 2. Average hailstone crystal structure for all stones analyzed, 1960-1961.

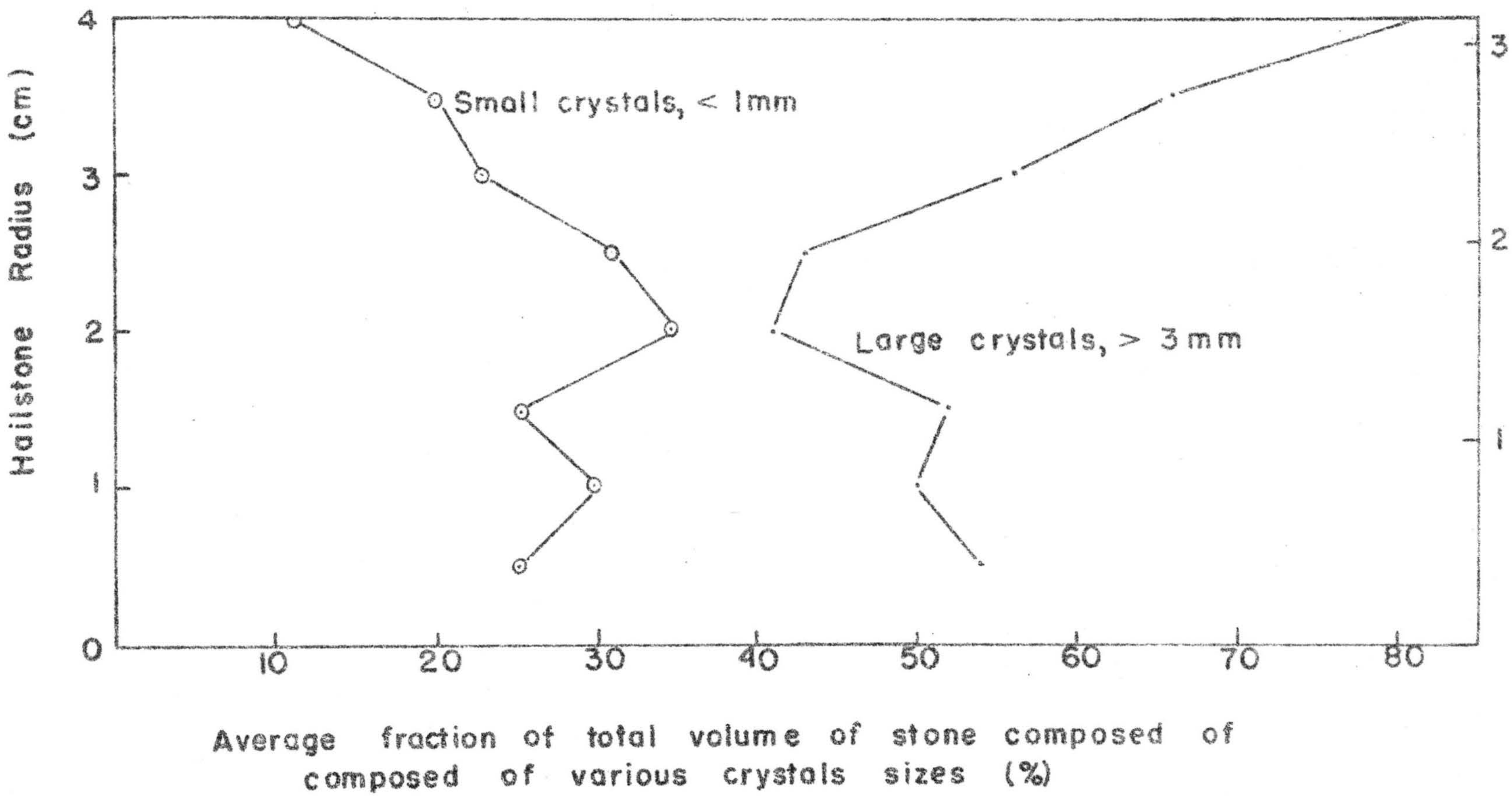


Fig. 3. Average crystal structure of hailstones, 1960-1961 (Data from Fig. 2).

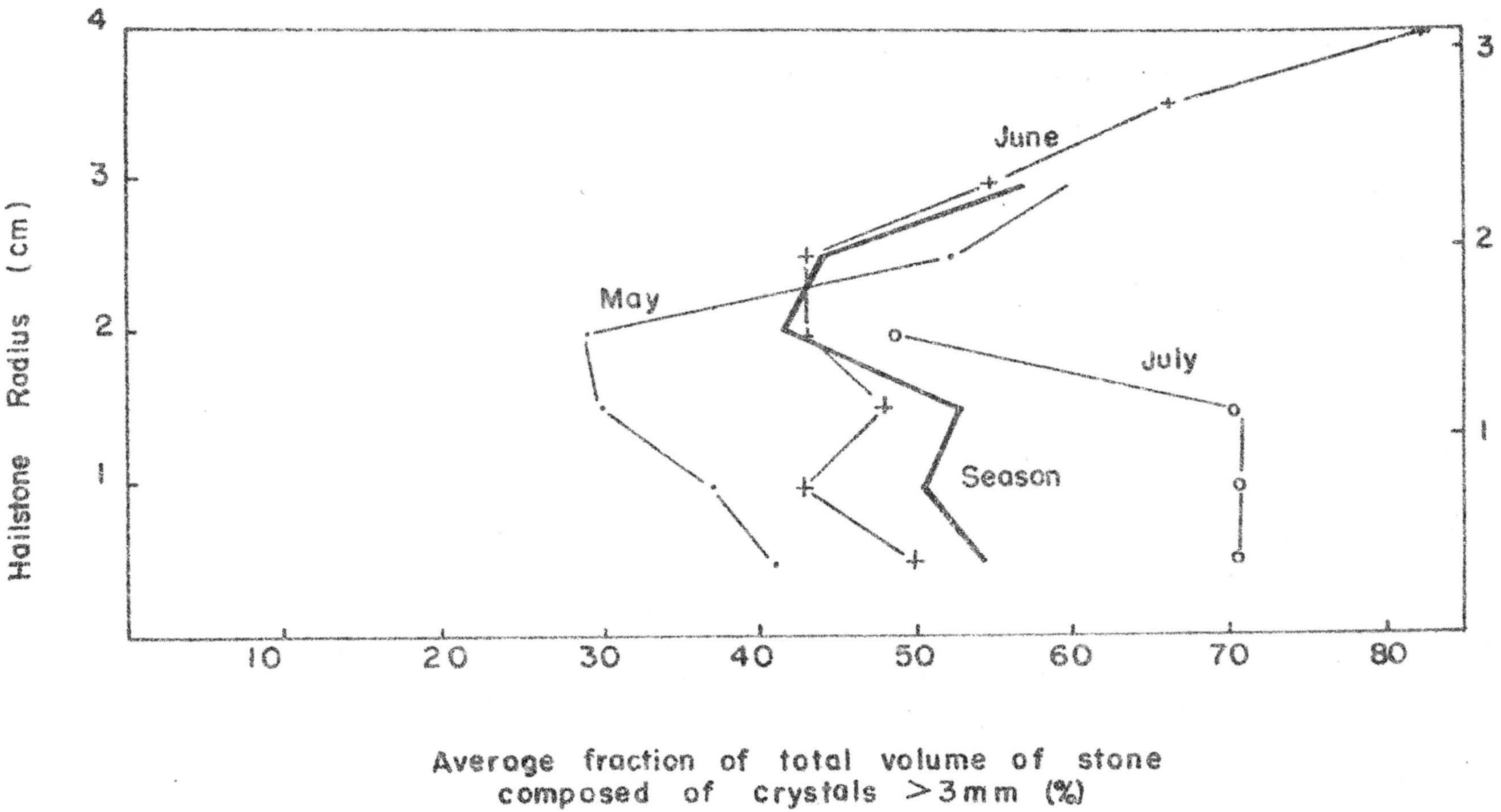


Fig. 4. Average crystal structure of hailstones by month, 1960-1961.

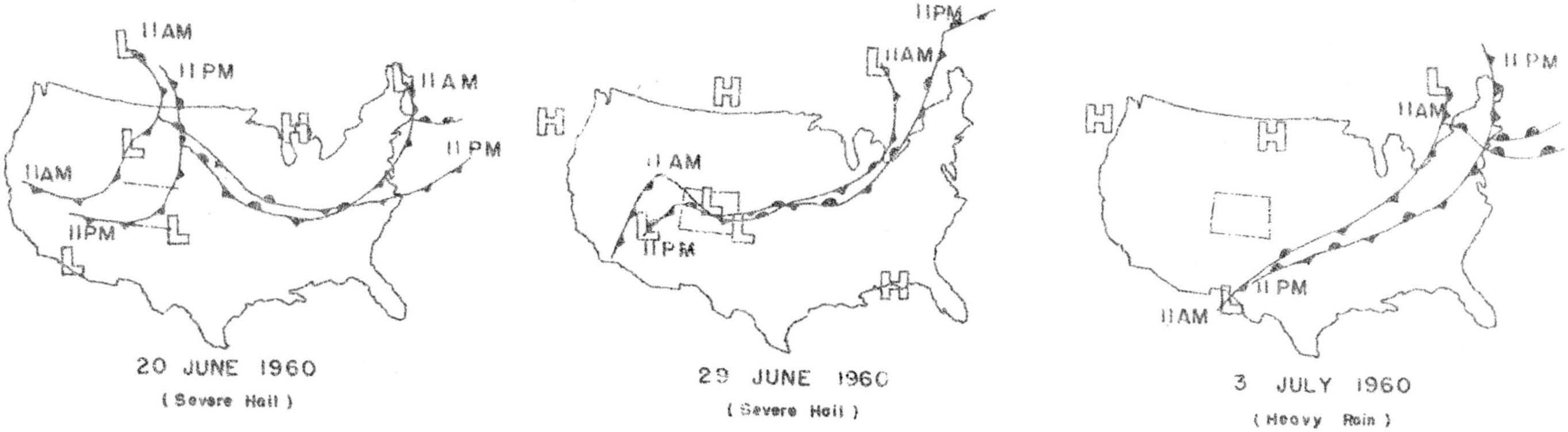


Fig. 5. Surface synoptic patterns.

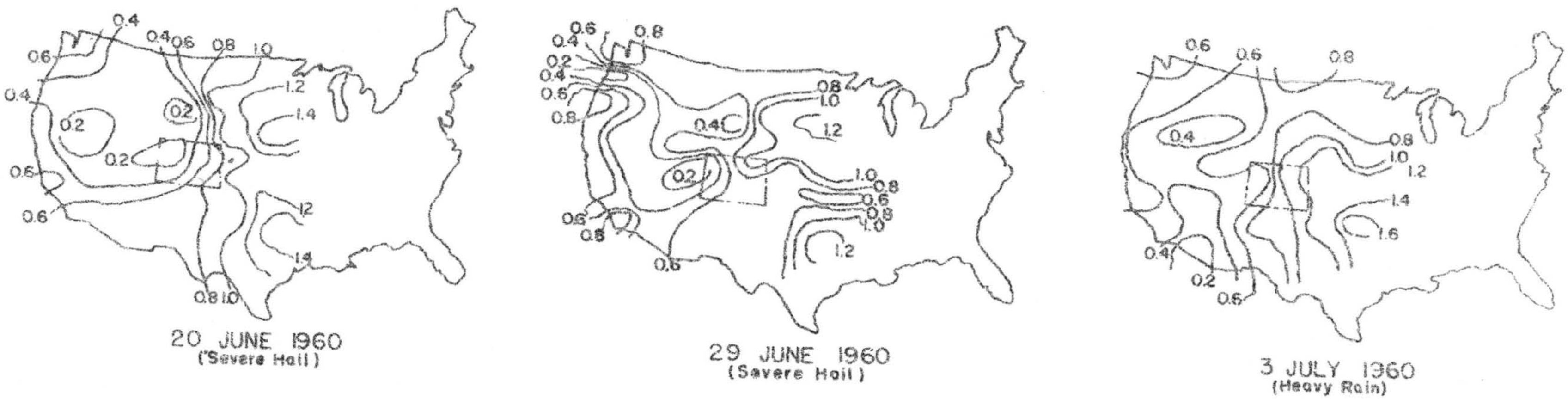


Fig. 6. Precipitable water, inches, 1700 MST, surface - 300 mb.

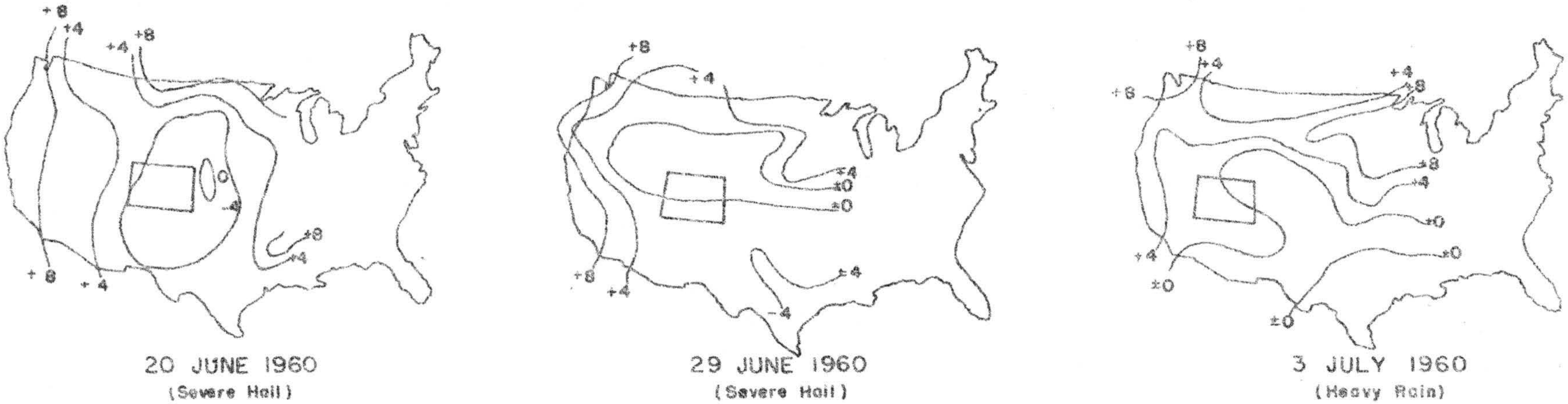


Fig. 7. Showalter stability index, Deg. C.

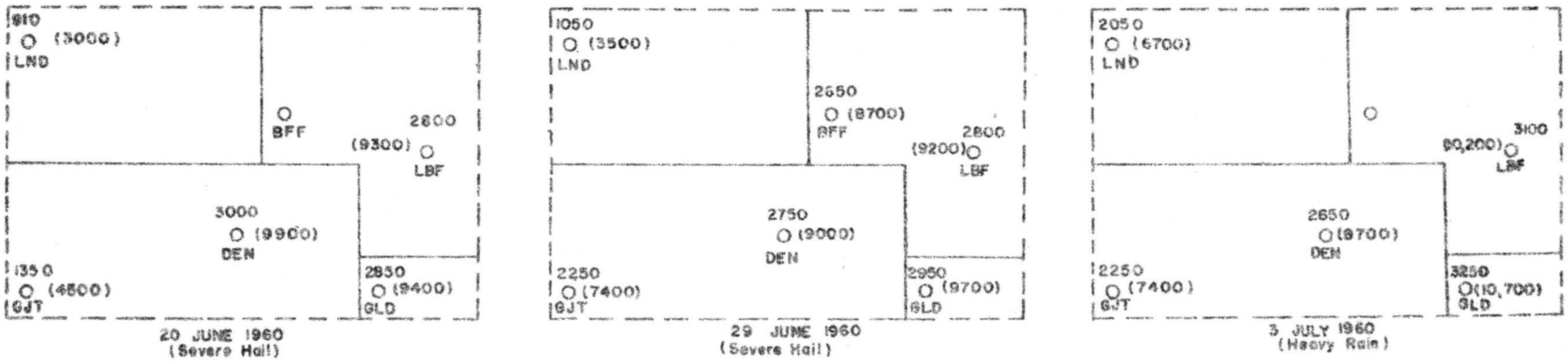


Fig. 8. Height of wet-bulb zero Deg. C above surface, meters. (Height in feet is given in parenthesis).

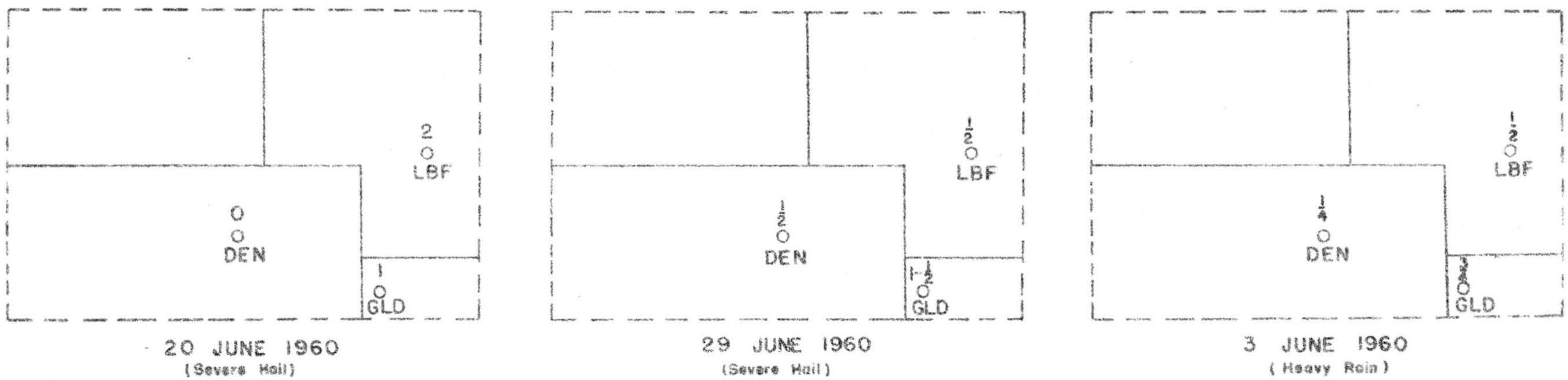


Fig. 9. Maximum hailstone size (inches) forecast by Fawbush-Miller technique, based on soundings from 1700 MST.

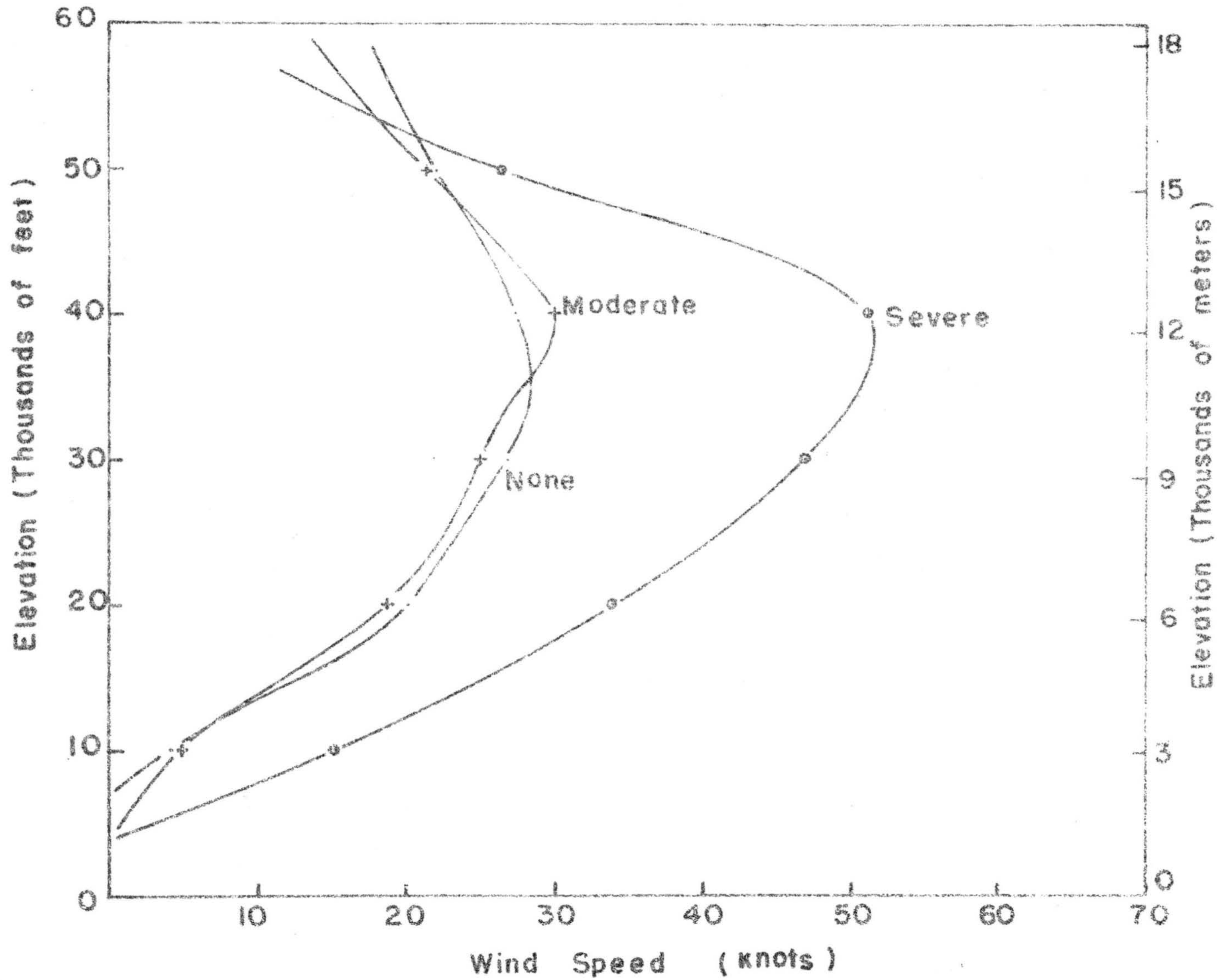


Fig. 10. Average wind profiles along mean wind direction for "severe hail", "light hail", and "no hail" categories, 1961. Each category consists of six days. Wind profiles are averages of DEN, LND, BFF, LBF, and GLD.