SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

Department of the Geophysical Sciences
The University of Chicago

PRECIPITATION IN THE 1960 FLAGSTAFF MESOMETEOROLOGICAL NETWORK

by

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SMRP Research Paper

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KENNETH A. STYBER

Mr. Styber joined our Mesometeorology Project in 1959 as a research meteorologist and actively engaged in the investigation of cumulus to cumulonimbus growth over the mesometeorological research network near Flagstaff, Arizona. As field director during 1960-1961, Mr. Styber participated in the design and operation of the Flagstaff network, which is primarily supported by the U. S. Air Force and partially by the U. S. Weather Bureau.

While attempting to establish a meteorological station at the top of Agassiz Peak, 12,350 ft. Mr. Styber was injured in a helicopter crash. On September 18, 1961 he died of injuries incurred during this accident.

Mr. Styber was born in Chicago, Illinois on November 11, 1933. In 1955 he graduated from the Illinois Institute of Technology with a B.S. in Mathematics, after which he attended St. Louis University. From 1956-1959 he served as a weather forecaster in the Air Force being stationed at Geiger Field, Washington and Osan, Korea. In 1959 he came to the University of Chicago to work on his M.S. in Meteorology, which he was to complete at the end of 1961.

Mr. Styber is survived by his parents, Mr. and Mrs. Elmer J. Styber of 1917 South 58th Court, Cicero, Illinois.

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ABSTRACT

During the summer of 1960, a mesometeorological network was established in a 30 x 40 mile area around San Francisco Mountain near Flagstaff, Arizona. Precipitation measurements were made using 165 small, transparent plastic cups and 165 aluminum-foil hail indicators. Instrument spacing of from one to four miles along servicing routes in the network area proved satisfactory. Both the rain gage and hail indicator provided reliable measurements. The small-cup rain gages were somewhat more effective in collecting rain up to 0.5 or 0.6 inch than standard gages. Personnel attempted to service the network each day prior to the afternoon convective activity; however, this was not always possible. For those measurements including rainfall of more than one day, separation into single-day amounts was effected. Analysis showed that the isohyets of maximum rainfall were elongated in the direction of the 700- to 500- mb winds. Practically all of the heavy rain storms were accompanied by hail. At least two of the hail areas were observed to be of an elliptical configuration, and were covered by locally heavy fogs. Coincidence of the axes of maximum daily precipitation and the axes of maximum total precipitation lead one to suspect the existence of preferred storm tracks.

I. DEVELOPMENT AND CALIBRATION OF THE RAIN GAGE

In the summer of 1960 a University of Chicago research group led by Dr. Tetsuya Fujita operated a network of meteorological stations in a 30 x 40 mile rectangle around San Francisco Mountain near Flagstaff, Arizona (1). A dense network of rain gages was envisioned, dependent upon the time and personnel available for daily servicing and the cost of each gage. Because of the length of the service routes and the large number of instruments involved, it was decided to devise a method that would allow for rapid measurements of precipitation in the field. Also, to simplify reduction of the data, we preferred that the measurements be direct, or that a conversion factor be a simple one.

A number of containers of various dimensions and shapes were investigated. And, finally, plastic cups were found to be quite satisfactory because they were inexpensive (five cents per cup), fairly durable, easily obtained locally, and allowed direct measurement of precipitation because of their transparency. The cups are slightly tapered cyclinders with inner diameters of 1.17 inches and 1.13 inches at the top and bottom, respectively (Fig. 1), and were available in three heights, 2.67, 2.85, and 3.15 inches.

Each cup was held by a rubber band onto a wooden stake that had been driven into the ground so that the top of each gage was about one foot above the ground. In order to minimize evaporation, approximately 1/2 inch of No. 2 diesel fuel was put into each gage. Precipitation settled to the bottom of the cup, where it was clearly discernible in the yellowish oil. (When viewed from the top, the precipitation had an oval or kidney-shaped configuration, as long as the amount was too small to cover the entire bottom of the cup.)

Calibration was performed in the laboratory by dropping known amounts of rain water into the diesel fuel. It was found that the precipitation continued to prefer the oval or kidney shape until an amount equivalent to 0.15 inch was reached. At this point, it appeared just as likely as not to cover the entire bottom. Above 0.15 inch, the rain always covered the bottom. From these results, a precipitation measurement chart was prepared (Fig. 2). To determine amounts of rain up to 0.15 inch, the observer placed the cup directly on the chart while holding the bottom in a horizontal direction. He then moved it from one drawing to the next in ascending order until he found a drawing which was

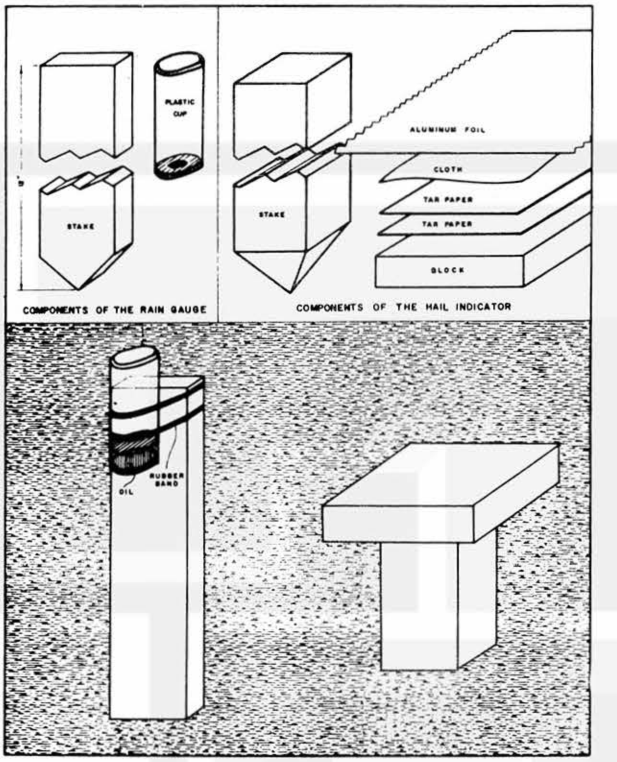

Fig. 1 Schematic diagram showing the simple cup rain gage and the hail gage used in the 1960 Flagstaff network.

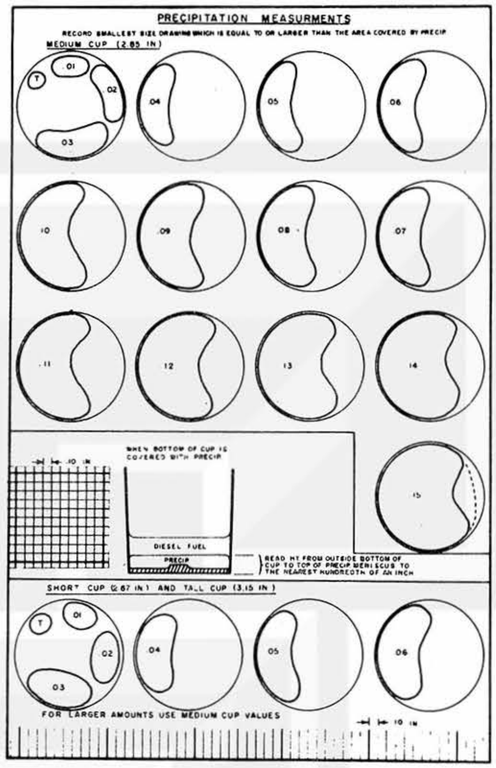

Fig. 2 Precipitation measurement chart. Service personnel estimated the rainfall below 0.15 inch by comparing the shape of the water bubble with that indicated in the chart. For a larger amount, the inch scale is provided to measure the height of the water meniscus from the outside bottom of the cup.

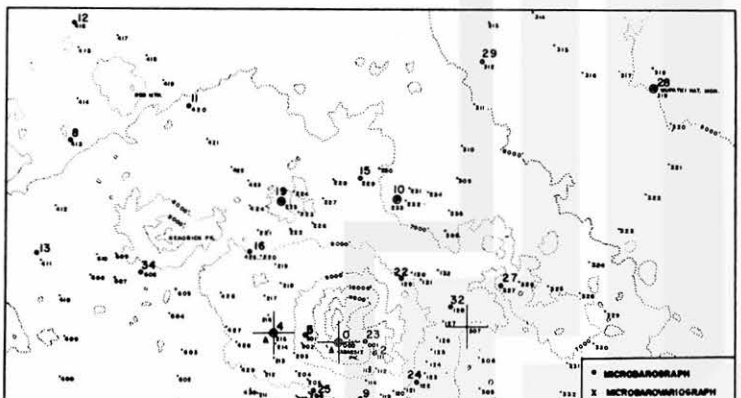

Fig. 3 Mesometeorological Network operated July 17-29 in the vicinity of Flagstaff, Arizona. There were about 165 non-recording rain gages, the same number of hail indicators, 33 microbarographs, 10 hygrothermographs, 10 wind recorders, a 16-mm time lapse camera and 2 T-11 cameras in the network.

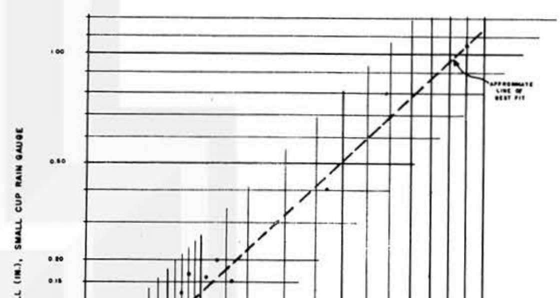

Fig. 4 Scatter diagram showing the amount of precipitation measured by both the cup rain gage and the standard gage, which were placed next to each other at the Airport, Wapatki and Walnut Canyon Stations.

equal to or larger than the area covered by precipitation.

When rain covered the bottom of the cup, the observer read the height from the <u>outside</u> bottom of the cup to the top of the water meniscus. For this, two scales marked in tenths of an inch were provided on the chart. To determine the correct amount of rain from the field reading two factors had to be taken into account. First, the thickness and geometry of the cup base added .09 inch to the correct height. Second, the slight taper of the cup added to the correct height. Let h be the height of the meniscus top measured from the outside bottom of the cup. The actual depth of the rain water after correcting the thickness and the geometry of the base is given by

$$h' = h - 0.09 \text{ (inch)}.$$

The amount of the rain in terms of the depth, h", is expressed by

$$h'' = h' \frac{(1.13 + 0.008h')^2}{(1.17)^2} \text{ (inch)}$$

which can be expanded into

$$h'' = -0.08 + 0.91h + 0.013h^2 + 0.00005h^3 \text{ (inch)}.$$

Although this expression is fairly convenient to use, a further simplification was made by anticipating that observations of 0.50 inch or more would be relatively infrequent. Indeed, it turned out that they accounted for less than 3% of all the observations. Thus, finally, the formula was reduced to

$$h'' = (0.91h - 0.08) \text{ (inch)}.$$

For larger readings, an error of about 4% is introduced; but this is altogether reasonable considering the magnitude of errors introduced by other factors such as the wind and the size of raindrops which might split along the edge of the cup.

II. THE RAIN-GAGE NETWORK

A network of 142 rain-gage stations was established to begin with, and later expanded to 165 stations. Figure 3 gives the location of the gages together with all of the other instruments in the network.

Five service routes were established so that each route connected stations as follows:

Route Number	Stations
1	100-132
2	199-235
3	300-343
4	400-431, 500, 501, 600-610
5	502-507

Stations on routes 1, 2, and 3 were serviced in ascending numerical order beginning in the morning and ending around 1400 hours. The order of collection on route 4 varied, but generally the southern portion was collected in the morning, the northern portion in the afternoon. Route 5 was serviced when convenient by the office staff, who were located at station 502 in Flagstaff. In addition, limited data were collected from stations 000 and 001 at the Top of Agassiz Peak and Doyle Saddle, respectively.

Observers entered all data collected at each station in a log together with the time and any comments that might be helpful in interpreting the data. The log was delivered personally to the office everyday. Amounts of precipitation were measured in hundredths of an inch as read on the rain-gage chart. No conversions were made in the field. Traces were recorded as "T." When the gage was missing or destroyed and there was no evidence of rain having occurred, the letter "M" was recorded. The letter "U" signifying "unknown," was used to indicate that, for some reason, the amount of rain could not be measured, but that there was definite evidence that rain had occurred since the previous day's reading. Such evidence might be wet ground, rain spots on the hail gage, some rain remaining in a cup that had cracked and leaked, or statements by residents that rain had occurred. The following table gives a summary of stations installed on a given storm day together with the number of observations that was recorded as unknown or missing and the percent of unknown or missing observations.

Date (July 1960)	Number of Stations Installed	Number of Observations Unknown	Number of Observations Missing	Percent of Missing or Unknown
16	142	0	4	3
17	144	0	7	5
18	146	0	4	3
19	145	0	10	7
20	146	0	3	2
21	146	5	13	12
22	165	5	5	6
23	165	4	8	7
24	164	1	5	4
25	165	0	5	3
26	165	0	5	3
27	165	5	7	7
28	164	1	4	3
29	164	0	8	5
	Total 2186	Total 21	Total 88	Average 5

In three locations--Flagstaff Airport (6), Wupatki National Monument (28), and Walnut Canyon National Monument (31)--the small cups were placed near the standard rain gages. The following table compares the amounts of rain recorded at these stations.

<table>
<tr><th></th><th colspan="2">AIRPORT</th><th colspan="2">WUPATKI</th><th colspan="2">WALNUT CANYON</th></tr>
<tr><th>DATE</th><th>Cup</th><th>Rain Gage</th><th>Cup</th><th>Rain Gage</th><th>Cup</th><th>Rain Gage</th></tr>
<tr><td>16</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>17</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>18</td><td>0</td><td>0</td><td>trace</td><td>0</td><td>0.09</td><td>0.05</td></tr>
<tr><td>19</td><td>0</td><td>0</td><td rowspan="2">trace</td><td rowspan="2">trace</td><td>0</td><td>0</td></tr>
<tr><td>20</td><td>trace</td><td>trace</td><td>0.02</td><td>0</td></tr>
<tr><td>21</td><td>trace</td><td>trace</td><td rowspan="2">trace</td><td rowspan="2">trace</td><td>trace</td><td>0</td></tr>
<tr><td>22</td><td>0.04</td><td>trace</td><td>0.13</td><td>0.07</td></tr>
<tr><td>23</td><td>trace</td><td>trace</td><td>0.16</td><td>0.11</td><td>0</td><td>0</td></tr>
<tr><td>24</td><td>0.41</td><td>0.44</td><td>0</td><td>0</td><td>0.01</td><td>0</td></tr>
<tr><td>25</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>26</td><td>trace</td><td>0</td><td>trace</td><td>0</td><td>trace</td><td>0</td></tr>
<tr><td>27</td><td>0.17</td><td>0.08</td><td rowspan="2">0.02</td><td rowspan="2">0.02</td><td rowspan="3">1.04</td><td rowspan="3">1.10</td></tr>
<tr><td>28</td><td rowspan="2">0.15</td><td rowspan="2">0.16</td></tr>
<tr><td>29</td><td>0.20</td><td>0.13</td></tr>
</table>

Two-or three-day totals are given in those instances where single-day totals were not available for both gages. These values are plotted in Fig. 4. It will be noted that the cups were somewhat more efficient in recording the amounts from a trace up to 0.6 inch. In fact, it appears that the small gage records around 0.004 inch of rain before the standard gage records any at all. This very likely reflects the fact that evaporation in the cup was negligible compared with that in the larger gages. That the standard gage was more effieient in collecting large amounts of rain is explained by considering the limited height of the cup, which allows the diesel fuel and perhaps some of the rain to splash out of the cup during the larger storms. The limited catching area of the cups and the effects of the winds generally associated with larger storms, are other factors that may explain the differences between the two gages.

In any event, the small cup rain gages proved to be excellent instruments from the standpoint of cost, reliability, ease of measurements, and accuracy.

III. REDUCTION OF RAINFALL DATA

In general, one expects the summer rainfall at Flagstaff to be of a convective nature, occurring mostly after 1400 hours. It was hoped that the rainfall amounts on a given day could be measured before that day's storm began, so that the amounts measured, for instance, on July 17 represent the rainfall that occurred on the 16th. Unfortunately, we were not able to service all stations each day before the rain began. In these cases, the measured precipitation included the amounts that had fallen on two days. This created a problem in separating the amount so as to give the correct precipitation for each day. A number of methods were used to minimize the separation error.

A. Cloud and Weather Observations. Personnel took observations of clouds and weather at least once an hour while in the field. They sketched their observations on translucent paper which overlayed a network base map. Since most of the persons in the field had little or no experience in weather observing, the observations were admittedly non-professional. Nevertheless, they often proved useful in locating storms because as many as five or six observations might be taken from different places at the same time.

B. Station Weather Observations. Personnel kept records of visible weather, if any, occurring at each station and comments such as those justifying an entry of "U" in the log.

C. Statements of Residents and Others. Much useful information about the time of weather occurrence was gained from local residents and others, including tourists, in the area. Forest Service and Park Service personnel (stations 3, 18, 19, 28, and 31) were especially helpful.

D. Statements of Observers. Project personnel were "interviewed" immediately upon return to the headquarters office. The data were carefully scanned, and entries that might present problems in interpretation or plotting were questioned. As it turned out, this interview proved to be a very important aspect of the project. Questioned immediately after servicing the network, observers were often able to provide quite detailed information which amplified or clarified the entries. Even as little as one day later they were usually unable to discuss in detail the day in question.

Many of the problems of separation were solved with relative ease because either (1) so small an amount was involved that separation, even if wrong, could produce no error greater than, say, 0.01 inch at either station, or (2) at the area in question little or no rain was observed to have fallen on one of the days. Of 2186 measurements, 163 (7.5%) required separation, but in only 67 (3.1%) was it necessary to attribute more than 0.01 inch to both of the days in question.

Separation in more difficult cases was attempted after the data had been plotted. At this point, a certain amount of cross-checking was possible because the routes were close to or intersected one another at various places. For example, station 425, which was usually serviced in the afternoon, lies between stations 220 and 221, which were usually serviced in the morning. Similarly, stations 307 and 308 were serviced early, while stations 127 and 128, and 132 were serviced late. A number of other route intersections may be noted. Reasonable separations were thus effected in a number of cases by comparing station to station in the areas of intersecting routes.

Certain cases were very difficult to separate by any of the means discussed above. Here the "most reasonable" analysis was made with the data on hand, the analysis being modified after comparison with radar photographs when available. Due to the MTI circuit, extending to 50 nautical miles from Winslow, radar coverage was limited to the sector northwest of San Francisco Mountain. Fortunately, the storms that created the greatest separation problem occurred in this area. Especially notable were the afternoon storms of July 28 and 29 and the morning storm of July 30. Since data for stations 417 through 425 were collected on the 29th during the afternoon rain, these rain amounts had to be attributed in part to the 28th and in part to the 29th. Few cross-checks are available in this area. To make matters worse, the data collections on the 30th for stations 411 through 425 were made while rain was in progress on the 30th. Only by using the radar photographs were we able to separate the data in what we felt was a reasonable manner. Shown in Fig. 5 are radar echoes in the northern portion of the network for every 20 min from 1340 to 1520 MST on the 29th. Two separate storm areas may be noted. The first storm developed over the northwestern slopes of Red Mountain at 1340 MST. It grew rapidly between 1410 and 1420 MST, remained nearly stationary until 1500 MST, and then moved out to the northwest. The second area is found in the north-central part of the network. The five echoes shown at 1520 MST spread out and merged into a single echo by 1530 MST. The radar echoes shown in Fig. 5 may be compared with the isohyet analysis of the 20th (Fig. 19).

IV. THE HAIL INDICATOR

A simple aluminum-foil hail indicator similar to that described by Schleusener and Jennings (2) was located near each rain gage (Fig. 1). A 3-1/2 x 3-3/4 x 3/4 inch piece of wood nailed to a stake driven in the ground served as the base for the indicator. The observer placed two pieces of tar paper and a piece of cloth on the wood surface and covered them with Reynolds Wrap Jr. light-duty aluminum foil. Original plans had called for the use of styrofoam under the foil, but none was available locally. As it turned out, the tar paper and cloth proved adequate.

The foils were replaced whenever impressions of any type were observed on them. It was found that rain generally made a smooth impression, while hail made a sharply defined impression which creased the foil. In a number of cases, the weave of the cloth was superimposed on the impression left by hail. Impressions made by soft hail were not nearly so well defined and were often filled with or surrounded by very small irregularly placed indentations.

No attempt was made to "read" the foils in the field. Instead, they were brought back to the office and examined there. After some experience it became fairly easy to distinguish between the different types of impressions. Foils collected after storms during which the hail size had been observed were closely examined to see if the size of the impressions was indicative of the hail size. Although no detailed laboratory calibration of impression versus hail size was attempted, it is felt that the hail sizes obtained after comparison with test foils were reasonably accurate.

The simple hail indicator proved to be an extremely reliable instrument. Only 15 foils were missing while a total of 2185 was collected. Examination of these foils confirmed 193 soft hail and 192 hail cases at the stations. On 27 foils, the type of hail could not be determined. As in the case of rain, a number of observations reflected more than a single day's hail; however, for hail no separation was attempted. Exceptions to this were instances in which it could be established by statements of residents and other people in the area that all of the hail had occurred on one of the days in questions. Of the 192 hail reports, 21 (11%) could not be separated into single-day totals.

Both the size and number of hailstone impressions are useful for discussing storm intensity. A breakdown of hail sizes shows 30, 46, 85, and 25 foils indicating 1/16, 1/8, 1/4, and 1/2 inch hail, respectively. There were also 6 reports in which no size was specified. The number of collected foils as the function of number and diameter of stones is tabulated in the table on the following page.

Number of stones \ Diameter of stones	1/8 inch	1/4 inch	1/2 inch
1 - 3	14	27	4
4 - 6	13	12	2
7 - 10	10	9	0
11 - 25	11	17	3
26 or more	7	16	1
No. not available	0	8	13

V. ANALYSIS OF THE RAIN AND HAIL DATA

The isohyet analyses for July 17-29 are given in Figs. 7 through 19. Upper-air winds obtained at the Flagstaff Airport are shown in the lower right corner of each analysis. As discussed by Fujita, Styber, and Brown (1), the daily isohyet pattern appears to be elongated in the direction of the 700- to 500-mb winds.

Shown on each isohyet analysis are 1/4 and 1/2 inch hail as determined from the hail indicators or as observed. A number of particularly intense storms were noted. On the 21st, a storm deposited mostly 1/4 inch hail along U.S. 66 west of Flagstaff. Soon after the storm, a dense fog developed, and highway traffic was curtailed.

On the 22nd, hail was observed in conjunction with heavy rain activity directly over the Peaks. Mt. Agassiz appeared to be covered with hail (1). On the 26th, a roughly elliptic area of 1/4 inch hail was observed south of the Peaks.

Two particularly interesting hail storms occurred on the 27th. The first covered an elliptic area around station 430. Hail of up to 5/8 inch diameter accumulated to a depth of 2 inches on the highway and in the forest (Fig. 6A), producing a locally heavy fog (Fig. 6B). The second storm occurrec between stations 325 and 327. Tourists in the area reported 1/2 inch hail accumulated to a depth of 2 inches. Precipitation in the area in the form of rain was light.

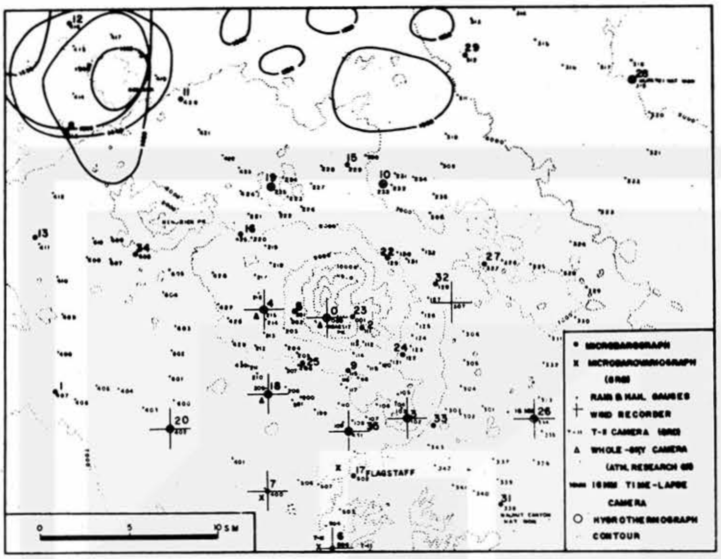

Fig. 5 Radar echoes over the northern portion of the network on July 29, 1960. Their boundaries were obtained by projecting the radar pictures from Winslow, Arizona onto the base map.

Fig. 6A and 6B Hail stones and fog in the vicinity of station 430. Aerial survey made by the Atmospheric Research group revealed the hail area was elliptic approximately 1-1/2 miles across.

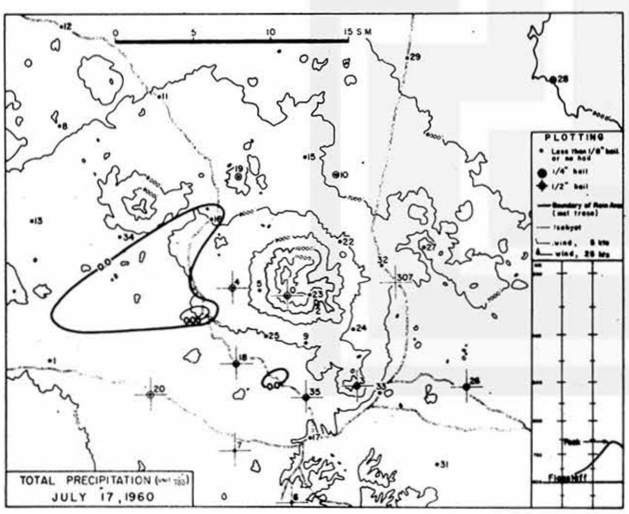

Fig. 7 Total amount of precipitation on July 17, 1960. This was the first day of the summer rain season in the Flagstaff area.

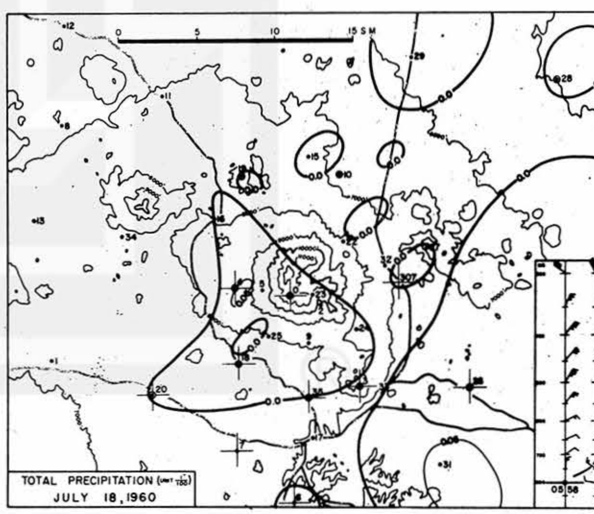

Fig. 8 July 18, 1960. Northeast winds which prevailed the whole day produced cumulonimbus clouds in line along the leeward side of the peaks.

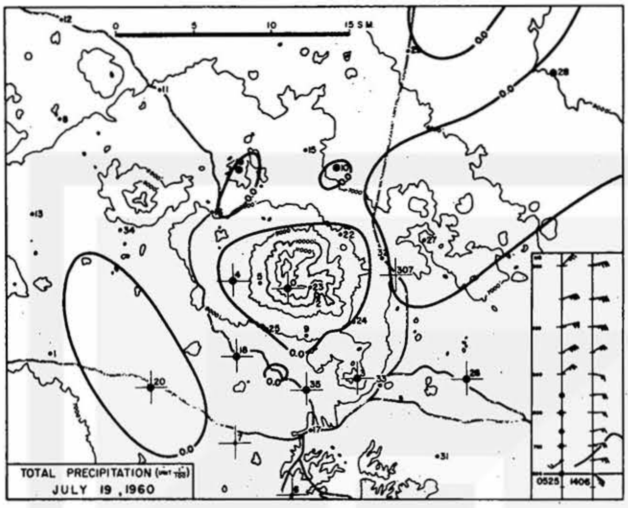

Fig. 9 July 19, 1960. Cumulus and cumulonimbus development was similar to that of the previous day.

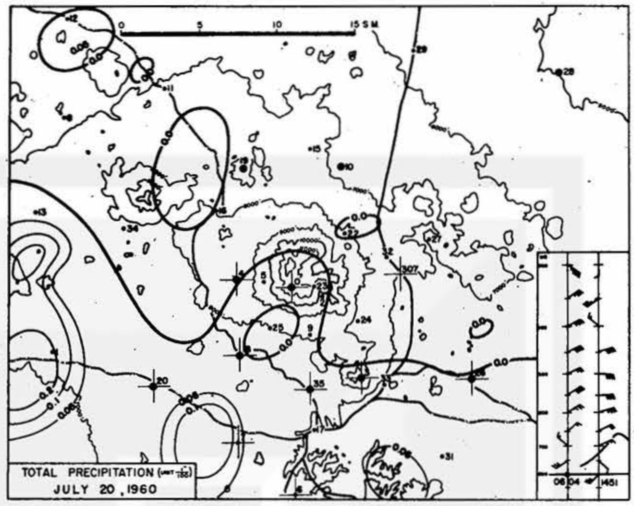

Fig. 10 July 20, 1960. Up to three tenths of an inch of rain fell over the southern part of the network, but no evidence of hail was reported.

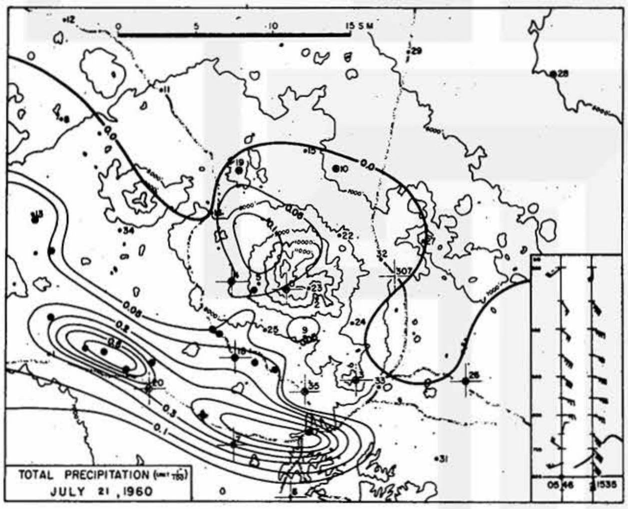

Fig. 11 July 21, 1960. For approximately one hour following 1300 MST, hail up to half an inch fell within a belt, 5 miles in width along highway 66.

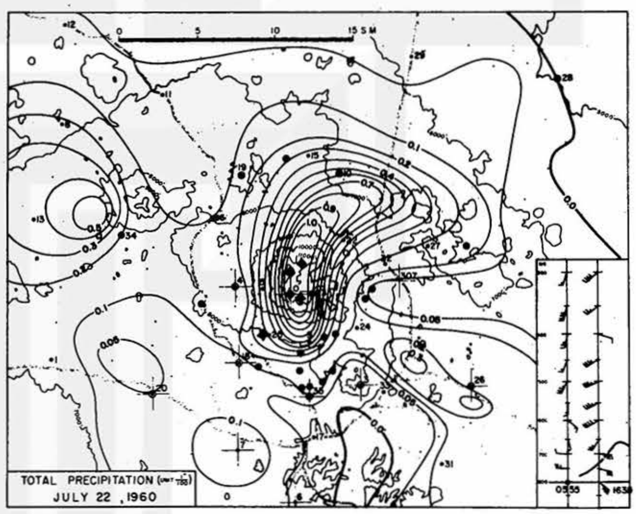

Fig. 12 July 22, 1960. Within one hour around 16 MST, the tops of San Francisco peaks above 10,000 ft became completely white.

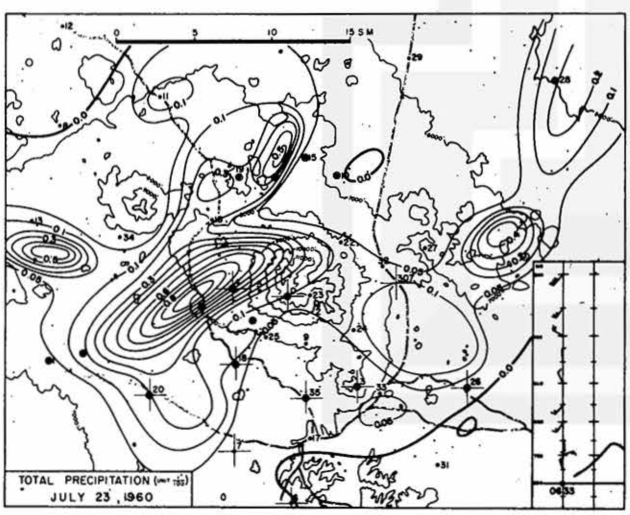

Fig. 13 July 23, 1960. The rain, which fell mostly in the afternoon, amounted to approximately one inch in some areas but the rain patterns were not related to the topography.

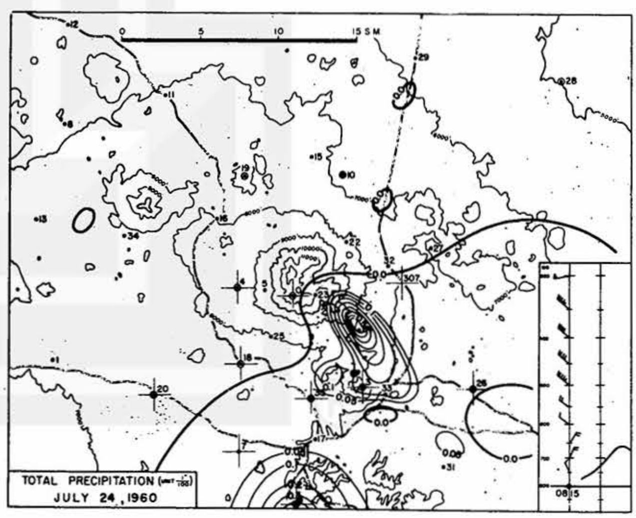

Fig. 14 July 24, 1960. Direction of the prevailing winds was northwest and small cumulonimbus produced a scattered small rain area.

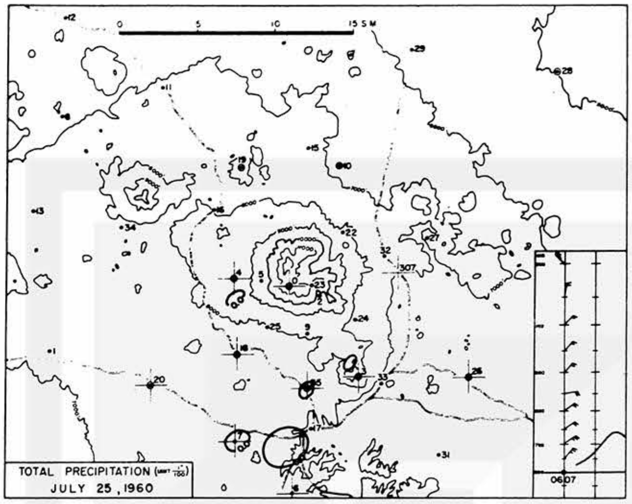

Fig. 15 July 25, 1960. Convective activity was limited to cumulus and to towering cumulus. At night, however, some rain and lightning were observed

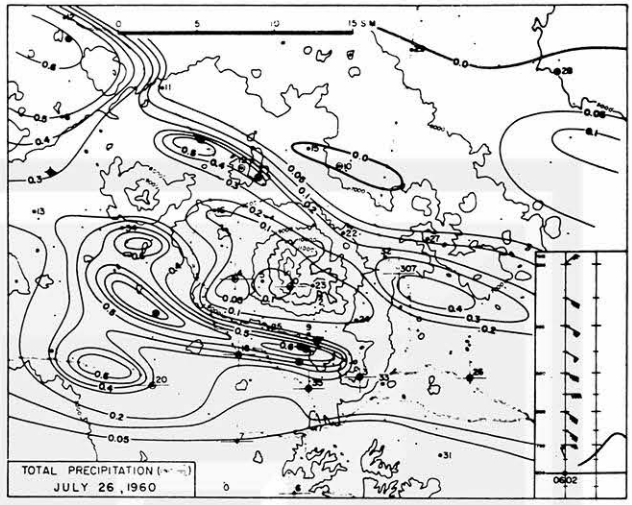

Fig. 16 July 26, 1960. A severe thunderstorm started around 7 PM and continued for two hours in a narrow belt extending west from Elden Mountain.

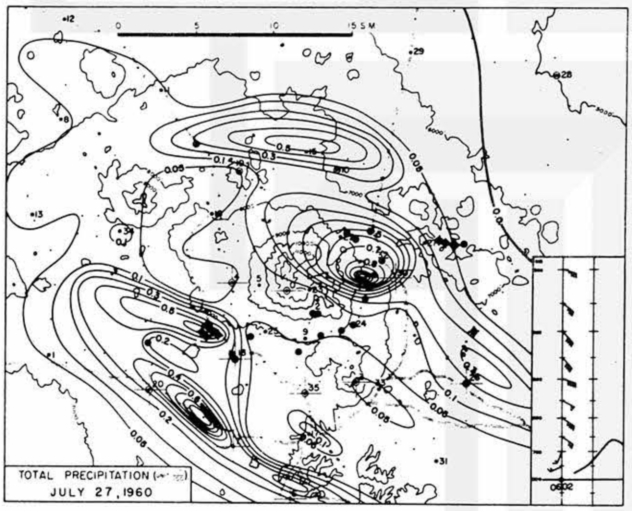

Fig. 17 July 27, 1960. Hailstorm shown in the photograph in Fig. 6 occurred in an elliptic area some two miles northwest of station 18.

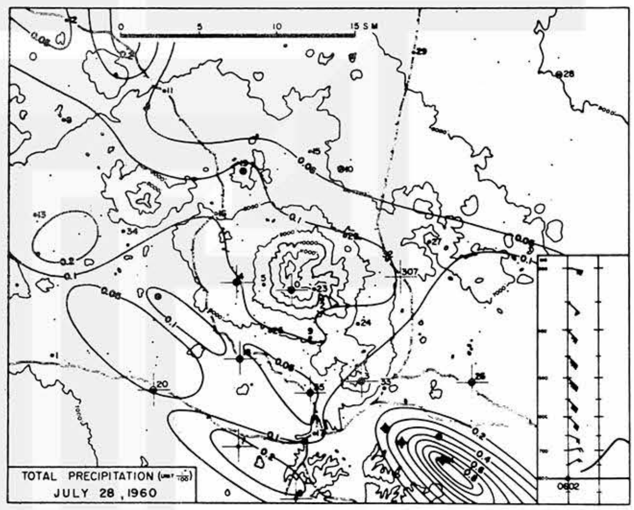

Fig. 18 July 28, 1960. Severe thunder was heard in the Flagstaff area around midnight, but there was little rain over the area.

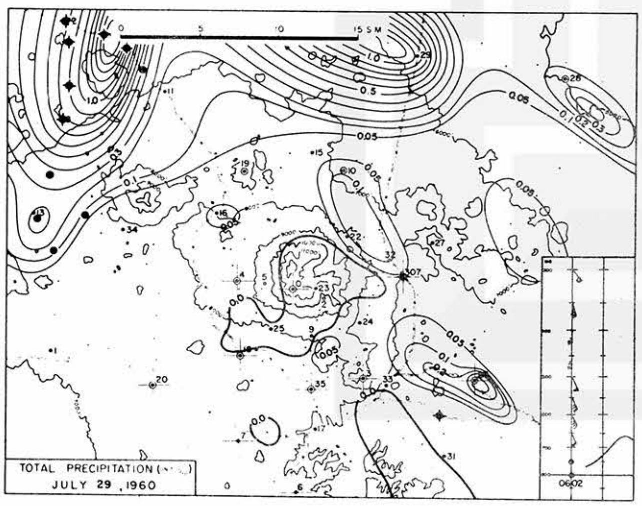

Fig. 19 July 29, 1960. The heavy hailstorm near the northwest corner of the network was confirmed by Winslow radar (Fig. 5).

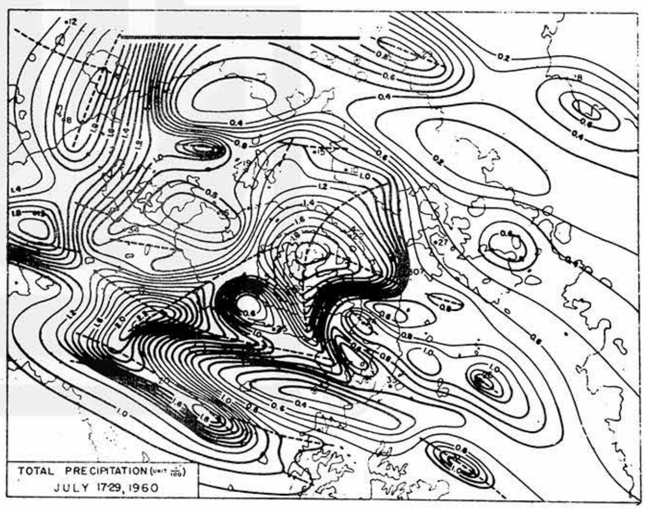

Fig. 20 Total amount of precipitation for July 17-29, 1960 over the Flagstaff Mesometeorological network. Units are in inches, and dashed lines indicate the track of each rainstorm.

Hail occurred on the 28th in the southeastern portion of the network along the maximum isohyet axis of a fairly intense storm. A particularly intense storm on the 29th produced hail over an extensive area in the northwest corner of the network.

One of the significant points brought out by the hail statistics is the high frequency of hail occurrence. Practically all storms that produced 0.5 inch of rain or more were accompanied by hail.

The daily rainfall amounts for each station were totalled for the period July 17-29. At stations where observations had been reported missing, amounts were extrapolated from the daily isohyet analysis. Analysis of total precipitation is shown in Fig. 20. Contour shading was used to emphasize the maxima and minima. Dashed lines indicate the axes of maximum precipitation of the separate storms as taken from the daily analyses.

We may note that repeated coincidence of the axes of maximum daily precipitation with the axes of maximum total precipitation. These results lead one to suspect the existence of preferred storm tracks in the Peaks area. Whether or not such tracks exist in a subject for future investigations.

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