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TECHNICAL NOTE 2734

SUMMARY OF AVAILABLE HAIL LITERATURE AND THE EFFECT OF HAIL ON AIRCRAFT IN FLIGHT

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SUMMARY

Available information on the hail phenomenon affecting aircraft in flight has been examined. This paper attempts to coordinate the present knowledge of hail with the effect of hail on aircraft in flight and includes (1) a digest of the literature on the physical properties, the occurrence, and the formation of hail, (2) a survey of the hail effect on aircraft in flight from analyses of 57 cases of airplanes damaged by hail, (3) a résumé of hail information for the benefit of pilots, forecasters, and ground operational personnel, and (4) an annotated hail bibliography of 552 articles for use of research personnel.

INTRODUCTION

As larger and better aircraft are built, and the reliability of instrument-flying techniques is increased, more and more routine operational flights are made during adverse weather in which hail, turbulence, and other atmospheric phenomena are encountered. Flying in such adverse weather has caused the aviation interests to become alarmed at the major structural damage caused by even brief encounters with hail. Present-day transport and military airplanes are expensive pieces of equipment, and on occasion a 10- to 30-second encounter with hail has caused damage severe enough to warrant scrapping the airplane. The problem of avoiding hail areas and thus reducing the occurrences of hail damage involves methods of hail detection, elimination, and/or prediction.

Inasmuch as all of the available information concerning hail can be ascertained only by a study of voluminous literature and unpublished data from many different sources, a compilation of available information on hail is necessary for an adequate understanding of the problem. This paper has been prepared, therefore, to meet this need and includes a compilation of the literature on the physical properties, occurrence and formation of hail, a study of hail damage to airplanes, a résumé of hail information for pilot and forecaster, and an annotated bibliography of 552 articles arranged chronologically by subject. The bibliography
includes the material published up to August 1950. For completeness, the references used in the text have also been included in the bibliography.

Acknowledgement is hereby made of the kind assistance and cooperation of the following persons, whose help was invaluable in compiling this paper:

For a great deal of the material used in the bibliography

Dr. C. F. Brooks, Blue Hill Observatory, Harvard University; and
Mr. Malcolm Rigby, Meteorological Abstracts and Bibliography, American Meteorological Society.

For an appreciable amount of data on hail damage, much heretofore unpublished

Mr. H. T. Harrison, Jr., United Air Lines, Inc.;
Mr. John Moore, Directorate of Flying Safety, U.S. Air Force; and
Mr. Richard J. Roth, Crop-Hail Insurance Actuarial Association.

For material on the theory of hail formation and current research on hail

Dr. Vincent J. Schaefer, General Electric Research Laboratory;
Dr. Helmut Weickmann, Evans Signal Corps Electronics Laboratory,
U.S. Army; and
Dr. E. J. Workman, New Mexico School of Mines.
This section presents information concerning hail phenomenon from the literature. In some cases the information is presented without comment, and no attempt is made to evaluate the reliability of one set of data over another set of data. The physical properties of hailstones are given with some comment as to the average properties of the stones as found on the ground. The frequency of occurrence of hailstorms is discussed. Theories concerning the formation of both hailstorms and hailstones are also covered.

**PHYSICAL PROPERTIES OF HAILSTONES**

**Definitions**

Although hail in its larger forms is readily identifiable, it becomes increasingly more difficult to identify in its smaller forms. Several of the hydrometeors that are similar to hail of the smaller variety are known as small hail, sleet, snow pellets, and snow grains. In order to identify hail from the other types of hydrometeors, the following definitions, normally used in the United States and given in reference 1 by the U.S. Weather Bureau, are used in the present paper:

"HAIL - Ice balls or stones, ranging in diameter from that of medium-size raindrops to an inch or more. They may fall detached or frozen together into irregular, lumpy masses. They are composed either of clear ice or of alternating clear and opaque snowflake layers. Hail often accompanies thunderstorm activity. Surface temperatures are usually above freezing when hail occurs. Determination of size will be based on the diameter, in inches, of normally shaped hailstones."

The present paper is primarily concerned with this type of hail.

"SMALL HAIL - Semitransparent, round or conical, grains of frozen water. Each grain generally consists of a smaller grain of soft hail as a nucleus, surrounded by a very thin ice layer, which gives it a glazed appearance. The grains are wet when they fall at temperatures above freezing. They are not crisp or easily compressible, and do not generally rebound or burst even when they strike hard ground."

"SLEET (ICE PELLETS) - Transparent, more or less globular, hard grains of ice about the size of raindrops, that rebound when striking hard surfaces. Its fall may be continuous, intermittent, or showery."
"SNOW GRAINS (GRANULAR SNOW) - The solid equivalent of drizzle. They take the form of minute, branched, star-like snowflakes, or of very fine simple crystals. At times they have the appearance of rime. They occur under meteorological conditions similar to those of drizzle, except that the temperature is lower."

"SNOW PELLETS (SOFT HAIL) - White, opaque, round or occasionally conical kernels of snow-like consistency, 1/16 to 1/4 inch in diameter. They are crisp and easily compressible, and may rebound or burst when striking hard surfaces. They occur almost exclusively in showers."

In the preceding definitions of hail and small hail no clear line of demarcation between the two is given. References 2 and 3 indicate that there is a discrepancy in the definition of small hail. Reference 2 gives the demarcation as 0.2 inch in diameter whereas reference 3 does not include the small-hail classification.

Composition

Although the usual hailstone consists of alternate layers of clear and opaque ice, with as many as 20 to 25 concentric layers, hailstones have been observed which were composed entirely of either clear ice or opaque ice. Some hailstones with the usual alternate shells of clear and opaque ice have a core of supercooled liquid water. A core containing an air bubble has occasionally been observed, but this type is rare. Because of the wide variance in the composition of the hailstones, no definite appearance of hailstones can be assured, although within a single hailstorm the composition of the stones varies only slightly. Hailstones may have a variety of extraneous matter contained in them; muddy and black hailstones have been reliably reported.

During the 1950 hail season at Denver, H. T. Harrison, Jr., manager of Weather Service for United Air Lines, Inc., analyzed the structure of
a few of the stones which fell during a storm on September 16th. The results of this analysis are presented below:

<table>
<thead>
<tr>
<th>Size (diam.) (in.)</th>
<th>Number of samples</th>
<th>Type of core (a)</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/8</td>
<td>9</td>
<td>9 opaque</td>
<td>2 0 2 0 3 0 1 0 1</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>5 opaque, 3 clear, 2 mixed</td>
<td>2 2 3 1 0 1 1 0 0</td>
</tr>
<tr>
<td>1 1/16</td>
<td>6</td>
<td>5 opaque, 1 clear</td>
<td>0 1 3 0 1 1 0 0 0</td>
</tr>
<tr>
<td>1 3/4</td>
<td>2</td>
<td>1 opaque, 1 clear</td>
<td>0 0 0 1 1 0 0 0 0</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
<td></td>
<td>4 3 8 2 5 2 2 0 1</td>
</tr>
</tbody>
</table>

(a) Nineteen of the 20 stones with an opaque core had an odd number of layers, whereas the 5 stones with a clear core all had an even number of layers.

Specific Gravity (Density)

Since a hailstone may be composed entirely of clear or opaque ice, the limits of its specific gravity are between 0.25 and 0.92. Little information concerning the actual specific gravity of hailstones is available; therefore, various sources have been used in the present paper to determine a representative value. The specific gravity of ice formed on airplanes has been found to range from 0.70 to 0.85. Reference 4 gives the specific gravity of ice collected at Mt. Washington as ranging from 0.45 to 0.92. In theoretical papers on hail in which an exact expression is required for calculations, specific gravities between 0.6 and 0.8 have been chosen. From a consideration of these values, the average specific gravity is evidently close to 0.7, and this value has been used when necessary in calculations presented in this paper. Inasmuch as density and specific gravity are numerically equal in the metric system, specific gravity has been used herein as specific gravity has a further advantage of being dimensionless.

Shape

Most hailstones have one of the following three shapes: spherical, conical, or discoidal. The spherical shape is by far the most common, especially when the hail is small. Some hailstones have also been observed in the shape of spheroids, pyramids, dumbbells, and so forth,
or as jagged, irregular lumps of ice. Furthermore, large hailstones of any shape may have many irregularities and protuberances. Numerous accounts of hailstones of unusual appearances can be found in the Monthly Weather Review issues of the first three decades of the present century.

Figure 1 is presented as an example of some of the typical forms that hailstones may take. Figure 1(a) is a reproduction of a photograph which appears in reference 5. These stones fell at Washington, D. C., on April 28, 1938. The conical shape is readily discernible. The stones of figure 1(b) fell at Potter, Nebraska, on July 6, 1928, and are reproduced from reference 6. The stone on the extreme left had the appearance of being formed by the amalgamation of two smaller stones. The stones shown in figure 1(c) fell in Czechoslovakia on June 13, 1946. This photograph is reproduced from an unpublished manuscript by Dr. Helmut Weickmann. The stones in the lower right corner of the photograph appear to be composed of one or two alternating layers of clear and opaque ice. The alternating layers in these stones are thicker and therefore more noticeable than in the usual stone.

Size

With a few exceptions, there have been no systematic observational programs for determining hailstone sizes. Although many reports have been published describing the size of the largest hailstones, the structure of hail, the amount of crop loss due to hail, and so forth, very little has been written on the hail size distribution within hailstorms. Observers tend to report the largest and moderate sizes of hail but fail to record the smaller sizes; therefore, the average compiled from these reports may be larger than is actually the case.

The most common sizes of hailstones measured on the ground at various regions have been analyzed by Eliot (India), Ruby (France), Hann and Süring (Central Europe), and Humphreys (United States), and have been found to be (reference 7):

<table>
<thead>
<tr>
<th>Region</th>
<th>Most common size (diam.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(in.)</td>
</tr>
<tr>
<td>India</td>
<td>0.2 to 1.2</td>
</tr>
<tr>
<td>France</td>
<td>0.2 to 0.8</td>
</tr>
<tr>
<td>Central Europe</td>
<td>Up to 1.2</td>
</tr>
<tr>
<td>United States</td>
<td>0.5 to 0.7</td>
</tr>
</tbody>
</table>
Eliot's study of 597 hailstorms in India gives the following indication of hail size frequency:

<table>
<thead>
<tr>
<th>Hail size (diam.)</th>
<th>Frequency (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(in.)</td>
<td>(cm)</td>
</tr>
<tr>
<td>Up to 0.2</td>
<td>Up to 0.6</td>
</tr>
<tr>
<td>0.2 to 1.2</td>
<td>0.6 to 3.0</td>
</tr>
<tr>
<td>Above 1.2</td>
<td>Above 3.0</td>
</tr>
</tbody>
</table>

After a study of 7 years' records, 1931 to 1937, United Air Lines, Inc. (reference 8) found that hailstones of walnut size (1 in.) or larger occur in about 1 out of 800 thunderstorms in the area between Chicago and Denver. The frequency of hail half this size is several times greater. During the period studied, there were 136 storms in the United States which produced hailstones 1 inch or larger; of these stones, 50 percent were 1 to 2 inches, 40 percent were 2 to 3 inches, and 10 percent were 3 inches or larger.

Accounts of storms of large hailstones are scattered throughout the literature. Apparently, the largest hailstones ever recorded in the United States are those which fell at Potter, Nebraska on July 6, 1928 (reference 6). Several of these stones are shown in figure 1(b), the largest stone being on the right. This stone measured 5.4 inches in diameter and weighed 1.5 pounds.

Hailstone size in relation to weight (spherical shape assumed) is shown in the following table:

<table>
<thead>
<tr>
<th>Hail size (diam.)</th>
<th>Weight (specific gravity 0.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(in.)</td>
<td>(lb)</td>
</tr>
<tr>
<td>(cm)</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.0017</td>
</tr>
<tr>
<td>1.0</td>
<td>.013</td>
</tr>
<tr>
<td>2.0</td>
<td>.11</td>
</tr>
<tr>
<td>3.0</td>
<td>.36</td>
</tr>
<tr>
<td>4.0</td>
<td>.85</td>
</tr>
<tr>
<td>5.0</td>
<td>1.66</td>
</tr>
<tr>
<td>6.0</td>
<td>2.86</td>
</tr>
</tbody>
</table>
Temperature

Inasmuch as the temperature of hailstones at the altitude of formation has not been determined because of measurement difficulties, other means must be used to estimate the probable temperatures. Temperatures inside hailstones, determined immediately after the stones strike the ground, have been found to be at, or less than, 0° C, and often between -5° C and -15° C. If the average atmospheric temperature aloft during hailstorms is considered, the temperature of hailstones at altitudes from 10,000 to 20,000 feet should generally be between the limits of 0° C and -20° C, although in some instances and at higher altitudes the temperature of the stones may temporarily be lower than -20° C.

OCCURRENCE OF HAILSTORMS

The climatology of hail is an important phase of the subject, since the knowledge of where and when hail occurs has a direct bearing on the effect of hail on airplane operation. This section discusses the occurrence of hailstorms in respect to local ground, geographical, hourly, seasonal, and vertical distributions of hail and, also, the duration of hailfall.

Local Ground Distribution

In agricultural areas where crops are damaged by hail, an observer may analyze the local ground distribution of particular hailstorms. Using this method, several investigators have studied the hail pattern on the ground; however, the instantaneous pattern on the ground or aloft has never been thoroughly investigated. Since the hailstorm nearly always has a movement with respect to the ground, the hail pattern produced on the surface has a length proportional to the speed of the storm and to the length of time the hail falls. On the other hand, the width of the hail area as seen on the ground is a direct measure of an instantaneous storm area.

Several studies of the local ground distribution of hailstorms have been made. Frank J. Phillips (reference 7), after studying the areas of hailstorms in Missouri, stated that hail appears in narrow bands ranging from 2 to 400 feet in width and up to a half mile or more in length. This study was a detailed one of only a few storms. Prohaska (reference 7) made a study of 113 European hailstorms having a length of 12.5 miles or more and found that the most common width ranged from 5 to 6 miles. Bürklin (reference 9) found from a study of damaging hailstorms at Württemberg over a 60-year period (1828 to 1887) that the smallest area damaged was 6 square miles and the greatest, 124 square miles.
The most complete study of hail areas to date was made by Hoyt Lemons (reference 10). This study included 2105 hailstorms that occurred in the United States over a 14-year period (1926 to 1939). The most common width was found to be 1 to 2 miles; however, the width varied considerably and ranged from a few yards to 75 miles. Figure 2 shows the results of Lemons' study of hailstorm widths.

Because of the restricted nature of the analyses made by Phillips, Prohaska, and Bühler, and because of the greater number of storms studied by Lemons, the latter's data seem to be the most representative.

Geographical Distribution

Although the occurrence of hail is generally associated with the occurrence of thunderstorms, the geographical distributions of the two are not the same. In general, the world-wide pattern of hail occurrence seems to be characterized by greater frequency in the "continental interiors of middle latitudes, diminishing seaward, equatorward and poleward" (reference 11). In order to provide the material for a detailed comparison of the thunderstorm and hail distribution patterns in the United States, the Weather Bureau evaluated 40 years of records (1904 to 1943) from 217 first-order stations. The results of this analysis are given in reference 12. Charts are included showing the average number of days with hail compared with days with thunderstorms, annually and monthly. These hail distribution charts include the "small hail" of the West Coast and, as a result, produce a rather significant looking maximum in that region, especially in the Pacific Northwest. Figures 3(a) and 3(b) show the average yearly distributions of hail and thunderstorms, respectively, over the United States. Figure 3(a), which does not include the Pacific Coast small hail, is taken from reference 13. (The small hail is of little concern to aviation operation.) Figure 3(b) is taken from reference 12.

The following table is given to show the greater frequency of hail in the United States and the decreased frequency northward, southward, and seaward:

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean annual frequency of hail days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galveston</td>
<td>0.9</td>
</tr>
<tr>
<td>New York</td>
<td>1.0</td>
</tr>
<tr>
<td>Milwaukee</td>
<td>2.0</td>
</tr>
<tr>
<td>Cheyenne</td>
<td>9.4</td>
</tr>
</tbody>
</table>
Lemons (reference 11) also made a comprehensive study of hail occurrence in low and high latitudes where there has been a lack of observational data. In very low latitudes hail is infrequent; however, at some subtropical localities the frequency of hail is as great as at middle latitudes, although usually smaller in size. Hail occurs more frequently and is more destructive at the higher ground elevations in low latitudes. In high latitudes hail may occur at both high and low elevations and, in many cases, the so-called hailstones are actually snow pellets. Hail at high latitudes is usually associated with frontal rather than thermal thunderstorms. The size of the stones is generally small and, because of the small concentration of people and crops, hail is of little consequence economically.

In the middle latitudes, which include the United States, appreciable data are available from crop damage. The magnitude of the annual hail damage can be realized from the following estimate of damage to three of the 1947 crops in the United States:

<table>
<thead>
<tr>
<th>Crop</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>$118,617,000</td>
</tr>
<tr>
<td>Corn</td>
<td>85,996,000</td>
</tr>
<tr>
<td>Tobacco</td>
<td>20,470,000</td>
</tr>
</tbody>
</table>

Statistics released by the Crop-Hail Insurance Actuarial Association of Chicago, based on claims for losses inflicted by hail (reference 14), are in reasonable agreement with the U.S. Weather Bureau maps of hail distribution (fig. 3(a)). Figure 4, which shows the 1950 crop-hail insurance rates (50 percent of which are used in paying claims), is based on these statistics. This figure is published here through the courtesy of the Crop-Hail Insurance Actuarial Association. When the insurance data are compared with the Weather Bureau statistics, discrepancies are found in certain small sections of the country. Several factors lead to these minor discrepancies, the chief of which is the difference in the methods of observations. The Weather Bureau statistics are based only on reported hailstorms at first-order stations, damage notwithstanding, whereas the Crop-Hail statistics take into account only those hailstorms which cause damage to crops and for which losses are claimed.

Another important consideration in determining the actual distribution of hail is the ratio of area to point frequency of hail occurrence. Although present statistics are based on point frequencies, it appears that area frequency would be more accurate. Alfred Angot (reference 9) of the French Meteorological Service estimated that an ideal reporting network for obtaining realistic area frequencies of hail should be one station for each 4 square miles. Nothing approaching such
a network, however, has ever been established. A. L. Shands (reference 15) of the U.S. Weather Bureau worked out a theoretical ratio of area to point frequency for the state of Iowa by using a network of 150 cooperative weather bureau stations. Results indicated a ratio of 15 to 1, which means that, if average point frequency of hail in Iowa is 4 days a year, hail should be found somewhere in the state about 60 days per year. During 1949, United Air Lines (reference 16) made a study of hailstorms in the Denver area. A total of 11 observation points in this area were used and the results were compared with the observational data released by the Weather Bureau station at Denver. During this period, 33 hailstorms were reported from the United Air Lines observational network, and the comparison gave an 11 to 1 ratio of area frequency to point frequency. Further observations with twice as many reporting points in the network were made in the Denver area during the 1950 hail season; however, the results are not yet available.

Shands also points out that when a single station in Iowa observes hail on only 1 day out of 12 days during which thunderstorms occur, the ratio builds up to almost 1 to 2 when the occurrence of hail over the state is compared with the occurrence of thunderstorms over the state. This ratio is comparable to the hail-thunderstorm ratio of 1 to \( \frac{1}{4} \) which was observed at the Denver Weather Bureau station during the 1949 hail season and the ratio of 1 to 1.3 reported by the United Air Lines observational network in the Denver area.

Although the Weather Bureau and the Crop-Hail Association present the most reliable statistics available on the distribution of hail in the United States, these statistics must be applied with discretion because of the limitations of the data upon which these statistics are based. Available information on the ratio of area to point frequency further substantiates the fact that hail distribution charts are good for comparison purposes but should not be used specifically for any one area.

**Hourly Distribution**

It is generally agreed that 50 percent of all hailstorms occur between 1400 and 1800 LST (local standard time) and less than 10 percent, between midnight and noon.

In 1944, United Air Lines (reference 17) reported that in the central and eastern United States large hail falls mainly in showers between 1200 and 2100 LST and is especially frequent between 1500 and 1800 LST. During the 1949 study of hailstorms in the Denver area (reference 16), the average time of occurrence in May was found to be 1300 LST but shifted to 1430 LST by September.
Lemons (reference 10) in a study of the hourly distribution of 2355 hailstorms in the United States over a 14-year period (1924 to 1939) has reported that one-third of all hailstorms that damaged crops occurred between 1600 and 1800 LST and two-thirds, between 1300 and 1900 LST. Figure 5, showing the hourly distribution of damaging hailstorms, is taken from reference 10.

Seasonal Distribution

Hail in the United States is generally a warm-season phenomenon, occurring chiefly in the spring and summer (reference 12 and 18). The country may be divided into three regions of hail occurrence: (1) the East and South, including the Gulf States, (2) the Interior from the Ohio Valley westward, including the Great Plains and the Rocky Mountains, and (3) the Pacific Coast area.

Early in January the light hail area begins in the South and gradually spreads northward. Most of the East and South have some hail from mid-March to mid-June, then there is a gradual waning of activity, especially in the coastal areas. A hail-free area appears along the Texas coast early in the year. This area moves northward and eastward until most of the inland area is free of hail by mid-October; however, some small areas with rugged terrain continue to have hail after October.

The Interior is characterized by a warm-season northward development and spread of hail activity. Beginning in February the hail area starts a northward and eastward movement from the southern Plain States until late in April, then it spreads north-westward over the Plains and Rockies until late June. By late September, southward recession and lessening intensity is evident. Early in October a hail-free area appears in Montana. This area begins a southward movement, fanning out in the north, until by early January it extends from Canada to Mexico.

Hail in the Pacific Coast area is chiefly a cool-season phenomenon. Even in the winter the frequency of real hail is low. Most of the hail in the West Coast States is small hail and does little damage.

Figures 6(a) and 6(b), respectively, show the months of maximum hailstorm and thunderstorm frequencies in various sections of the United States. From a comparison of the two figures it can be seen that in most sections the month of maximum frequency of hail is earlier than the month of maximum frequency of thunderstorms. These two figures were taken from reference 12, although figure 6(a) was modified slightly in order to eliminate some of the very small monthly hail variations in the northeast.
Vertical Distribution

Very little data are available on the vertical distribution of hail aloft. The Thunderstorm Project (reference 19), although not carried out in the areas of maximum hail occurrence, has shed some light on the subject. During 551 cloud traverses by airplanes in thunderstorms and potential thunderstorms over Florida in 1946, hail was reported in 22 cases, or 4 percent of the traverses. In Ohio in 1947, 812 cloud traverses were made through thunderstorms and hail was reported on 51 occasions, or 6 percent. In almost all of the cases where hail was encountered, the stage of development of the cloud could not be classified. Table I, taken from reference 19, gives a detailed breakdown of the hail intensities and the flight altitudes at which hail was encountered in Florida and Ohio.

Hail was encountered most often at 16,000 feet over Florida, and at 10,000 feet over Ohio. It appears that the region of hail in any storm and the duration of hail in that region are relatively small. When hail was present in a cloud, it was found in only 25 percent or less of the traverses through the storm at the level of its occurrence. Seldom was hail found at more than one or two levels in the same storm. It therefore appears that hail occurs in very narrow bands within thunderstorm clouds and occurs less frequently above 20,000 feet.

Duration of Hailfall

Most authors seem to be rather reluctant to commit themselves on the duration of hailfall, and when a commitment is made the phraseology is ambiguous; wording such as "less than an hour" and "a few minutes" is typical. Phillips (reference 7) found that the most common duration of hailstorms in Missouri was only "several minutes". Eliot (reference 7), who considered a large number of hailstorms in India, concluded that in most cases hail lasted 30 minutes or less.

Although frequently hailstorms are reported for periods much longer than 15 minutes, the average duration of a hailstorm in the United States is about 15 minutes at any particular point. Figure 7, taken from reference 20, shows hail 2 feet deep which fell at Trinidad, Colorado, on June 14, 1937. It is highly improbable that this large amount of hail could fall in a period as short as 15 minutes, since it is roughly equivalent to 12 inches of rainfall. Numerous reports of hail a foot or more deep are also available.
FORMATION OF HAIL

Theories on the formation of thunderstorms (potential hail-producing storms) are few in number, rather well-developed, and in basic agreement. The situation in regard to theories on formation of hailstones is quite different. Many theories exist postulating different physical processes, but no one theory has been found to be completely satisfactory. The purpose of this section is to give an account of some of these theories on hailstorm and hailstone formation.

Hailstorm Development

Hailstones fall almost exclusively from convective-type clouds, although hail does not fall from all thunderstorms. The mechanism by which thunderstorms develop has been well-established, and numerous references describing this mechanism are available in textbooks and elsewhere. The most complete and recent report on thunderstorms is reference 19. Although the mechanics of thunderstorms has been established, the problem as to which thunderstorms produce hail is known in only the broader sense. In general, the more violent storms produce hail.

Detailed surface and upper air information is necessary to understand the cause of these storms. The chief factor involves atmospheric instability, a thermodynamic condition in which vertical currents, once induced, are favored and accelerated. The degree of instability and the vertical extent determine the magnitude of the vertical currents; heating and frontal or orographic lifting initiate these currents. As the air ascends it cools adiabatically and, if sufficient moisture is present, it condenses and forms clouds. With additional lifting, precipitation develops. In most cases the precipitation does not develop until the top of the cloud extends at least above the freezing level. The life cycle of the thunderstorm cell may be divided into three phases: the building, the mature, and the dissipating stages. It is thought by many that hail, if present, occurs late in the building stage or early in the mature stage.

Theories of Hailstone Development

Although numerous theories are available concerning the formation of hailstones, most theories are limited to an explanation of only a particular method of hail formation. William Ferrell in 1885 theorized that whirlwinds of tornadic character could form and hold heavy hailstones in the air until their final fall to the ground. Bigelow later contradicted this theory, as it did not explain how the centrifugal force of the hailstone could be counteracted in the tornado. Both Hann and Kassner have
proposed theories for the formation of hailstones. Hann suggested that they are formed by the explosion of larger spherical stones, whereas Kassner suggested that small precipitation particles of ice grow conical by accretion of supercooled cloud droplets on their bases. (See reference 21.)

Formation in ascending currents.- "Elementary Meteorology" (reference 22), published in 1894, included much general information on thunderstorms and hail. Davis suggested that hail is produced in active convectional storms by the freezing of raindrops that have been formed at low levels and carried upward by the central ascending currents to altitudes of very low temperature; the frozen raindrops, becoming coated with a layer of snow, increase in size until they fall through the less active currents. This process may be repeated several times. Humphreys (reference 23) supports this theory and has made it the most widely accepted theory of hail formation.

Knowing the drag of a sphere of a given size, Humphreys (reference 24) computed the magnitude of the vertical velocity necessary to sustain hailstones (specific gravity 0.7) of the same size, as follows:

<table>
<thead>
<tr>
<th>Diameter of hailstone (in.)</th>
<th>Velocity necessary to sustain (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>49</td>
</tr>
<tr>
<td>4</td>
<td>83</td>
</tr>
</tbody>
</table>

The velocities given in the table appear reasonable, especially those which sustain the smaller hailstones. Grimminger (reference 25) carried the analysis of Humphreys further by taking into account the effect of turbulence in the air stream. (This so-called fine-grain turbulence is not the large-scale turbulence usually considered by meteorologists.) The drag of a sphere is partially affected by the intensity of the fine-grain turbulence. Grimminger calculated that, with a great amount of turbulence, the speed of the upward current necessary to sustain the hailstone is roughly double the speed under normal conditions.

Some theoretical work has been done to determine the upper limits of hailstone size. E. G. Bilham and E. F. Relf (reference 26) based their investigation on aerodynamic considerations of the drag of a sphere in vertical currents. The relation between the terminal vertical velocity and hail diameter was deduced from the values of the drag coefficient (obtained from observations on spheres towed by airplanes) and a plot of the data resulted in an S-shaped curve which indicated that, as the
terminal velocity increases, the hail diameter increases, decreases, and then increases again. (This S-shaped curve results from the sharp change in the drag coefficient of a sphere at a Reynolds number near 350,000.) Since the second part of the S-curve represents unstable conditions and since the third part would require vertical velocities above practical limits, it was determined that the first part of the curve represented the true theoretical range in the relationship between terminal velocity and hail diameter. The theoretical upper limit of hailstone size in vertical currents was found to be about 5 inches in diameter and the maximum weight, about 1.5 pounds. This upper limit is in good agreement with the size of the largest stones found on the ground.

Formation during descent only.- In 1938 T. E. W. Schumann (reference 27) pointed out that, although vertical currents aid the formation of hailstones, it is not necessary that they be of sufficient magnitudes to lift the hailstones during formation or even to suspend them. Once a solid core is formed to which other cloud droplets or raindrops may adhere, such a particle accumulates ice on descent. The amount of ice accumulated is dependent on the length of fall (time) and the liquid water content of the air. For example, Schumann has calculated that, with a vertical wind velocity of only 8 meters per second and a concentration of water of 13 grams per cubic meter, a hailstone 3.2 inches in diameter (specific gravity 0.6) can be formed in falling from 29,500 to 13,000 feet (9 to 4 km). Schumann points out that, although a water concentration of 13 grams per cubic meter is above average, it is not uncommon.

E. Gaviola and F. Alsina Fuertes (reference 21) also are of the opinion that upward currents are not a necessity in the formation of hailstones. These authors assumed that hailstones form initially from cloud particles of supercooled water droplets and ice or snow crystals. After initial formation a hailstone can grow, while falling only, by successive wetting and solidifying as it collides with other cloud particles. The initial stone, while it is wet, grows by accretion of snowflakes, but it soon becomes solid because the liquid phase gives up its latent heat to bring the temperature of the snowflakes up to 0° C. Once the hailstone is solid, no more snowflakes adhere to it; it now has to collide with supercooled water droplets to become wet again. When the hailstone becomes wet, a clear ice layer is formed, which grows as long as colliding supercooled droplets predominate over ice and snow crystals. When the hailstone again becomes solid, an opaque layer forms. The alternating layers of the hailstone are thus produced. By assuming an absolute humidity of 10 grams per cubic meter, the authors made calculations which show that a hailstone would take about 5 minutes to fall from 26,000 to 13,000 feet (8 to 4 km) through an atmosphere at rest, and would grow into a 2-inch hailstone.
Formation in convectional vortex rings.- Robert E. Horton (reference 28) has indicated that hail may form in convectional vortex rings. The moisture within the vortex ring has a circular movement around the ring, such that ascending and descending currents of moist air result. No explanation, however, is given of the manner in which accretion occurs when hailstones grow in size or of the temperature of the hailstones relative to the surrounding air. It is assumed that the hailstones form a clear ice layer on ascent and an opaque layer on descent. Atmospheric vortex-ring cloud systems occur in conjunction with violent convection storms and, when these systems occur, the ascending moist air is concentrated within the vortex rings. Conditions favorable for the formation of these convectional vortex rings are also shown to be favorable for the production of hailstones. The vortex-ring condition produces hailstones of uniform size and layers and has sufficient ascent velocity to sustain large hailstones. The vortex-ring clouds are likely to produce large hailstones, whereas the tubular-type clouds are likely to produce hailstones of various forms, sizes, and different internal structures, but generally of a small size.

Formation similar to icing on aircraft.- Dr. Helmut Weickmann* has developed theories on the formation of hailstones based on icing research experiments conducted in Germany during World War II. The original experiments were conducted to investigate the meteorological conditions associated with ice formation on aircraft; in later years Dr. Weickmann used the same data to arrive at his theories on hail formation.

Weickmann proposes the theory that opaque ice may result from two different processes: first, by individual crystallization of cloud droplets at the surface of the falling hailstone, and second, by air bubbles becoming imbedded in water which freezes quickly. The essential condition for the formation of clear ice involves the freezing process which must progress slowly enough to allow coagulation of the deposited droplets before freezing. Since the rate of crystallization is slow near 0° C and increases with decreasing temperature, the formation of clear ice near 0° C and the formation of opaque ice at lower temperatures can be expected. With a high liquid-water content in the clouds, however, the rate of crystallization may be slow even at low temperatures.

The apparatus used in the aircraft-icing research conducted by Dr. Weickmann is shown in figure 8. Figures 9, 10, and 11 indicate typical samples of ice collected during the course of this investigation. The

*Dr. Weickmann is now employed by the U.S. Army Signal Corps at the Evans Electronics Laboratory, Belmar, New Jersey. During 1950 he revised and translated into English his original paper on "The Formation of Hailstones" and has kindly sent a copy of the revised paper to the authors.
hailstones of figure 1(a) show a similarity to the ice deposits of figures 9 and 10, in that they both have a conical shape and an opaque appearance. Similarity is also noted between the hailstones of figure 1(c) and the ice of figure 11; both have wart-like irregularities and a predominance of clear ice. The clear-ice appearance is caused by the exceedingly slow rate of crystallization which allowed the cloud droplets to coagulate before freezing occurred; the slow rate of crystallization is a result of the high moisture content and near-freezing temperature.

**Contribution from nucleation experiments.**- It has been ascertained experimentally that a cloud containing water droplets of below-freezing temperature can be converted into an ice-crystal cloud by the addition of either dry-ice pellets or silver-iodide crystals to the cloud. Project CIRRUS, headed by Drs. Irving Langmuir and Vincent Schaefer and sponsored by the Armed Services, has been conducting basic research on cloud physics since 1947. References 29 to 36 include most of the work done on this project pertinent to the hail problem.

Dr. Langmuir, Dr. Schaefer, and others believe that destructive hailstones form in certain thunderstorms when a minimum of sublimation nuclei is present. Preliminary data show that the number of sublimation nuclei in the atmosphere is extremely variable—from 100 to 1,000,000 per cubic meter. Future experimental investigations may prove the theory that destructive hailstones (over \( \frac{1}{2} \text{-inch in diameter} \)) form only in clouds where the nuclei count is low, say below 5,000, whereas seeding of these clouds to obtain only rain might require a higher count, 20,000 or more. (The numbers of nuclei given here are for quantitative comparison only.) If this theory can be proved, it would be comparatively easy to increase the nuclei in potentially dangerous hail areas to an amount which would eliminate destructive hail and still not cause abnormal rain.

A cloud-seeding project (reference 37) has been in operation in the Rogue River Valley section of southwestern Oregon since May 1949. (The techniques used in this project are similar to those advocated by the personnel of Project CIRRUS.) Hail is reported to have damaged up to one-half the fruit crops in the Rogue River Valley in each of the 38 years previous to 1949, with one exception. So far as is known, hail has not fallen on the project area since the project has been active.

The operators of this project, Messrs. Harvey Brandau and Eugene Kooser, believe, as do Drs. Langmuir and Schaefer, that the greater the number of ice crystals within clouds, whether naturally or artificially formed, the less chance there is of hail forming. The "overseeding" method, consequently, is used in this project. The nature of the seeding material and the method of application to the cloud has not been released as yet. The investigators agree with others that hail is formed during
the formative and transition stages of a thunderstorm's development and
in the portions of supercooled clouds having temperatures between -5° C
and -39° C, regardless of the altitude of occurrence.

Other theories.- F. H. Ludlam (reference 38) calculates the condi-
tions of growth of a hailstone by the process of accretion on the basis
of its heat budget. The coagulation process gives the growing ice
particle a coat of supercooled water which commences to freeze at the
ice surface. A rise of temperature occurs as the latent heat of fusion
is liberated, and the temperature at the ice surface and within the
liquid film tends to rise to 0° C. This particle, however, loses heat
to the environment both by conduction and evaporation; the rate of
growth is then dependent upon the rate at which this heat loss can pro-
ceed. According to Ludlam, this explanation is also true for larger
ice particles even at temperatures as low as -20° or -30° C. The pres-
ence of alternate layers of clear and opaque ice in the hailstone is
considered to be the result of successive passages of the hailstone
through critical conditions caused by changes in radius, falling speed,
temperature, pressure, and liquid water content in the cloud.

Dr. E. J. Workman (reference 39) has for a number of years been
investigating thunderstorm electrification. Although no theory on the
formation of hail is made by Dr. Workman, he associates the formation
of hail with the lightning phenomenon. During laboratory experiments,
it was determined that a charge is generated as water, which contains
a slight amount of contaminants, freezes. The sign and magnitude of
this charge is determined by the nature and amount of contaminant pres-
ent. This electrical effect occurs only during the freezing process.
Applying these experiments to thunderstorms, Dr. Workman theorizes that
the electricity of the thunderstorm is generated during the formation
of hailstones. Assumption of this mechanism for the production of
thunderstorm electricity suggests possibilities for the control of
lightning discharges.

Concluding remarks.- From the foregoing description of hail-
formation theories, it can be seen that most of the theories start with
certain basic assumptions and then are developed with emphasis on a
particular phase of the hail-formation process. Points of similarity
include (1) vertical currents, (2) temperature variations, (3) hailstone
layer formation, and (4) time or path length requirements. Although
Schumann, Gaviola, and Alsina Fuertes emphasize hail formation on descent
only, they do not deny that hail may also form in ascending currents and
consider that small upward currents retard the fall of the stone.
Although Horton described in detail the vortex-ring type of hailstorm,
which includes both ascending and descending currents, he also believes
that the tubular-convection type of hailstorm occurs by the ascending-
current method presented by Humphreys. Gaviola, Alsina Fuertes, Ludlam,
and Weickmann show much similarity on the formation of opaque and clear
ice layers.
With the growth of aviation, the problems that have arisen from aircraft encountering hail during routine flights have become more and more significant. These hail encounters can cause severe damage to aircraft, in some cases as high as $25,000 per encounter. Nearly all external components of the aircraft, especially the nose section and the leading edges of the wing and tail, are subject to damage. In the early days of aviation, instrument flying was not a common practice; however, now that more and better instruments are installed in aircraft, pilots are not averse to fly for an appreciable time through cloud formations and to land with weather conditions below contact minimums. As a result, aircraft are encountering more frequently thunderstorms in which hail falls. This section deals with the resultant hail damage to aircraft and possible means of eliminating such damage.

EXTENT OF HAIL DAMAGE TO AIRPLANES

The search for information on hail damage to airplanes has revealed that very few articles have been published on the subject, but that appreciable information is scattered among the operational, maintenance, and safety records of the airlines, the U.S. Air Force, and other agencies. Data on 47 cases of hail damage to airplanes are presented as tables II to V. In some of these cases only a small amount of information is available. Table II(a) includes eight cases of hail damage to larger-transport airplanes; table II(b) gives seven cases of damage to smaller-transport airplanes; and table III lists seven cases of hail damage to military airplanes. Limited case histories are given for cases 23 to 47 in tables IV and V. Table IV gives 16 cases of hail damage to transports, whereas table V includes seven cases of damage to military airplanes and two sample cases of damage to airplanes on the ground. All 47 cases presented in tables II to V occurred in the United States except one, which occurred just over the Mexican border. After the analyses of the 47 cases were completed, 31 additional cases became available and have been included herein (table VI) as supplementary information only.

From the photographs available on airplane damage caused by hail, a series of 27 photographs have been included in the present paper as figures 12 to 21. All of the pictures have been taken from the cases presented in the tables.
Wing and Tail Damage

The leading edges of the wing and the tail, as would be expected, were the most susceptible to damage. The amount of damage to leading edges that required extensive repair is shown in a subsequent section. The leading edges of thermally de-iced airplanes, because of the method of construction, are more susceptible to damage than are wings with more leading-edge stiffeners. Wing and tail leading-edge damage can be seen in figures 13(b), 13(c), 13(d), and 14(f). Figure 21 shows the damage sustained by an F-82 fighter-type airplane equipped with thermal de-icing. In addition to the leading edges, the control surfaces are frequently damaged, especially if the surfaces are fabric covered, as in the Douglas DC-3, Beech D18S, and others. Figure 16 illustrates damage to a fabric-covered wing surface of a DC-3.

Fuselage Damage

Damage to the fuselage is generally confined to the forward sections, that is, the nose and the cockpit areas. Windshields or canopies or both are sometimes broken or cracked to such an extent that pilots fear that normal cruising speeds would cause the broken pieces to be blown into the cockpit. With respect to the damage to windshields, the damage caused by hail may be amplified in airplanes with pressurized cockpits because of the added stress from internal pressure. Occasionally one side of the fuselage is damaged more than the other. This condition is presumably caused by the pilot skidding the airplane, thus exposing one side of the aircraft to the falling stones. Plexiglass nose coverings are affected in much the same manner as windshields. Fuselage damage is shown in figures 12(a), 13(a), 14(a), and 17(a); windshield damage, in figures 14(c) and 17(b).

Engine and Propeller Damage

Engine cowlings are damaged to about the same extent as leading edges. Ignition harnesses on engines are frequently damaged sufficiently to require replacement. Cooling fins also are very susceptible to damage. (The only instance of engine failure during an encounter with hail was reported in a Lockheed Constellation which experienced a simultaneous failure of all four engines; this failure was probably due to blocking of the air intakes by hailstones. The engines were restarted after the airplane had left the hail and turbulence area.) Propellers and propeller assemblies are damaged to some extent, but again the damage reported has never been extensive enough to be serious. Types of damage to engines and propellers can be noted in figures 14(b), 18(d) and 20(d).
Accessory Damage

Turrets, radar coverings, antenna loop housings, and landing and navigational lights are the chief accessories that are subject to damage. Landing lights that are imbedded in the leading edge of the wing are, for obvious reasons, more susceptible to damage than are the retractible type. Accessory damage is shown in figure 14(d).

CORRELATION OF HAILSTONE SIZE WITH AIRPLANE DAMAGE

In order to determine the extent of damage caused by various-size hailstones at varying impact velocities, the Indianapolis Experimental Station of the CAA conducted tests on the metal portions of typical Douglas DC-6 and DC-3 wing sections (references 40 and 41). Ice spheres, frozen in appropriate molds, were made in sizes of 0.75, 1.25, and 1.88 inches in diameter (weighing approximately 0.1, 0.5, and 1.6 oz, respectively) and were fired by a compressed-air gun at the wing sections at speeds ranging from 110 to 460 miles per hour. The resulting damage and amount of indentation are shown photographically in figures 22 and 23 and, graphically in figure 24.

The following facts and inferences may be drawn from the CAA tests:

(1) The extent of damage varies with the mass of the hailstone, the impact velocity, the impact angle, and the type (thickness, strength, and shape) of the material hit by the hail.

(2) Hailstones less than 0.75 inch in diameter do not cause significant damage at airplane speeds between 200 and 300 miles per hour.

(3) Leading-edge dents sufficiently large to require repair, say 0.1-inch deep, were produced on a DC-6 wing section (0.040-inch 75S-T aluminum) by

(a) A 0.75-inch ice sphere at 420 miles per hour
(b) A 1.25-inch ice sphere at 300 miles per hour
(c) A 1.88-inch ice sphere at 210 miles per hour

A DC-3 wing section (0.045-inch 24S-T aluminum) was damaged to the same extent by ice spheres of the same three sizes at speeds of 300, 180, and 120 miles per hour, respectively.

(4) Two-inch hailstones cause extensive damage to airplanes at speeds above 300 miles per hour. At 378 miles per hour, a 1.88-inch ice sphere caused the surface of a 75S-T aluminum skin to stave in over an appreciable area; at 294 miles per hour it had the same effect on 24S-T aluminum skin.
It is not immediately evident how the results of the CAA tests can be extrapolated to situations not specifically covered by the tests; however, an analysis can be made as follows to determine approximately how the depth of dent depends upon impact velocity, skin thickness, and type of material. It is assumed that the impact is normal to the skin, that a small flat circular portion of skin is affected by the hailstone, that the deformation of this portion is conical, that the deformation is resisted entirely by the membrane stress produced by the stretching of the skin, that the stretching of the skin is a purely plastic and irreversible action (the radical membrane stress has, at all times, a constant value equal to the yield stress of the material), that the depth of the dent is small compared with the radius of the affected portion of skin, and, finally, that all the kinetic energy of the ice sphere is absorbed in straining the skin.

On the basis of the foregoing assumptions, the force \( F \) necessary to produce a deflection \( d \) beneath the force is given by

\[
F = (2\pi r)(\sigma_y t)d = 2\pi \sigma_y td
\]

where \( r \) is the radius of the circular portion of skin affected, \( \sigma_y \) is the yield stress of the material, and \( t \) is the skin thickness. The strain energy absorbed by the aluminum skin with a deflection \( d \) is equal to the external work done upon it, or

\[
\text{Strain energy} = \frac{1}{2} Fd = \pi \sigma_y td^2
\]

The kinetic energy of the hailstone prior to impact is given by

\[
\text{Kinetic energy} = \frac{1}{2} MV^2
\]

where \( M \) is the mass of the hailstone and \( V \) is the impact velocity. Equating kinetic energy to strain energy and solving for \( d \) gives the following expression for the depth of the dent:

\[
d = \frac{V\sqrt{M}}{\sqrt{2\pi \sigma_y t}}
\]
This result may also be written as

\[ d = k \frac{V\sqrt{W}}{\sqrt{\sigma_y t}} \]

where \( W \) is the weight of the hailstone and \( k \) is a proportionality constant. The theoretical value of \( k \) is 0.00053 when \( V \) is measured in miles per hour, \( W \), in grams, \( \sigma_y \), in kips per square inch, and \( t \) and \( d \), in inches.

Because of the many assumptions made in the theoretical analysis, it would be better to adjust the value of \( k \) empirically to account for additional factors which were eliminated in the original assumptions. Known combinations of values of \( d, V, W, \sigma_y, \) and \( t \) from the CAA tests were therefore substituted in the formula and an experimental value of \( k \) was calculated. The resulting values were not constant but varied as shown in the following table:

<table>
<thead>
<tr>
<th>( d/t )</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Between 0.0002 and 0.0004</td>
</tr>
<tr>
<td>15</td>
<td>Between 0.0005 and 0.0007</td>
</tr>
<tr>
<td>25</td>
<td>Between 0.0008 and 0.0010</td>
</tr>
<tr>
<td>35</td>
<td>Between 0.0010 and 0.0012</td>
</tr>
</tbody>
</table>

ESTIMATION OF HAILSTONE SIZE FROM AIRPLANE DAMAGE

By analyzing 52 photographs covering 11 cases of actual hail damage to airplanes, the authors of the present paper attempted to estimate the sizes of hailstones encountered by these damaged airplanes. Since photographs are generally taken of only the more seriously damaged aircraft, it is logical to assume that the hailstones causing the damage shown in these photographs are among the largest encountered by aircraft. These photographs are, therefore, a record of extreme cases rather than of average cases.

In order to estimate the sizes of the hailstones which caused the airplane damage in the 11 cases, the last formula of the previous section, solved for \( W \), was used in conjunction with the previous table. The depth \( d \) of the largest single isolated dent on each damaged part was estimated from the photographs by several qualified aircraft inspectors (isolated dents were used in order to eliminate the effects
of cumulative damage by numerous hits in the same place); the yield stress \( \sigma_y \) and the skin thickness \( t \) were obtained from the maintenance manuals on the particular type of airplane; and the impact velocity \( V \) was taken to be the true airspeed of the airplane at the time of encounter. A specific gravity of 0.7 was assumed in converting \( W \) to the size (diam.) of the hailstone.

The results of the calculations of maximum hailstone size are shown in the next to last column of the following table. Because of the variation in the depths of the dents over various components of the airplane constructed of the same type of aluminum alloy and the lack of precision in the factor \( k \), the most probable single value of the estimated hailstone size is given, together with an indication of the range of possible error for each case. Since the kinetic energy of a hailstone is probably the most significant index of its ability to inflict damage, the kinetic energy for each case (based on the most probable hailstone size) is given in the last column of the table for comparison purposes only.

<table>
<thead>
<tr>
<th>Case</th>
<th>Photograph of damage (fig.)</th>
<th>Type of airplane</th>
<th>Estimated true airspeed (mph)</th>
<th>Maximum hailstone size (diam.) (in.)</th>
<th>Kinetic energy of impact (ft-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>DC-6</td>
<td>270</td>
<td>1.3 ± 0.2</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>DC-6</td>
<td>295</td>
<td>1.4 ± 0.3</td>
<td>105</td>
</tr>
<tr>
<td>7</td>
<td>14</td>
<td>DC-6</td>
<td>360</td>
<td>1.5 ± 0.3</td>
<td>195</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>DC-4</td>
<td>185</td>
<td>1.7 ± 0.3</td>
<td>50</td>
</tr>
<tr>
<td>11</td>
<td>17</td>
<td>DC-3</td>
<td>225</td>
<td>1.5 ± 0.2</td>
<td>75</td>
</tr>
<tr>
<td>15</td>
<td>--</td>
<td>18</td>
<td>1.3 ± 0.2</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>18</td>
<td>B-29</td>
<td>200</td>
<td>1.8 ± 0.2</td>
<td>100</td>
</tr>
<tr>
<td>17</td>
<td>19</td>
<td>B-29</td>
<td>220</td>
<td>1.7 ± 0.2</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>20</td>
<td>B-29</td>
<td>265</td>
<td>1.4 ± 0.2</td>
<td>85</td>
</tr>
<tr>
<td>20</td>
<td>--</td>
<td>A-26</td>
<td>270</td>
<td>1.5 ± 0.2</td>
<td>120</td>
</tr>
<tr>
<td>22</td>
<td>21</td>
<td>F-82</td>
<td>305</td>
<td>1.6 ± 0.2</td>
<td>165</td>
</tr>
</tbody>
</table>

\(^{a}\)Reference 42 states that circular templates were fitted into the dents caused by the hail, and it was found that the size of the hail was predominantly \( 1\frac{3}{8} \) inches in diameter. This figure compares favorably with the calculated size of 1.4 inches.

On the basis of the evidence shown in this table, the largest hailstones likely to be encountered in flight appear to be about 2 inches in diameter.
ANALYSIS OF FLIGHT AND WEATHER CONDITIONS ASSOCIATED WITH ENCOUNTERED HAILSTORMS

Geographical Distribution and Time of Occurrence

The geographical locations of 57 airplanes at the time they encountered damaging hailstorms during cross-country flights over the United States are presented in figure 25(a). These accidents, for which more complete information is given in tables II to IV, were used to analyze the geographical distribution of hail encounters. (Additional cases became available after the analysis was completed and are included in figure 25(b).) Figure 25(a) includes 10 cases, not given in the tables, in which only a location is known. Inquiries concerning the occurrence of damaging hail over the North Atlantic and North Pacific Oceans adjacent to the United States did not reveal any cases of significant aircraft damage. Figure 25(a) shows the following distribution of hail encounters:

(1) Seventy-five percent of the cases occurred between the Mississippi River and the Continental Divide (shaded area)

(2) Only one case occurred west of the Continental Divide

(3) Only one case occurred east of the Mississippi River where the ground contour is under 500 feet.

Since a large percentage of the cases involve airplanes on transcontinental airways, and since the dense air traffic starts at New York and fans out along four transcontinental routes to the Pacific Coast with varying traffic volume, the figure does not give a true picture of the geographical distribution of hail aloft, especially east of the Mississippi River. The figure, however, does give a realistic picture of the risk of aircraft exposure to damaging hail and, from a consideration of the limited number of cases, favorable comparison is observed with the average annual number of days with hail (fig. 3(b)) and the crop-hail insurance rates (fig. 4). For ease of comparison, the locations of the 57 cases have been superimposed on these charts (figs. 3(b) and 4) and are shown as figures 26(a) and 26(b), respectively.

The region of maximum hail occurrence, indicated by all three distribution methods, is located between the Mississippi River and the Continental Divide and extends from Montana and North Dakota to New Mexico and Texas. An examination of the charts shows that the greatest hail frequency on the ground is in the western half of this region. It was therefore decided to divide the region arbitrarily into two approximately equal areas along the 2000-foot ground contour. Although the limited number of hail encounters is about evenly divided within these areas, the risk of encountering hail west of the 2000-foot contour should be greater because of the smaller volume of air traffic west of this contour. Figure 26(b) shows a marked increase in crop-hail insurance
rates west of the 2000-foot contour. The increase in hail frequency in this area may be partly explained by the increased upslope flow of east winds which result in the overriding of warm moist air over the north-south stationary front that often extends along the east slope during the spring and the summer months.

The monthly distribution of hail damage to 47 airplanes is shown in figure 27 and indicates that: (1) Out of 47 cases, 30 (64 percent) of the hail accidents, occurred during April, May, and June; and (2) May was the month of maximum occurrence, with 12 cases or 26 percent of the hail accidents. In the region between the Mississippi River and the 2000-foot contour, the maximum number of hail cases occurred during April and rapidly diminished to none by July. In the region between the 2000-foot contour and the Continental Divide, the maximum number of hail encounters occurred during May and gradually diminished to none by November (fig. 27).

The hourly distribution of hail damage to 34 airplanes is shown in figure 28. This figure indicates that: (1) Out of 34 cases, 19 (56 percent) occurred between 1400 and 1800 LST; and (2) out of 34 cases, 29 (85 percent) occurred between 1400 and 2200 LST. These results compare favorably with Lemons' hourly distribution of hailstorms presented in figure 5 which shows 52 percent occurring between 1400 and 1800 LST and 80 percent occurring between 1400 and 2200 LST.

The available data showed no correlation between the hourly distribution and the monthly distribution. In the small number of cases available (only 34), there appears to be no significant difference in the hourly distribution between geographical regions.

Thunderstorms Associated with Hail Encountered in Flight

Further studies were conducted to ascertain the weather factors associated with hail encountered by airplanes. The thunderstorms associated with these encounters were classified as to type: cold front, warm front, or air mass. Of 47 cases, 28 (59 percent) could be attributed to cold-front action, whereas 13 (28 percent) were caused by air-mass activity alone; the remaining 6 cases (13 percent) were caused by warm-front action. (Since more than half of the hail cases were caused by cold-front action, pilots should be more cautious than usual when flying in or near cold-front thunderstorms, especially during the spring and summer months.) The percentage of hail cases attributed to cold fronts is even more pronounced east of Indiana, where 8 of the 10 hail cases were from cold-front activity (fig. 29). It was also found that the cold-front storms occurred most frequently between 1400 and 2200 LST and reached a maximum at 1600 to 1700 LST. Most of the air-mass storms occurred at 1400 to 1500 LST and were practically negligible at other times.
Air-mass instability and the height of the freezing level were investigated to determine whether these factors could be correlated with hailstorm activity. Synoptic weather maps and upper-air soundings of the day of the hail encounter were examined, but no significant correlations could be found. The columns in tables II and III entitled "General weather situation" and "Estimated freezing level" are included for completeness of the case histories and for possible use in future research studies.

In-Flight Weather Observations When Hail Was Encountered

In the great majority of the accidents caused by hail, thunderstorms were visible in the vicinity. Occasionally, hail was encountered outside but near a thunderstorm. This hail was presumed to have blown out of the anvil of a cloud. In every case in which a thunderstorm was not mentioned specifically in the report of the encounter, indications were that a thunderstorm was present. In cases 1 to 22, (tables II and III) it will be noted that, in all but two instances; turbulence, drafts, lightning, and/or radio static were observed. Of the two cases where none of these phenomena was mentioned, one was an encounter with hail in the clear and the other was not fully reported - the airplane ran into hail shortly after take-off while flying through rain but apparently not through clouds. The onset of hail and turbulence or drafts was almost simultaneous in several cases.

IN-FLIGHT AVOIDANCE BY RADAR DETECTION

Many military airplanes are now equipped with radar which can be used to detect areas of precipitation. By using this equipment, the pilot can avoid the precipitation area; but if it is necessary to fly through the precipitation, which may extend over a large area, the pilot is unable to pick the safest route, as the radar gives no indication of the type or intensity of precipitation. Military and civilian air-transport operators have therefore become interested in determining the practicability of air-borne radar which enables the pilot to avoid the dangerous areas within thunderstorms and squall lines and to fly through precipitation clouds with safety and comfort.

American Airlines, Inc. (reference 43) investigated the use of radar for in-flight avoidance of severe turbulence and heavy precipitation (including hail) in thunderstorms and squall lines. The flight tests made with specially built radar equipment gave no conclusive results on hail avoidance; however, the tests indicated that future research in this direction could lead to the avoidance of damaging hail.
On the assumption that good correlation existed between rate of change of rainfall rate (rainfall gradient) and maximum turbulence, a modern 3-centimeter radar set was modified for this investigation so that the PPI scope would indicate the rainfall gradient. Since the strength of the radar echo depends upon the number and the size of the precipitation particles and the path length in the cloud, the variation in the strength of the return signal is a function of the precipitation. The echo on the PPI scope of this modified radar set has the usual appearance except that the center section of the echo is erased when the rate of precipitation is above a predetermined amount. The spacing between the no-echo area and the erased-echo area gives a measure of rainfall gradient.

During the flight tests the airplane flew a total of 600 miles through, or immediately adjacent to, 40 thunderstorms. Hail, graupel, or snow pellets (soft hail) were collected by a hail catcher (fig. 29) 32 times during these flights. A typical example of the small hail and graupel caught in the hail catcher during flights through thunderstorms at a temperature just above freezing (40°C) is shown in figure 30; a typical example of snow particles and soft hail caught at a temperature just below freezing (0 to -5°C) is illustrated in figure 31 (reference 44). Difficulty was encountered in catching hailstones at cloud temperatures just below freezing because soft hail, slush, and snow particles were also present and caused the surface of the hail catcher to become coated with ice.

When the 32 hail encounters during these test flights were analyzed, it was found that 31 cases occurred in the heavy-rain area and only 1 case occurred in the light-rain area. The PPI scope indicated that, of the 31 encounters which occurred in heavy rain, 28 cases (90 percent) occurred during the first 15 seconds (distance, 1 mile) of heavy rain following the light rain. In no instance, however, were hailstones encountered larger than 3/4 inch in diameter. From the limited data available, hail appears to be generally located in the heavy-rain area and close to the outer periphery of that area.
CORRELATION OF AVAILABLE INFORMATION ON HAIL

Previous sections have presented the information available from literature on the hail phenomenon and a survey of hail as it affects aircraft operations. Although the material in these sections has been presented independently, it is closely associated. In addition, the material in each of the previous sections suggests ways to avoid or to reduce hail damage to aircraft. This section, therefore, correlates the hail information previously discussed and serves as a guide in the avoidance or reduction of hail damage.

GENERAL FEATURES

Small solid particles (called small hail) apparently form in every thunderstorm and melt before falling to the ground. In the more violent thunderstorms, however, these initial solid particles continue to enlarge into hailstones by the sublimation and condensation processes, and a certain size appears to predominate in each storm. Hail occurs in narrow bands during the mature stage (or late in the growing stage) of the thunderstorm cycle and is closely associated with the heavy-rain area.

Hail is usually composed of alternating layers of clear and opaque ice and has an average specific gravity of 0.7. The shape of most hailstones is spherical, although conical and discoidal stones frequently form. The size of hail aloft may vary from its size on the ground, as the stone may continue to grow during its final descent to the earth, or may melt partially after it falls into regions of above-freezing temperatures. Although the largest hailstone authentically recorded in the United States measured 5.4 inches in diameter and weighed 1.5 pounds, the average size of hail reported on the ground is about 0.6 inch in diameter and its weight, 0.05 ounce. The average size of hail aloft is unknown; however, calculations made from the extent of hail-damaged airplanes indicate that the size of hailstones encountered aloft ranges up to about 2 inches in diameter and the weight up to 1.8 ounces. A United Air Lines study showed that, in the area between Chicago and Denver, hailstones larger than 1 inch occur in about 1 out of 800 thunderstorms, whereas hailstones larger than 2 inches occur in about 1 out of 1600 thunderstorms.

Although hail is associated with thunderstorms, the geographical distributions of the two are not the same. Hail occurs with greater frequency in the continental interiors of the middle latitudes, diminishing in frequency seaward, equatorward, and poleward. The distribution and
occurrence of hail-producing thunderstorms which cause airplane damage over the United States are outlined as follows:

(1) Seventy-five percent of the damaging hail encountered by airplanes occurs between the Mississippi River and the Continental Divide. This distribution agrees with ground weather reports and crop-hail insurance rates as shown in figure 26.

(2) Sixty-four percent of the hail which causes airplane damage occurs during April, May, and June. This period compares favorably with the months of maximum hailstorms reported on the ground as April, May, and June (fig. 6(a)).

(3) Fifty-six percent of the hailstorms encountered aloft occur between 1400 and 1800 LST, whereas, 85 percent occur between 1400 and 2200 LST. These percentages are in close agreement with ground reports of 52 and 80 percent, respectively (fig. 5).

(4) Fifty-eight percent of the damaging hail encountered by airplanes is caused by cold-front thunderstorms, whereas, 28 percent is caused by air-mass thunderstorms. The cold-front storms occur most frequently between 1400 and 2200 LST; most of the air-mass storms occur at 1400 to 1500 LST and are practically negligible at other times.

(5) Pilot reports indicate that the horizontal distance flown in hail averages 5 miles but ranges from 1 to 30 miles. Surface data show that the most common width of the hailstorms is 1 to 2 miles but widths ranging from a few yards to 75 miles have been reported.

(6) The Thunderstorm Project showed that hail was seldom found at more than one or two levels in the same storm and that it occurred most frequently at an altitude between the freezing level and 20,000 feet.

AIRPLANE OPERATION AND HAIL

Although no fatal airplane accident is known to have been caused solely by hail, this phenomenon has caused severe damage to airplanes, in some cases as high as $25,000 per encounter. The nose section and the leading edges of the wing and tail are subject to severe damage, and windshields have been broken or cracked to such an extent that pilots feared that normal cruising speeds of the airplanes would cause the broken pieces to be blown into their eyes. The extent of damage varies with the mass of the hailstone, the impact velocity, and the type of material hit by the hail. Hailstones less than 0.75 inch in diameter do not cause significant damage at aircraft speeds between 200 and 300 miles per hour. Calculations from photographs of hail-damaged
airplanes indicate that the largest hailstones likely to be encountered in flight are about 2 inches in diameter.

From the analysis of flight and weather conditions associated with hailstorms, it is evident that, until radar or other hail-detection equipment becomes available, successful hail avoidance is directly dependent upon pilot judgment. In order to exercise good judgment, the pilot should (1) be familiar with the occurrence of hail and the effect of hail on aircraft, (2) know the over-all weather conditions before take-off, (3) obtain the latest in-flight weather advisories, and (4) be aware of potential developments so that he can recognize and evaluate them as they occur. If a pilot has a general understanding of when and where hail forms and the weather conditions associated with hailstorms, he knows when he should discuss hail during preflight weather briefing with the forecaster and when he should require additional pertinent weather information during flight. Unexpected hail encounters could thus be reduced.

If the location and time of the flight coincide with possible hailstorm conditions, visual pilot observation should be made (if possible) of all thunderstorm clouds that are in line with or directly adjacent to the flight path of the aircraft. Since the degree of severity of a thunderstorm can be associated with the stage of its life cycle, and since hail usually occurs during the mature stage, greater caution should be taken by the pilot when is is flying near or through this stage of the storm. A mature storm can be described as having a sharp-edged cauliflower appearance, and usually sharp cloud-to-ground lightning. A dissipating storm can be identified by its wispy-edged appearance and cloud-to-cloud, flickering-type lightning. The disadvantage of decreased visibility during night operations is partially overcome by the facts that only 25 percent of the hailstorms occur during the hours of darkness and that lightning is more readily visible at night.

Many military and commercial pilots make use of visual soft spots in navigating through cumulo-nimbus clouds. A so-called visual soft spot, however, is not always a reliable means of determining the best path through a thunderstorm, because hail has been occasionally reported in the clear air outside thunderstorm clouds. As a result of recent experiences of this nature, at least one airline advises pilots to stay away from the edges of cumulo-nimbus clouds when the temperatures at flight altitudes are below freezing. It should also be remembered that, although hail may not be encountered by aircraft passing through a thunderstorm, damaging hail may be encountered in another storm within the same general area or at a different altitude in the same storm.

After the airplane enters a thunderstorm and encounters hail, the pilot must decide whether he should turn to get out of the hail area or continue through the hail area on his original heading. It appears
that, after hail is encountered, the type of evasive action to be taken depends again on pilot judgment and the decision should be based on all known factors regarding the position of the airplane with respect to the storm. If the flight path is parallel to the edge of the storm, a turn is obviously the best solution. If the relative position of the storm is unknown, the best course is to continue through the storm. This course is especially advisable when instrument flight conditions, poor radio reception, and other adverse factors are involved. The speed of the airplane, however, has a profound effect on the amount of damage sustained and should be reduced as soon as possible.

Hail damage may be reduced in future aircraft operations by the elimination of destructive hail or by aircraft avoidance of hailstorms by means of radar detection. Attempts have been made to eliminate destructive hail by seeding potential hailstorms, and the Rogue River Valley Hail Prevention Project has been successful in eliminating hail over a limited area in Oregon. American Airlines, Inc. has experimented with a modified radar set which detects the rainfall gradient (the rate of change of rainfall rate with distance), a parameter which may have good correlation with turbulence and hail. Although some accepted conclusions have been reached with respect to turbulence, no definite conclusions can as yet be drawn concerning hail.

FORECASTING HAIL

The meteorologist can be of great assistance in minimizing the hail hazard to airplanes by placing increased importance on forecasting damaging hail and potential hail-producing thunderstorms. Since most hail exists in narrow bands within thunderstorm clouds that are in the late building or early mature stage, the meteorologist must first analyze all available information which can be used to forecast thunderstorms. At present two methods are used to forecast thunderstorms - the parcel method and the slice method; both require data from upper-air soundings. The parcel method is in more common use today, as it is simpler to use and sufficient with our present knowledge. The slice method is much more complicated, but if properly applied it should give more accurate results. One representation which makes use of the parcel method is the Theta-E map. This map shows the fields of equivalent potential temperature and of moisture content, both drawn for a selected level (generally 700 millibars).

If thunderstorms are assured, the meteorologist can turn his attention to a forecast of possible hail. No specific rules can be given for forecasting hail, as associated weather conditions appear to vary with the locality; however, it is well understood that the lapse rate, moisture content, and lifting forces are important factors involved in forecasting the severity of thunderstorms and the possibility of hail. A
United Air Lines study (reference 8) revealed that the frequency of thunderstorms producing large hail (1-inch in diameter or larger) is 1 in 400 when the lapse rate, as indicated by the nearest sounding, is greater than 2.5° C per 1000 feet. The frequency is only 1 in 1200 when the lapse rate is smaller than 2.5° C per 1000 feet. Large hail appears more frequently when the base of this unstable region is below 7000 feet. In addition, the moisture content of the air should be above 70 percent relative humidity for a depth of 15,000 feet, and this moist layer should straddle the freezing level.

A certain amount of lifting is required to instigate vertical convective currents which are necessary for the development of hail-producing thunderstorms, and, therefore, the thermal, orographic, and frontal lifting forces should be given careful consideration. Air-mass hailstorms can be produced from a large amount of thermal lifting force alone, but the geographical distribution and time of occurrence of air-mass hailstorms indicate that, in the majority of cases, both orographic and thermal lifting forces may be required. As the greatest number of frontal hailstorms occur in the late afternoon, it also appears that both frontal and thermal lifting forces usually are necessary for frontal hailstorms. Since cold fronts produce the majority of hailstorms which result in airplane damage, the meteorologist should be extremely careful in locating all fronts on the synoptic weather map and in detecting the first signs of the development of prefrontal squall lines. Some cold fronts and prefrontal squall lines are very weak at night, but with added solar heating during the day they intensify and produce the lifting forces required for severe thunderstorms and hailstorms.

A certain amount of judgment on the part of the meteorologist must be used in forecasting hail. Local forecasting experience gained by a meteorologist who is stationed at one locality for a long period of time is probably the most significant factor which contributes to the accuracy of his hail forecasts. By analyzing the climatological records of the forecast area, a meteorologist in a new location can obtain valuable information on the types of synoptic patterns and on the critical values of the upper-air elements which prevail when hailstorms occur. A typical analysis of the weather conditions associated with hailstorms has been made by United Air Lines for the Denver area (reference 16).

In general, the meteorologist is able to detect potentially dangerous hail situations when making an area or route forecast, and during preflight briefing he should warn the pilot of the possibility of hail when this condition exists. After take-off, efforts should be made to transmit hail information to the pilot when pilot in-flight weather reports and the latest surface observations indicate that hail exists but was not forecast for the area.
In summarizing the general requirements for the forecasting of severe thunderstorms and hailstorms, the following points should be kept in mind:

(1) **Amount of moisture aloft:** Although a sounding may show great degrees of instability, no clouds develop if the atmosphere is exceedingly dry. A layer should be considered moist if the relative humidity is above 70 percent. The moist layers should cluster about the freezing level.

(2) **Height and thickness of the unstable layer:** Cumulus clouds form with the instability entirely below the freezing level, but for the cumulus to reach severe thunderstorm proportions and cause hail the unstable layer should extend at least 15,000 feet above the cloud base.

(3) **Height of the freezing level:** Hail is more likely to form with a low freezing level (springtime conditions), since more of the unstable region is in temperatures below 0° C.

(4) **Amount of thermal heating:** For vertical convective currents to begin, a certain amount of surface heating is required. This amount can be determined by calculating the dry adiabatic temperature at the convective condensation level and estimating the expected maximum surface temperature.

(5) **Amount of orographic or frontal lifting:** Trajectory of the air over geographical or frontal slopes can be used to determine how much the air will be lifted. A layer already unstable will of course become more unstable upon lifting.

(6) **Amount of local forecasting experience:** By studying the climatological records of the particular area where hail forecasts are to be made, valuable information can be obtained on the type of synoptic patterns and on the critical values of the upper-air elements which prevail in the area during days when hailstorms occur.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., January 17, 1952
REFERENCES


   Geophysics Union (Washington), vol. 30, no. 1, Feb. 1949,
   pp. 29-45.

29. Langmuir, Irving: Summary of Results Thus Far Obtained in Artificial
   Nucleation of Clouds. First Quarterly Progress Rep., Project
   CIRRUS, General Electric Research Lab. (Schenectady), July 15,
   1947, pp. 4-11.

    Occasional Rep. No. 3, Project CIRRUS, General Electric Research
    Lab. (Schenectady), June 1, 1948.

31. Langmuir, Irving: The Production of Rain by a Chain Reaction in
    No. 1, Project CIRRUS, General Electric Research Lab. (Schenectady),
    April 15, 1948.

32. Schaefer, Vincent J.: The Occurrence of Ice Crystal Nuclei in the
    Free Atmosphere. Occasional Rep. No. 20, Project CIRRUS, General
    Electric Research Lab. (Schenectady), Jan. 15, 1950.

33. Schaefer, Vincent J.: The Detection of Ice Nuclei in the Free
    Atmosphere. Occasional Rep. No. 9, Project CIRRUS, General Electric
    Research Lab. (Schenectady), Jan. 15, 1949.

34. Langmuir, Irving: Progress in Cloud Modification by Project CIRRUS,
    Occasional Rep. No. 21, Project CIRRUS, General Electric Research
    Lab. (Schenectady), April 15, 1950.

    Electric Research Lab. (Schenectady), July 15, 1948.

    at Terminal Velocity in Air. Occasional Rep. No. 7, Project CIRRUS,
    General Electric Research Lab. (Schenectady), Nov. 1, 1948.

    (Philadelphia), vol. 120, no. 7, July 1950, pp. 19, 60, and 61.
    Also condensed form in the Readers Digest (Pleasantville), vol. 57,

38. Ludlam, F. H.: The Composition of Coagulation-Elements in Cumulo-
    Jan. 1950, pp. 52-58.


TABLE I
FREQUENCY (N) AND PERCENTAGE DISTRIBUTIONS OF VARIOUS HAIL
INTENSITIES AT GIVEN ALTITUDES
[From reference 19]

(a) Florida Thunderstorms (1946)

<table>
<thead>
<tr>
<th>Hail intensity</th>
<th>Flight altitude, (ft MSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6,000</td>
</tr>
<tr>
<td>----------------</td>
<td>-------</td>
</tr>
<tr>
<td>N Percent</td>
<td></td>
</tr>
<tr>
<td>Light</td>
<td>0</td>
</tr>
<tr>
<td>Percent</td>
<td>0</td>
</tr>
<tr>
<td>Moderate</td>
<td>0</td>
</tr>
<tr>
<td>Percent</td>
<td>0</td>
</tr>
<tr>
<td>Heavy</td>
<td>0</td>
</tr>
<tr>
<td>Percent</td>
<td>0</td>
</tr>
<tr>
<td>No hail</td>
<td>96</td>
</tr>
<tr>
<td>Percent</td>
<td>96</td>
</tr>
<tr>
<td>Total</td>
<td>96</td>
</tr>
<tr>
<td>Percent</td>
<td>96</td>
</tr>
</tbody>
</table>

(b) Ohio Thunderstorms (1947)

<table>
<thead>
<tr>
<th>Hail intensity</th>
<th>Flight altitude, (ft MSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5,000</td>
</tr>
<tr>
<td>----------------</td>
<td>-------</td>
</tr>
<tr>
<td>N Percent</td>
<td></td>
</tr>
<tr>
<td>Light</td>
<td>1</td>
</tr>
<tr>
<td>Percent</td>
<td>1</td>
</tr>
<tr>
<td>Moderate</td>
<td>0</td>
</tr>
<tr>
<td>Percent</td>
<td>0</td>
</tr>
<tr>
<td>Heavy</td>
<td>0</td>
</tr>
<tr>
<td>Percent</td>
<td>0</td>
</tr>
<tr>
<td>Unclassified</td>
<td>1</td>
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<tr>
<td>Percent</td>
<td>1</td>
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<tr>
<td>No hail</td>
<td>110</td>
</tr>
<tr>
<td>Percent</td>
<td>98</td>
</tr>
<tr>
<td>Total</td>
<td>112</td>
</tr>
<tr>
<td>Percent</td>
<td>100</td>
</tr>
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</table>
## Table 11: Case Histories of Brawl Damage to Transport Airplanes

(a) Larger-transport airplanes

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of airplane</th>
<th>Date</th>
<th>Time</th>
<th>Location</th>
<th>Damage</th>
<th>Ballistics mass, calculated from pictures (lb.)</th>
<th>Estimated true airspeed in blow (mph)</th>
<th>Altitude (ft MSL)</th>
<th>Air temp. (°F)</th>
<th>General flight direction</th>
<th>En-Flight weather conditions before encounter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Douglas DC-6</td>
<td>Sept. 14, 1947</td>
<td>1515 CST</td>
<td>NE, Mexico; 25 miles SW of Monclova</td>
<td>Nose section, fuselage above windshield, cowling, leading edges of wing, and so forth</td>
<td>1.3 ± 0.7</td>
<td>270</td>
<td>18,000</td>
<td>0</td>
<td>NW</td>
<td>VIP Clearance: Changed course twice to go around small but towering cumulus; large cumulo-nimbus directly ahead and to right having a top 10 miles in diameter at 30,000 ft and extending higher. Two small cumulus to left; tops 20 to 25,000 ft. Stratus overhanging deck at 20,000 ft. Went under stratus and just left of cumulo-nimbus. Encountered heavy rain and saw one flash lightning to right. No precipitation ahead or to left. Rain.</td>
</tr>
<tr>
<td>2</td>
<td>Douglas DC-6</td>
<td>April 27, 1948</td>
<td>1600 EST</td>
<td><strong>St. Ohio; Zanesville</strong></td>
<td>Leading edges of wing and tail, cowling, and nose section</td>
<td>Unknown</td>
<td>295</td>
<td>18,000</td>
<td>-10</td>
<td>W</td>
<td>VIP Clearance: Ran into squall line in eastern Ohio, slowed to 170 mph 1/2 mile. Smooth after first entering cloud, light rain after a few minutes; an updraft increased airspeed to 250 mph IAS, then moderate hail.</td>
</tr>
<tr>
<td>3</td>
<td>Douglas DC-6</td>
<td>May 3, 1949</td>
<td>0200 EST</td>
<td>E. Tennessee; 30 miles N. of Knoxville</td>
<td>Nose section, fuselage and dowe above windshield, wing tip, propellors, deck, cowling, air scoop, and oil cooler</td>
<td>1.4 ± 0.3</td>
<td>295</td>
<td>19,000</td>
<td>0</td>
<td>NE</td>
<td>VIP Clearance: Tops of clouds 11,000 ft. Lighting visible to south of course. A front was moving across the southeast. Through northern Tennessee, tops were 15,000 ft with some higher. Went through several tops with no turbulence; then into a top with heavy hail immediately after entry.</td>
</tr>
<tr>
<td>4</td>
<td>Douglas DC-6</td>
<td>May 29, 1949</td>
<td>1915 CST</td>
<td>SW, Texas; Midland</td>
<td>Windshield, nose cap battered, cowling, and leading edges dented; repair cost $15,146</td>
<td>Unknown</td>
<td>270</td>
<td>16,000</td>
<td>5</td>
<td>W</td>
<td>VIP Clearance: Encountered broken to scattered thunderstorms with slight wing icing, but no appreciable turbulence; then ran into hail. Outside temperature reported 57°F.</td>
</tr>
<tr>
<td>5</td>
<td>Douglas DC-6</td>
<td>June 29, 1949</td>
<td>0245 CST</td>
<td>**St. Oklahoma; 30 miles W. of Oklahoma City</td>
<td>Nose cap dented, paint off engine cowling, small dents in horizontal and vertical stabilizers</td>
<td>Unknown</td>
<td>170</td>
<td>16,000</td>
<td>Unknown</td>
<td>W</td>
<td>VIP Clearance: A line of thunderstorms extended northeast-southwest on the take-off. Entered cloud after climbing 16,000 ft. Encountered hail immediately. Altitude limited to 16,000 ft because of engine trouble.</td>
</tr>
<tr>
<td>6</td>
<td>Douglas DC-6</td>
<td>March 29, 1949</td>
<td>0305 CST</td>
<td>St. Illinois; Bloomington</td>
<td>Leading edges and nose dented</td>
<td>Unknown</td>
<td>170</td>
<td>7,000</td>
<td>4</td>
<td>NE</td>
<td>VIP Clearance: Between layers at 7,000 ft to central Illinois. Went on instruments with light turbulence. After 10 min it became apparent they were near center of thunderstorm activity, with moderate to heavy rain and considerable lightning. Slowed to 160 mph IAS then through light hail.</td>
</tr>
<tr>
<td>7</td>
<td>Douglas DC-6</td>
<td>May 29, 1949</td>
<td>0210 CST</td>
<td>SW, Texas; Guadalupe Pass</td>
<td>Nose, windshield, and all leading edges; repair cost $2,000</td>
<td>1.5 ± 0.3</td>
<td>360</td>
<td>14,000</td>
<td>6</td>
<td>W</td>
<td>VIP Clearance: A line of thunderstorms extended from eastern New Mexico south-southwest into Mexico. Overcast at 20 to 25,000 ft. From thunderstorms eastward, joining thunderstorms at 20,000 ft. Tops of clouds to north estimated 30,000 ft. Hail was reported on ground with thunderstorms and dust to 15,000 ft. Slowed to 270 to 350 mph IAS to enter, anticipated light to moderate turbulence and rain; 2 min after entering cloud airspeed built up to 275 mph IAS then ran into hail.</td>
</tr>
<tr>
<td>8</td>
<td>Lockheed Constellation</td>
<td>April 25, 1948</td>
<td>1730 CST</td>
<td><strong>St. Louisiana; Alexandria</strong></td>
<td>Damage not mentioned. (Several passengers injured because of hitting the ceiling.)</td>
<td>Unknown</td>
<td>270</td>
<td>20,000</td>
<td>Unknown</td>
<td>SW</td>
<td>VIP Clearance: On top of broken clouds at 10,000 ft, but through occasional light rain from a very high broken deck above. Air smooth, then a violent downdraft with light rain becoming very heavy rain. Quickly changed to updraft and heavy hail began.</td>
</tr>
</tbody>
</table>

*Pictures of hail damage in these cases are shown in figures 12 to 14.
**C refers to central.
TABLE II. - CASE HISTORIES OF BAIL DAMAGE TO TRANSPORT AIRPLANES - Continued

(a) Larger-transport airplanes - Concluded

<table>
<thead>
<tr>
<th>Case</th>
<th>Weather conditions during encounter</th>
<th>Defensive action by pilot</th>
<th>Associated weather phenomena</th>
<th>General weather situation</th>
<th>Estimated freezing level (ft)</th>
<th>Constructive remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Under overhang of a thunderstorm. Bail in very narrow band not restricting visibility. Bail, 15 sec in clear.</td>
<td>270° left turn and climbed.</td>
<td>No rain. One lightning flash. No turbulence.</td>
<td>Numerous air-mass thunderstorms. Little data available.</td>
<td>18,000 or lower</td>
<td>Unavoidable.</td>
</tr>
<tr>
<td>#2</td>
<td>In thunderstorm. Bail 2 min.</td>
<td>None.</td>
<td>Light to moderate turbulence. Moderate updraft.</td>
<td>A north-south squall line and possible cold front through the area. Air mass was moist and unstable, very suitable for thunderstorms.</td>
<td>11,000</td>
<td>Bail was forecast. Impress pilots to use extreme care and minimum safe speed when bail is probable.</td>
</tr>
<tr>
<td>#3</td>
<td>In top of thunderstorm. Bail 2 to 3 min.</td>
<td>180° left turn.</td>
<td>Severe turbulence with bail. Poor radio reception.</td>
<td>Flight parallel and just ahead of northeast-southeast cold front. Air-mass information not available.</td>
<td>13,000</td>
<td>Caution pilots that if one thunderstorm does not have turbulence and bail this fact does not mean that all thunderstorms in the area do not.</td>
</tr>
<tr>
<td>#4</td>
<td>Through thunderstorm. Bail 15 to 60 sec.</td>
<td>None.</td>
<td>Extreme turbulence for several minutes with the bail.</td>
<td>East-west cold front to south of the area. Thunderstorms more numerous to south of area. No reliable radio data available.</td>
<td>13,000</td>
<td>Meager information was available. Advise pilot to make complete post-flight report for future guidance of other personnel.</td>
</tr>
<tr>
<td>#5</td>
<td>Into thunderstorm. Bail 10 min.</td>
<td>Descended to 15,000 ft.</td>
<td>Excessive St. Mao's fire.</td>
<td>No fronts. Air mass moist and unstable, good for convective thunderstorms.</td>
<td>14,000</td>
<td>Bail was forecast. Aircraft encountered bail at low airspeed, resulting in only minor bail damage. Impress pilots that if all equipment is not functioning properly, be extremely cautious.</td>
</tr>
<tr>
<td>#6</td>
<td>Into thunderstorm. Heavy bail 15 sec. Light to moderate bail for 60 sec, estimated.</td>
<td>Slowed from 150 to 140 mph TAS.</td>
<td>Very heavy rain showers. Moderate turbulence. Appreciable lightning.</td>
<td>North-south cold front or occlusion passing area at time of accident. Air mass very moist and unstable with lifting.</td>
<td>9,500</td>
<td>Advise pilots to fly through thunderstorms at a rather high altitude rather than at a medium altitude. Warn pilots to keep airspeed low when there is any danger of bail.</td>
</tr>
<tr>
<td>#7</td>
<td>In cloud 3 min before bail was encountered. Bail 60 sec.</td>
<td>Immediate left turn.</td>
<td>Appreciable lightning. Moderate (not severe) turbulence.</td>
<td>Maps differ on synoptic situations. Cold front or squall line, oriented east-west, passed area at time of accident. Air mass would only produce thunderstorms with at least 5,000 ft lift.</td>
<td>14,000</td>
<td>Warn pilot that when bail is imminent to slow plane as much as possible. Caution pilots that visible &quot;soft spots&quot; in the thunderstorm area are often deceiving without the support of radar.</td>
</tr>
<tr>
<td>#8</td>
<td>Bail not clear. Bail less than 3 min.</td>
<td>None; because of engine stoppage.</td>
<td>Rain; severe turbulence; severe up and downsraight.</td>
<td>Northeast-southwest squall line and cold front passing the area. Thunderstorms reported on ground almost everywhere.</td>
<td>13,000</td>
<td>Unavoidable.</td>
</tr>
</tbody>
</table>

*Pictures of bail damage in these cases are shown in figures 12 to 14.*
<table>
<thead>
<tr>
<th>Case</th>
<th>Type of airplane</th>
<th>Date</th>
<th>Time</th>
<th>Location</th>
<th>Damage</th>
<th>Ballistic data, calculated from pictures (in.)</th>
<th>Estimated true airspeed in bank (mph)</th>
<th>Altitude (ft MSL)</th>
<th>Air Temp. (°F)</th>
<th>General Flight Direction</th>
<th>In-flight weather conditions before encounter</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Douglas DC-4</td>
<td>Aug. 15, 1948</td>
<td>1945 EST</td>
<td>WV, Virginia; 40 miles NE of Roanoke</td>
<td>Leading edges of wings, horizontal and vertical stabilizers, engine cowling, both elevators, and nose section.</td>
<td>1.7 ± 0.3</td>
<td>185</td>
<td>8,000</td>
<td>10</td>
<td>SW</td>
<td>IFR Clearance: Altitude 8,000 ft; circumnavigated few small thunderstorms; in and out of others; encountered rain and light hail for 1 to 2 min in these clouds; top possibly 15,000 ft; clouds all around, 40 min after takeoff entered very light (light brown) clouds with surf, at reduced speed; hail intensity increased.</td>
</tr>
<tr>
<td>10</td>
<td>Consolidated Vultee Liner</td>
<td>May 19, 1949</td>
<td>1945 EST</td>
<td>WV, West Virginia; 30 miles W. of Elkins</td>
<td>Dents in leading edges, some engine (pro-peller) trouble during flight.</td>
<td>Unknown</td>
<td>205</td>
<td>11,000</td>
<td>3</td>
<td>E</td>
<td>IFR Clearance: Through central West Virginia; weather looked best to north and east. Flew around four large thunderstorms and picked a &quot;soft spot&quot; in the fifth; went between layers, light rain became moderate with some sleet; then ran into hail.</td>
</tr>
<tr>
<td>11</td>
<td>Douglas DC-3</td>
<td>May 8, 1946</td>
<td>1655 MDT</td>
<td>CO, Colorado; 60 miles N. of Denver</td>
<td>Both wing tips, horizontal and vertical stabilizers, props, windshields, cockpit, ignition harness, and nose section.</td>
<td>1.5 ± 0.2</td>
<td>235</td>
<td>9,000</td>
<td>7</td>
<td>NW</td>
<td>IFR Clearance: Long narrow belt of clouds just above flight level, estimated 8,000 ft high; turned 150° left and descended 300 ft to go under clouds; updraft took plane from 8,100 to 10,000 ft into base of clouds; then downdraft and hail.</td>
</tr>
<tr>
<td>12</td>
<td>Douglas DC-3</td>
<td>May 12, 1947</td>
<td>2045 COT</td>
<td>AR, Arkansas; 60 miles E. of Little Rock</td>
<td>Elevator ripped, windshield cracked, landing lights broken, and nose section.</td>
<td>Unknown</td>
<td>160</td>
<td>2,500</td>
<td>20</td>
<td>SW</td>
<td>IFR Clearance: Circumnavigated storms; under clouds; rain; night; lightning intense and blinding; then maybe into clouds; little hail and severe downdraft; 180° left turn; heavy hail during turn.</td>
</tr>
<tr>
<td>13</td>
<td>Douglas DC-3</td>
<td>May 10, 1946</td>
<td>2045 MDT</td>
<td>NM, New Mexico; Clovis</td>
<td>Cowling dented, nose glass and landing lights broken.</td>
<td>Unknown</td>
<td>170</td>
<td>6,000</td>
<td>12</td>
<td>SW</td>
<td>IFR Clearance, second part of trip: Night; under storm clouds with base 6,500 ft; lightning to right and left; encountered hail; small clouds obscured thunderstorms.</td>
</tr>
<tr>
<td>15</td>
<td>Beech D18S</td>
<td>June 19, 1948</td>
<td>1700 EST</td>
<td>WV, West Virginia; Martinsburg</td>
<td>Horizontal and both vertical stabilizers, nose glass, and landing lights.</td>
<td>1.3 ± 0.2</td>
<td>170</td>
<td>7,000</td>
<td>Unknown</td>
<td>SE</td>
<td>IFR Clearance: Encountered severe turbulence and little hail in one cloud; into clear with broken clouds underneath; went around next thunderstorm and 9 min later encountered hole between 2 cloud sections of vertical development. Severe turbulence and hail; 180° left turn with violent updraft on right wing.</td>
</tr>
</tbody>
</table>

*Pictures of hail damage in these cases are shown in figures 15 to 17.
**For evaluation purposes the Douglas airplanes DC-3, C-47, and 840 are all classified as Douglas DC-3.
***For evaluation purposes the Beech airplanes D18S, J8E, and C-15 are all classified as Beech D18S.
****C refers to central.
<table>
<thead>
<tr>
<th>Case</th>
<th>Weather conditions during encounter</th>
<th>General weather situation</th>
<th>Estimated freezing level (ft)</th>
<th>Constructive remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>In thunderstorm. Hail 10 min. Hail 8 min.</td>
<td>Northeast-southwest weak cold front. Flight was made parallel to front and may have been in cold front. Numerous air-mass thunderstorms ahead of front.</td>
<td>13,500</td>
<td>Impose forecasts that positions of fronts and possibility of hail should be considered and included in forecasts to pilots. Caution pilots to select a route perpendicular to active cold front. Warm pilots to report by radio all unusual weather encountered to help forecasters and other pilots.</td>
</tr>
<tr>
<td>10</td>
<td>Between cloud layers. Hail 90 sec.</td>
<td>Rain. Appreciable lightning. No radio reception.</td>
<td>12,000</td>
<td>Caution pilots that &quot;soft spots&quot; are not always &quot;safe&quot; when radar is not available.</td>
</tr>
<tr>
<td>11</td>
<td>Just in or under cloud base. Hail 40 sec. Hail size 3/4 to 2 in. in diameter. Noises terrific.</td>
<td>No rain. Light turbulence. Severe downdraft - downdraft 1000 ft per min.</td>
<td>10,000</td>
<td>Impose forecasts to watch for definite fronts and keep associated thunderstorm activity in mind. Caution pilots not to fly under the hood while in marginal VFR weather.</td>
</tr>
<tr>
<td>12</td>
<td>In edge of thunderstorm. Hail 2 min.</td>
<td>Northeast-southwest upper cold front probably passed area at time of the accident. All radar scope in this area indicated thunderstorms were likely.</td>
<td>12,000</td>
<td>Weather was worse than forecast. Caution pilots that night flying through intense thunderstorms is dangerous. Warm pilots to change from VFR to IFR before VFR weather is flown into. Warm pilots to check range weather reports during adverse weather conditions.</td>
</tr>
<tr>
<td>13</td>
<td>Under cloud. Hail 30 sec. estimated.</td>
<td>Northeast cold frontal activity in the area. Air mass good for thunderstorms and precipitation.</td>
<td>11,000</td>
<td>Caution pilots that night flights are dangerous in thunderstorm area, especially when surrounding cloud decks obscure vision.</td>
</tr>
<tr>
<td>14</td>
<td>In stratus cloud and into edge of thunderstorm. Hail 4 min.</td>
<td>Northeast-southwest weak surface warm front in visibility. Probably air-mass thunderstorms also. No radar scope available.</td>
<td>14,000</td>
<td>Remind forecasters to give pilots all weather information, including fronts on route. Advise pilots that it is safer in thunderstorm area to fly on top of the stratus cloud deck where cumulus can be seen and not through stratus decks where visibility is limited.</td>
</tr>
<tr>
<td>15</td>
<td>In edge of thunderstorm. Hail close to cloud. Hail 2 min. estimated.</td>
<td>Northeast-southwest cold front in the area moving east. Air-mass data not available.</td>
<td>13,000</td>
<td>First hail encountered showed intensity of thunderstorm. Ground observers reported heavy storms in this area that day. Advise pilots of nature of storm activities and consequences, especially in thunderstorm areas. Warm forecasters that hail should be considered when briefing pilots.</td>
</tr>
</tbody>
</table>

*Pictures of hail damage in these cases are shown in figures 15 to 17.*
### Table III - Case Histories of Ball Damage to Military Airplanes

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of Airplane</th>
<th>Date</th>
<th>Time</th>
<th>Location</th>
<th>Damage</th>
<th>Flight conditions</th>
<th>In-flight weather conditions before encounter</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Boeing B-29</td>
<td>Oct. 31</td>
<td>0100 CST</td>
<td><strong>N. Texas; 40 miles E. of Dallas</strong></td>
<td>All leading edges of wings, horizontal and vertical stabilizers, all engine cowlings, propeller cuffs, cooling fins, cylinders; nose glass cracked.</td>
<td>Altitude (ft MSL) 14,000; Air temp (°C) -3; General flight direction NNE.</td>
<td>IFR Clearance: Night; radar inoperative; front sighted; VFR - flew parallel to line of thunderstorms, then through clear hole between two thunderstorms on left. Encountered severe turbulence and hail, turned 40° right, out of hail.</td>
</tr>
<tr>
<td>17</td>
<td>Boeing B-29</td>
<td>June 3</td>
<td>1345 CST</td>
<td><strong>N. Montana; 30 miles N. of Billings</strong></td>
<td>Leading edges of wings, horizontal stabilizers, engine cowlings, and cooling fins.</td>
<td>Altitude (ft MSL) 10,000; Air temp (°C) 6; General flight direction SW.</td>
<td>IFR Clearance: Radar inoperative; could see scattered showers and various cloud formations. Pilot under hood. Went east of route to miss one storm. Entered shelf of clouds for a short time (5 min) and encountered rain, severe turbulence and hail; then into clear. Received radio report by another pilot - severe storm and tornado west of Billings - route was changed.</td>
</tr>
<tr>
<td>18</td>
<td>Boeing B-29</td>
<td>Aug. 1</td>
<td>1945 CST</td>
<td><strong>N. Wyoming; 40 miles NW. of Casper</strong></td>
<td>Leading edges of both wings, horizontal and vertical stabilizers, engine cowling, ignition harness, navigation lights.</td>
<td>Altitude (ft MSL) 20,000; Air temp (°C) -14; General flight direction W.</td>
<td>IFR Clearance: Radar inoperative; northeast-southeast squall line seen ahead at 16,000 ft. No breaks in squall line, so flew through. Entered cloud; then severe turbulence and rain; updraft took plane up 1,000 ft; 180° left turn; hail started in turn. Climbed to 28,000 ft; cloud tops 38,000 ft. Notified ATC to tell all pilots in vicinity.</td>
</tr>
<tr>
<td>19</td>
<td>Boeing B-29</td>
<td>Aug. 11</td>
<td>1430 CST</td>
<td><strong>N. South Dakota; 15 miles NE. of Rapid City</strong></td>
<td>Leading edge both wings, horizontal and vertical stabilizers, 28 engine cylinders, all ignition harnesses, propeller cuffs dented.</td>
<td>Altitude (ft MSL) 9,000; Air temp (°C) 10; General flight direction SW.</td>
<td>IFR Clearance: Changed to VFR over destination. In radio contact with tower; letting down from 10,000 ft; circumnavigated small thunderstorm; hail at 9,000 MSL under edge of thunderstorm; visibility 15 mi. Made 90° left turn; notified control tower to warn other pilots in vicinity. Ball at airport; pilot was not warned by radio.</td>
</tr>
<tr>
<td>20</td>
<td>Douglas A-26</td>
<td>June 16</td>
<td>1845 CST</td>
<td><strong>N. Iowa; 120 miles NE. of Omaha</strong></td>
<td>Vertical and horizontal stabilizers; air scoop; windshield, engine cowlings, gun mount covers.</td>
<td>Altitude (ft MSL) 5,500; Air temp (°C) 25; General flight direction SSW.</td>
<td>VFR Clearance: Flying under high broken cloud and beneath two cumulus (small thunderstorms). Possibly flew through this white cloud at edge of cumulus base when hail was encountered. Copilot was in control and made post-flight report as the pilot was busy with the radio.</td>
</tr>
<tr>
<td>21</td>
<td>North American F-51</td>
<td>April 7</td>
<td>1300 CST</td>
<td><strong>N. Illinois; 20 miles NE. of St. Louis</strong></td>
<td>Both wing tips, horizontal and vertical stabilizers; propeller spinner dented.</td>
<td>Unknown; Altitude (ft MSL) 1,800; Air temp (°C) 11; General flight direction SW.</td>
<td>VFR Clearance: Still climbing after take-off; encountered hail under clouds in light rain.</td>
</tr>
<tr>
<td>22</td>
<td>North American F-51</td>
<td>June 17</td>
<td>1700 CST</td>
<td><strong>N. Nebraska; Alliance</strong></td>
<td>Leading edge of wings, horizontal and vertical stabilizers; windshield broken; propeller spinners, air scoop.</td>
<td>Altitude (ft MSL) 25,000; Air temp (°C) -20; General flight direction NE.</td>
<td>IFR Clearance: IFR weather with occasional breaks overhead; while waiting for approval to let down under IFR, turbulence increased; windshield icing and lightning was observed; 30 sec in hail. Let-down approved. Flew into clear 20 sec after hail.</td>
</tr>
</tbody>
</table>

*Pictures of hail damage in these cases are shown in figures 18 to 21.
**C refers to central.
<table>
<thead>
<tr>
<th>Case</th>
<th>Weather conditions during encounter</th>
<th>Evasive action by pilot</th>
<th>General weather situation</th>
<th>Estimated freezing level (ft)</th>
<th>Constructive remarks</th>
<th>Additional notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Through edge of thunderstorm. In cloud 7 min. Ball 30 sec.</td>
<td>90° right turn</td>
<td>Severe turbulence.</td>
<td>Northeast-southwest cold front passed area. Thunderstorms associated with cold front. Air mass unstable below freezing level, but dried out above.</td>
<td>12,000</td>
<td>Impress forecasters to use the slim method with frontal passage to improve thunderstorm forecasts. Caution pilots to keep aircraft under in operation and use it before flying through frontal activity.</td>
</tr>
<tr>
<td>17</td>
<td>In roll cloud and edge of thunderstorm. Ball started 1 min after entering cloud.</td>
<td>None.</td>
<td>Rain started upon entering cloud. Extreme turbulence with altitude variations of 400 ft.</td>
<td>Mostly air-mass thunderstorms. A cold front to the east could have enhanced activity. Air mass unstable enough to produce thunderstorms with good boiling. Even more unstable to the south.</td>
<td>15,000</td>
<td>Caution forecasters to consider carefully thunderstorm forecasts. Impose pilots to listen to range weather reports. Advise pilots to report by radio all unusual weather encountered.</td>
</tr>
<tr>
<td>18</td>
<td>Edge of thunderstorm. In cloud and turbulence area for 5 min. Ball 60 sec. Ball size of golf ball. Noise terrific.</td>
<td>100° left turn. Near low angle to north to get around equi- lice.</td>
<td>Severe turbulence. Violent updrafts from 15,000 to 20,000 ft.</td>
<td>No fronts. This air mass had been producing thunderstorms over the area for the past 6 days. Heavy thunderstorms should have been forecast by considering the radioncide.</td>
<td>14,000</td>
<td>Advise pilots that in group flights aircraft with radar should lead group through intense thunderstorms. Forecast to pilots unknown.</td>
</tr>
<tr>
<td>19</td>
<td>Under overhang of thunderstorm. Ball 20 sec. Ball on ground at airport.</td>
<td>90° left turn. Dangerous at destination.</td>
<td>None reported.</td>
<td>Severe turbulence.</td>
<td>12,000</td>
<td>Radar availability and use unknown. Warm forecasters that hail should be considered when briefing pilots for flights through intense thunderstorm areas. Impose all personnel with the importance of immediate and accurate dissemination of unusual weather phenomena.</td>
</tr>
<tr>
<td>20</td>
<td>In edge of cumulus cloud. Ball 15 to 30 sec.</td>
<td>None.</td>
<td>Severe to moderate radio static.</td>
<td>Scattered thunderstorms caused by pre-cold frontal condition. Air mass was such that heating alone should not produce thunderstorms. Several squall lines did not report any rain or thunderstorms; only towering cumulus.</td>
<td>15,000</td>
<td>Advise pilots with no instrument rating to stay well clear of clouds. Warm pilots that clouds of vertical development and convective can be obscured by surrounding cloud decks.</td>
</tr>
<tr>
<td>21</td>
<td>Under cloud base in light rain. Ball 15 sec.</td>
<td>None. Winter shower area.</td>
<td>Light rain.</td>
<td>East-west warm front to south-moving north. Air mass through Missouri unstable with some dry areas; enough to set off thunderstorms with warm frontal lifting and heating.</td>
<td>12,000</td>
<td>Unavoidable.</td>
</tr>
<tr>
<td>22</td>
<td>In cloud. Ball 50 sec. Left cloud 20 sec after ball stopped.</td>
<td>None. Received approval to let down area.</td>
<td>Moderate turbulence, wind, ash from lightning.</td>
<td>Probably an east moving upper cold front was passing the area. Air mass information not available.</td>
<td>14,500</td>
<td>Unavoidable by pilot. Approach ball was reported on ground in Wyoming and Kansas on this date. Improvised ground personnel to transmit ball information to pilots and forecasters.</td>
</tr>
</tbody>
</table>

*Pictures of ball damage in these cases are shown in Figures 18 to 21.*
<table>
<thead>
<tr>
<th>Case</th>
<th>Type of airplane</th>
<th>Date</th>
<th>Location</th>
<th>Damage</th>
<th>Weather situation</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>Douglas DC-6</td>
<td>Sept. 7, 1946</td>
<td>NW, Nebraska; Kayo Center</td>
<td>Nose, wing, stabilizers, elevators, controls, navigation lights, and pitot tube.</td>
<td>Northeast-southwest cold front.</td>
<td>None</td>
</tr>
<tr>
<td>26</td>
<td>Douglas DC-3</td>
<td>June 1940</td>
<td>SE, Montana; Miles City</td>
<td>Nose and leading edge of wing, windshield broken, Engine pushed out of housing, used.</td>
<td>Unknown.</td>
<td>Pilot flying into storm, encountered hail for a very short time as he made immediate turn out of the hail area.</td>
</tr>
<tr>
<td>27</td>
<td>Douglas DC-3</td>
<td>April 20, 1944</td>
<td>**KC, Texas; Abilene</td>
<td>Navigational lights broken.</td>
<td>East-west cold front.</td>
<td>None</td>
</tr>
<tr>
<td>28</td>
<td>Douglas DC-3</td>
<td>June 9, 1944</td>
<td>** Jong; Guadelupe Pass</td>
<td>Leading lights and windshield.</td>
<td>Air mass.</td>
<td>None</td>
</tr>
<tr>
<td>29</td>
<td>Douglas DC-3</td>
<td>March 19, 1945</td>
<td>**KC, Kansas; Anthony</td>
<td>Nearer all components of plane damaged.</td>
<td>Northeast-southwest cold front.</td>
<td>After encountering hail apparently in thunderstorm, pilot made immediate right turn. Ball 40 sec at 10,000 ft MSL.</td>
</tr>
<tr>
<td>30</td>
<td>Douglas DC-3</td>
<td>July 10, 1945</td>
<td>E. Pennsylvania; Summit Hill</td>
<td>Wings and stabilizers, Numerous dents all over plane. Engine damage.</td>
<td>Northeast-southwest cold front.</td>
<td>Apparently flew into thunderstorm. Heavy andvent with hail. 15 sec of heavy ball at 9,000 ft MSL.</td>
</tr>
<tr>
<td>31</td>
<td>Douglas DC-3</td>
<td>Aug. 19, 1945</td>
<td>S. Wyoming; Between Cheyenne and Salt Lake City</td>
<td>Elevators stripped. Holes in both ailerons, cockpit windows cracked on right side. Dents in fuselage.</td>
<td>Air mass or pre-cold front activity.</td>
<td>None</td>
</tr>
<tr>
<td>33</td>
<td>Douglas DC-3</td>
<td>March 10, 1946</td>
<td>** KC, Texas; San Antonio</td>
<td>Leading edges of wings and stabilizers, Leading light broken.</td>
<td>North-south upper cold front.</td>
<td>None</td>
</tr>
<tr>
<td>34</td>
<td>Douglas DC-3</td>
<td>April 10, 1946</td>
<td>** NE, Texas; Dallas</td>
<td>Holes in left elevator.</td>
<td>East-west post cold front.</td>
<td>None</td>
</tr>
<tr>
<td>35</td>
<td>Douglas DC-3</td>
<td>June 11, 1947</td>
<td>** E. Ohio; En route to Pittsburgh</td>
<td>Four tears in upper side of both elevators.</td>
<td>Air mass; may be stationary front to south.</td>
<td>Through severe hail and thunderstorm.</td>
</tr>
<tr>
<td>36</td>
<td>Douglas DC-3</td>
<td>Aug. 27, 1947</td>
<td>S. Wyoming; 5 miles N. of Laramie</td>
<td>Windshields and astrozone broken. Minor dents in leading edge of wing and nose.</td>
<td>North-south stationary front.</td>
<td>Sighted raingrower over mountainous terrain while under VFR conditions at 8,500 ft MSL. Encountered hail briefly while circling navigations show. Pilot made an immediate turn.</td>
</tr>
<tr>
<td>38</td>
<td>Beech D18S</td>
<td>April 23, 1949</td>
<td>** VA, Virginia; Norfolk</td>
<td>Windshield broken. Other damage unknown.</td>
<td>Cold front or pre-frontal squall line.</td>
<td>Other aircraft in same area avoided hail by changing course. Ballistics approximately 1 by 1 inch observed 6 miles northwest from same storm.</td>
</tr>
</tbody>
</table>

*For evaluation purposes the Douglas airplanes DC-3, C-47, and NAC are all classified as Douglas DC-3.
**For evaluation purposes the Beech airplanes D18S, J18S, and C-45 are all classified as Beech D18S.
***C refers to central.
<table>
<thead>
<tr>
<th>Case</th>
<th>Type of airplane</th>
<th>Date</th>
<th>Location</th>
<th>Damage</th>
<th>Weather situation</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>Boeing B-29</td>
<td>May 17, 1949 1:30 CST</td>
<td>*C. Oklahoma; 5 miles E. of Ardmore</td>
<td>Leading edge of wing and stabilizers. Engine cowling. Nevada's window cracked.</td>
<td>Air-mass thunderstorm developed in a north-south line.</td>
<td>Flying west-southeast. Entered IFR conditions 30 miles WNW. of Oklahoma City at 10,000 ft MSL and started to climb. Encountered light rain which changed quickly to light snow. Heavy hail for 5 min between 6,000 and 8,000 ft. Began to clear at 10,000 ft.</td>
</tr>
<tr>
<td>40</td>
<td>Boeing B-17</td>
<td>April 1, 1949 1930 CST</td>
<td>Gulf of Mexico; 650 miles SW. of Mobile, Ala.</td>
<td>Minor dents on fusing and propeller. Windshield and astrodome broken.</td>
<td>Northeast-southeast cold front.</td>
<td>Flying northeast. Engine power was reduced and other precautions taken before entering cold front. Encountered severe turbulence and heavy rain, followed by severe turbulence, hail and continuous lightning for 10 min at 5,000 ft MSL.</td>
</tr>
<tr>
<td>41</td>
<td>North American B-25</td>
<td>April 6, 1949 1930 CST</td>
<td>**NE. Missouri; 40 miles NE. of Springfield</td>
<td>Nose glass, leading lights and cowling.</td>
<td>Air mass.</td>
<td>VFR clearance through area of severe turbulence for 15 min.</td>
</tr>
<tr>
<td>42</td>
<td>North American B-25</td>
<td>June 3, 1949 2000 CST</td>
<td>**NE. New Mexico; 12 miles NE. of Las Vegas</td>
<td>Minor dents in leading edge of wing. Nose plug glass broken.</td>
<td>East-west cold front.</td>
<td>Flying south under VFR conditions. Thunderstorms forecast en route. Turned left to avoid small rain showers in front of thunderstorm at 9,000 ft MSL. Encountered hail for 4 min. Small center estimated 4 miles to right with base 5,000 ft above ground. Clouds passed from right to left.</td>
</tr>
<tr>
<td>43</td>
<td>North American B-25</td>
<td>July 16, 1949 1800 CST</td>
<td>NE. Colorado; 10 miles W. of Arvada</td>
<td>Leading edge of wings and stabilizers. Nose and engine cowling. Pilot canopy broken.</td>
<td>Air mass.</td>
<td>Flying northwest under VFR conditions at 7,500 ft MSL. Thunderhead observed 10 miles ahead. When 3 miles from nearest cloud, hail was encountered for 10 to 15 min. Pilot made a shallow diving turn to left.</td>
</tr>
<tr>
<td>44</td>
<td>North American B-25</td>
<td>Oct. 10, 1949 1200 CST</td>
<td>N. Texas; 30 miles NE. of Pampa</td>
<td>Nose and all leading edges of wing and stabilizers. Various glass light covers broken.</td>
<td>Northeast-southeast stationary front southwest of area with a southeast cold front moving in from northwest.</td>
<td>Flying northwest under IFR conditions. Flight at 10,000 ft MSL between stratus-cloud decks and then into stratus. Strong cross wind from left. Encountered rain, changing to light rain and snow, with light turbulence changing to moderate, then into hail with heavy rain and snow. Updrafts carried plane to 12,000 ft, then in downdraft to 10,000 ft, then in updraft to 13,000 ft. Violent turbulence and hail for 3 to 4 min. During these severe conditions pilot made 180° turn and returned to 12,000 ft.</td>
</tr>
<tr>
<td>45</td>
<td>Lockheed P-39</td>
<td>May 31, 1949 1000 CST</td>
<td>N. Louisiana; 10 miles W. of Houston</td>
<td>Control surfaces, intake ducts, and stabilizers damaged.</td>
<td>Air mass.</td>
<td>Four planned penetrations of a thunderstorm were made over a 45-minute period to test equipment. Altitude 20,000 to 22,000 ft MSL; 283 M.P.H. to 300 M.P.H. Lightning and moderate turbulence. Hail was not detected during flight and no unusual noise was heard. VFR equipment was not affected by electrical disturbances.</td>
</tr>
<tr>
<td>46</td>
<td>Cessna Robert type</td>
<td>April 9, 1944</td>
<td>N. Texas; Pampa</td>
<td>Wood and/or fabric of 195 aircraft damaged.</td>
<td>North-south cold front.</td>
<td>Base organizations warned of high winds. Range space not available. Ball 1 ft. in diameter for 60 sec.</td>
</tr>
</tbody>
</table>

*Damaged on ground. **C refers to control.
<table>
<thead>
<tr>
<th>Case</th>
<th>Type of airplane</th>
<th>Date</th>
<th>Location</th>
<th>Damage</th>
<th>Altitude [FT MSL]</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Boeing B-50</td>
<td>May 8, 1950 1930 EST</td>
<td>SC, Nebraska; 20 miles S. of Omaha</td>
<td>Substantial - 13 pictures of damage available.</td>
<td>6,500</td>
<td>IFR Clearance: Hail encountered during climb after take-off.</td>
</tr>
<tr>
<td>102</td>
<td>Boeing B-50</td>
<td>June 28, 1950 0100 MST</td>
<td>SD, South Dakota; 6 miles NW. of Sioux Falls</td>
<td>Substantial - 20 pictures of damage available.</td>
<td>15,000</td>
<td>IFR Clearance: Hail encountered during climb through cold front with radar in operation.</td>
</tr>
<tr>
<td>103</td>
<td>Boeing B-50</td>
<td>June 11, 1951 1730 CST</td>
<td>SC, South Carolina; 24 miles N. of Waco</td>
<td>Substantial - No pictures available.</td>
<td>12,500</td>
<td>IFR Clearance.</td>
</tr>
<tr>
<td>104</td>
<td>Boeing B-50</td>
<td>Aug. 31, 1951 1630 CST</td>
<td>SC, Kansas; 20 miles WNW. of Topeka</td>
<td>Substantial - 5 pictures of damage available.</td>
<td>25,000</td>
<td>IFR Clearance: Circumnavigating thunderstorm with radar in operation; windshield damage caused decompression of cabin.</td>
</tr>
<tr>
<td>105</td>
<td>Boeing B-50</td>
<td>Feb. 1, 1952 1430 CST</td>
<td>TN, Texas; 30 miles WNW. of Cleburne</td>
<td>Substantial - 7 pictures of damage available.</td>
<td>19,000</td>
<td>IFR Clearance: Radar in operation; windshield damage caused decompression of cabin.</td>
</tr>
<tr>
<td>106</td>
<td>North American B-25</td>
<td>Feb. 12, 1950 1900 CST</td>
<td>NE, Nebraska; 15 miles W. of Lincoln</td>
<td>Substantial - 4 pictures of damage available.</td>
<td>6,000</td>
<td>IFR Clearance.</td>
</tr>
<tr>
<td>107</td>
<td>North American B-25</td>
<td>May 11, 1950 1500 MST</td>
<td>TX, Texas; 30 miles N. of Dallas</td>
<td>Substantial - 7 pictures of damage available.</td>
<td>19,000</td>
<td>IFR Clearance.</td>
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<tr>
<td>108</td>
<td>North American B-25</td>
<td>May 13, 1950 1930 CST</td>
<td>TX, Texas; 5 miles WNW. of Abilene</td>
<td>Substantial - 11 pictures of damage available.</td>
<td>5,000</td>
<td>IFR Clearance.</td>
</tr>
<tr>
<td>110</td>
<td>North American B-25</td>
<td>June 21, 1951 1950 MST</td>
<td>CO, Colorado; 70 miles NNE. of Denver</td>
<td>Substantial - 6 pictures of damage available.</td>
<td>5,000</td>
<td>IFR Clearance.</td>
</tr>
<tr>
<td>111</td>
<td>North American B-25</td>
<td>Sept. 11, 1951 1900 CST</td>
<td>TX, Texas; 50 miles NW. of Wink</td>
<td>Substantial - 6 pictures of damage available.</td>
<td>9,000</td>
<td>VFR Clearance.</td>
</tr>
<tr>
<td>112</td>
<td>Douglas B-25</td>
<td>May 11, 1950 1400 MST</td>
<td>NM, New Mexico; 30 miles N. of El Paso, Texas</td>
<td>Substantial - 6 pictures of damage available.</td>
<td>6,000</td>
<td>VFR Clearance.</td>
</tr>
<tr>
<td>113</td>
<td>North American P-51</td>
<td>Mar. 24, 1950 1200 CST</td>
<td>AL, Alabama; Birmingham</td>
<td>Substantial - 4 pictures of damage available.</td>
<td>Unknown</td>
<td>IFR Clearance changed to VFR: Hail encountered during descent from 22,000 ft.</td>
</tr>
<tr>
<td>114</td>
<td>Lockheed P-38</td>
<td>May 19, 1950 1900 CST</td>
<td>SC, South Carolina; 30 miles N. of Savannah</td>
<td>Substantial - 6 pictures of damage available.</td>
<td>30,000</td>
<td>VFR Clearance changed to IFR: Hail encountered in the vicinity of cold front.</td>
</tr>
<tr>
<td>115</td>
<td>Republic F-84</td>
<td>Apr. 3, 1950 1100 CST</td>
<td>KY, Kentucky; 20 miles W. of Monticello</td>
<td>Substantial - 6 pictures of damage available.</td>
<td>25,000</td>
<td>IFR Clearance.</td>
</tr>
<tr>
<td>116</td>
<td>Republic F-84</td>
<td>June 5, 1951 1400 CST</td>
<td>NM, New Mexico; 50 miles N. of Roswell</td>
<td>Substantial - 5 pictures of damage available.</td>
<td>25,000</td>
<td>VFR Clearance changed to IFR: Two aircraft in formation flight.</td>
</tr>
</tbody>
</table>

*C* refers to central.
<table>
<thead>
<tr>
<th>Case</th>
<th>Type of airplane</th>
<th>Date</th>
<th>Location</th>
<th>Damage</th>
<th>Altitude (ft MSL)</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>117</td>
<td>Republic P-124</td>
<td>June 7, 1951</td>
<td>*NC. New Mexico; 50 miles W. of Tucson</td>
<td>Substantial - 5 pictures of damage available.</td>
<td>25,000</td>
<td>VFR Clearance changed to IFR; Two aircraft in formation flight.</td>
</tr>
<tr>
<td>118</td>
<td>North American F-85</td>
<td>June 19, 1951</td>
<td>1500 CST</td>
<td>5 miles E. of Limestone</td>
<td>Substantial - 5 pictures of damage available.</td>
<td>8,000</td>
</tr>
<tr>
<td>119</td>
<td>Beech NG-7</td>
<td>Apr. 27, 1951</td>
<td>1200 CST</td>
<td>25 miles S. of Lafayette</td>
<td>Substantial - 5 pictures of damage available.</td>
<td>8,000</td>
</tr>
<tr>
<td>120</td>
<td>Beech AT-11</td>
<td>May 23, 1951</td>
<td>1830 CST</td>
<td>W. Texas; 20 miles W. of Sanderson</td>
<td>Substantial - 4 pictures of damage available.</td>
<td>2,900</td>
</tr>
<tr>
<td>121</td>
<td>Lockheed T-33</td>
<td>Sept. 1, 1951</td>
<td>1415 CST</td>
<td>GB. Alabama; Troy</td>
<td>Substantial - 6 pictures of damage available.</td>
<td>30,000</td>
</tr>
<tr>
<td>122</td>
<td>Beech C-45</td>
<td>Aug. 21, 1950</td>
<td>1630 CST</td>
<td>*C. New Mexico; 20 miles SW. of Las Vegas</td>
<td>Substantial - 9 pictures of damage available.</td>
<td>1,000</td>
</tr>
<tr>
<td>123</td>
<td>Curtis C-46</td>
<td>May 14, 1950</td>
<td>1610 CST</td>
<td>*NC. Mississippi; 15 miles S. of Columbus</td>
<td>Substantial - 10 pictures of damage available.</td>
<td>5,000</td>
</tr>
<tr>
<td>124</td>
<td>Fairchild C-82</td>
<td>July 18, 1951</td>
<td>1200 CST</td>
<td>*SC. Wyoming; 20 miles W. of Rawlins</td>
<td>Substantial - 3 pictures of damage available.</td>
<td>12,000</td>
</tr>
<tr>
<td>125</td>
<td>Douglas DC-6</td>
<td>Apr. 29, 1950</td>
<td>1200 CST</td>
<td>*C. Louisiana; Baton Rouge</td>
<td>Substantial</td>
<td>14,000</td>
</tr>
<tr>
<td>126</td>
<td>Douglas DC-6</td>
<td>May 29, 1950</td>
<td>Unknown (Between Oakland, Calif. and Chicago, Ill.)</td>
<td>Substantial</td>
<td>Unknown</td>
<td>None.</td>
</tr>
<tr>
<td>127</td>
<td>Douglas C-39</td>
<td>May 19, 1950</td>
<td>1300 CST</td>
<td>NB. Mexico; 60 miles S. of Victoria</td>
<td>Substantial</td>
<td>6,000</td>
</tr>
<tr>
<td>128</td>
<td>Boeing F-97</td>
<td>July 22, 1951</td>
<td>1905 GMT</td>
<td>Luxembourg; 90 miles SW. of Reims Main Air Base</td>
<td>Substantial - 8 pictures of damage available.</td>
<td>8,000</td>
</tr>
<tr>
<td>129</td>
<td>Lockheed F-80</td>
<td>May 28, 1951</td>
<td>1630 Korean Time</td>
<td>Japan; Honchu</td>
<td>Substantial - 3 pictures of damage available.</td>
<td>22,000</td>
</tr>
<tr>
<td>130</td>
<td>Avro York</td>
<td>July 9, 1949</td>
<td>1705 LST</td>
<td>S. America; S. Brazil</td>
<td>Substantial</td>
<td>8,500</td>
</tr>
<tr>
<td>131</td>
<td>De Havilland Mosquito</td>
<td>May 11, 1945</td>
<td>after 1600 GMT</td>
<td>S. England</td>
<td>Substantial</td>
<td>4,500</td>
</tr>
</tbody>
</table>

*C refers to central.
(a) Actual size of hailstones which fell at Washington, D. C., on April 28, 1938. (From reference 5.)

(b) Hailstones which fell at Potter, Nebraska, on July 6, 1928, on 10-ounce glass tumblers. Hailstone at extreme right measured 17 inches in circumference (5.4 inches in diameter) and weighed $\frac{11}{2}$ pounds. (From reference 6.)

Figure 1.- Photographs of typical forms of large hailstones.
(c) Ballstones which fell in Czechoslovakia on June 13, 1946.

(Fig. unpubl. ms. by Dr. Helmut Weickmann.)

Figure 1 - Concluded.
Figure 2.- Width of path of damaging hailstorms based on 2105 hailstorms from 1924 to 1939. (From reference 10.)
(a) Average annual number of days with hail for years 1899 to 1938.
(From reference 13.)

Figure 3.- Annual hail distribution and thunderstorm distribution over continental United States.
(b) Average annual number of days with thunderstorms for years 1904 to 1943. (From reference 12.)

Figure 3. - Concluded.
Figure 4. - The 1950 crop-hail insurance rates. (Rates shown are for basic crops such as wheat, oats, corn, and so forth, and are adjusted to uniform policy basis.)
Figure 5.- Hourly distribution of damaging hailstorms. Based on 2335 hailstorms from 1924 to 1939. (Adapted from reference 10.)
Figure 6.- Geographical distribution of the months normally having the most hailstorms and those having the most thunderstorms. (Adapted from Reference 12.)

(a) Hailstorm distribution.
Figure 6. - Concluded.
Figure 7.- Hail 2 feet deep which fell during a thunderstorm at Trinidad, Colorado, June 14, 1937. (From reference 20.)
(a) Ice collection rake located over cockpit.
(b) Three cylinders of collection rake as seen from inside of cockpit.

Figure 8.- Photographs of the ice collection rake used in German ice research on Junker Ju 90 aircraft.

Figure 9.- Opaque ice deposits obtained in strato-cumulus clouds at temperature of -13° C. Cloud-droplet radius, 4.5 microns.
Figure 10.- Opaque ice deposits obtained in alto-cumulus clouds at temperature of -13° C. Cloud-droplet radius, 5 to 7 microns.

Figure 11.- Clear ice deposits obtained in the upper part of stratus clouds near 0° C. Cloud-droplet radius, 8 to 9 microns.
(a) Nose section, fuselage over cockpit, engine cowling 2, and spinner.

Figure 12. - Hail case 1. DC-6 airplane. (Time in hail 15 sec; TAS 270 mph.)
(a) Nose section, fuselage over cockpit, and engine cowlings 2 and 3.

Figure 13.- Hail case 3. DC-6 airplane. (Time in hail 2 to 3 min; TAS 295 mph.)
(b) Left wing.

(c) Right wing.

Figure 13.- Continued.
(d) Vertical stabilizer.

(e) Engine 1. Cowling, spinner, and propeller.

Figure 13.- Concluded.
(a) Nose section and fuselage above cockpit. (Windshield has been replaced.)

Figure 14. - Hail case 7. DC-6 airplane. (Time in hail 60 sec; TAS 360 mph.)
(b) Engine 3. Cowling and spinner.

Figure 14.- Continued.
(c) Inner panel of main windshield and curved direct-vision windows.

(d) Loop-antenna housings.

Figure 14.—Continued.
(e) Right horizontal stabilizer.

(f) Top of vertical stabilizer.

Figure 14.- Concluded.
Figure 15.- Hail case 9. DC-4 airplane. Nose section. (Time in hail 8 min; TAS 185 mph.)

Figure 16.- Hail case 14. DC-3 airplane. Right elevator. (Time in hail unknown; TAS 170 mph.)
(a) Nose section, windshield, and top of fuselage.

(b) Windshield from inside of cockpit.

Figure 17.- Hail case 11. DC-3 airplane. (Time in hail 40 sec; TAS 225 mph.)
Figure 18.- Hail case 16. B-29 airplane. (Time in hail 30 sec; TAS 200 mph.)

(a) Leading edge of right wing.

(b) Right horizontal stabilizer.
Figure 19.- Hail case 17. B-29 airplane. (Time in hail unknown; TAS 220 mph.)
(a) Right-horizontal-stabilizer tip.

(b) Spinner and propeller cuff. Engine 2.

Figure 20.- Hail case 19. B-29 airplane. (Time in hail 20 sec; TAS 265 mph.)
(a) Spinner and air scoop.

Figure 21.- Hail case 22. F-82 airplane. (Time in hail 30 sec; TAS 305 mph.)
(b) Leading edge of left wing and bomb rack.

(c) Leading edge of right wing and bomb rack.

Figure 21.- Concluded.
Figure 22.- Results of the impact tests on 0.040-inch 75S-T aluminum (DC-6) wing section. (From reference 40.)

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>ICE SPHERE</th>
<th>DIAMETER inches</th>
<th>WEIGHT grams</th>
<th>VELOCITY mph</th>
<th>INDENTATION inches</th>
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<td>2.3</td>
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NOTE: 1. MEASURED FROM 6 INCH LONG BASE LINE
2. ANGLE OF IMPACT 60 DEGREES
3. APPROXIMATE VELOCITY 450 TO 475 MPH
4. " " " "
5. TOTAL INDENTATION MEASURED FROM STRAIGHT LINE BETWEEN STIFFENERS

(a) For 0.75- and 1.25-inch-diameter ice spheres.
(b) For 1.88-inch-diameter ice spheres.

Figure 22.- Concluded.
(a) For 0.75- and 1.25-inch-diameter ice spheres.

Figure 23.- Results of the impact tests on 0.045-inch 24S-T aluminum (DC-3) wing section. (From reference 40.)
(b) For 1.88-inch-diameter ice spheres.

Figure 23.- Concluded.
Figure 24.- Effect of impact velocity on the extent of hail damage to aluminum wing sections. (From reference 40.)

(a) 0.040-inch 75S-T aluminum. DC-6 airplane.

(b) 0.045-inch 24S-T aluminum. DC-3 airplane.
(a) Location of 57 cases. (Number of each location indicates case number from tables II to IV.)

Figure 25.- Location where hail damaged airplanes in flight.
(b) Location of 83 cases. (These cases include the 57 accidents included in fig. 25(a) plus 26 additional cases added after completion of the analysis.)

Figure 25.- Concluded.
(a) Chart of average number of days with hail. (Adapted from figs. 3(a) and 25.)

Figure 26.- Distribution of 57 cases where hail damaged airplanes superimposed on charts showing annual distributions of hail and crop-hail insurance rates.
Figure 27.— Monthly distribution of hail damage to 47 aircraft with respect to geographical location in the United States.

Figure 28.— Hourly distribution of hail damage to 34 aircraft over the United States.
Figure 29.- Hail-catcher installation on American Airlines Convair (Flagship Gamma). (From reference 44.)

Figure 30.- Small hail or graupel in the hail catcher obtained while flying through a thunderstorm at temperature just above freezing, $4^\circ$ C. (The graupel observed on the surface did not damage subsequent hailstones that entered the cotton.) (From reference 44.)

Figure 31.- Thin layer of packed ice in the hail catcher from snow particles, slush, and soft hail obtained while flying through a thunderstorm at temperature just below freezing, $0^\circ$ to $-5^\circ$ C. (From reference 44.)
BIBLIOGRAPHY

The pages that follow include a comprehensive list of articles concerning information on hail and hail formation. This compilation was made by the authors through sources made available to them in contacts with the Blue Hill Observatory, the American Meteorological Society, the Evans Electronic Laboratory, and others.

Many of these documents were not available to the National Advisory Committee for Aeronautics so that accuracy of the citations could not be ascertained. Those articles which are available to the NACA and for which the citations have been checked against the sources are indicated in the lists by the use of an asterisk preceding the citation.

For the convenience of the reader, this bibliography is divided into sections according to subject matter and in chronological sequence as follows:

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In addition, brief abstracts are included after the citations, when this information was accessible, as well as a notation of the source of availability.

The following bibliographies on hail are available for supplementary hail literature to the NACA Bibliography: (Bibliography (1) includes approximately 580 articles of old, foreign literature which is not included in the NACA Bibliography. Bibliography (4) includes about 80 articles of more recent foreign literature which has not been included here:)


(3) 1949: Meteorological Office Library of Great Britain (Subject Catalogue, Section on Hail). Material included for years 1900 to 1949. (Microfilm available).

A.- HAIL IN GENERAL

1850 - 1899


1900 - 1929


A-13. Ward, Robert DeCourcy: The Climates of the United States. Ginn & Co. (Boston), 1925, pp. 335-338. 1 figure. Points out certain characteristics of hail, occurrence with thunderstorms, narrow area over which it falls, and prevalence in the spring. Reference to hail damage. Figure shows annual number of days with hail during the frostless season.


1930 - 1939


A-17. Aujeszky, Laszlo: A "tiszta jégeső" kérdése. (The Problem of "Pure Hail.") Időjárás (Budapest), vol. 24, no. 14, Nov.-Dec. 1938, pp. 233-242; summary in German, pp. 264-265. (Available Lib. of Congress.) Equations. Definition of "pure hail" which is claimed to be more destructive than when found with other forms of precipitation, damage from pure hail.


Morandi, Luis: Actividades meteorológicas en el Uruguay; una investigación metódica de la frecuencia e intensidad del granizo en el Uruguay. (A methodical investigation of the frequency and intensity of hail in Uruguay.) Revista Meteorológica (Montevideo), Año 3, no. 11, July 1944, pp. 297-298. (Available U. S. Weather Bur. Lib.) Describes project to begin in January 1945 whereby persons untrained in meteorology will take hail observations throughout the country.


*A-31. Anon.: Survey of Hail Studies. Hdqrs., Air Weather Service (Washington), Feb. 1949, 27 pp., 5 tables, 32 references. Report deals with: (a) conditions which are known or appear to be present whenever hail occurs, (b) formation and growth of hail, and (c) data available as to size, frequency, and distribution of hail. Reviews briefly most recent work on theories of hail formation and problems facing meteorologists and forecasters.

A-32. Escobar, V., Ismael: Estudio sobre el granizo. (Study on Hail.) Nimbus, La Paz (Bolivia), Año 1, no. 3, July-Sept. 1949, pp. 1-32; no. 4, Oct.-Dec. 1949, pp. 14-29. Several figures and tables. Specific information on hail in Bolivia. One table shows monthly hailstorms for 121 stations over periods varying from 2 to 30 years. Another table gives seasonal distribution. Also includes a general discussion of hail formation, structure, and damage.
B.- HAIL STRUCTURE

PREVIOUS TO 1850


1850 - 1899


1900 - 1919


B-32. Smith, Wellington: The Structure of Hailstones. Monthly Weather Rev., vol. 34, no. 6, June 1906, pp. 277-278. 1 figure. All stones observed were dished or hollowed toward center; some had holes. Some gave off bubbles when placed in water.


1920 - 1929


B-42. Arnold, James W.: Hailstorm of March 3, 1920, at Broken Arrow, Okla. Monthly Weather Rev., vol. 48, no. 3, March 1920, p. 158. The hailstones were conical in shape, 0.5 inch in diameter, and composed of clear ice.


1930 - 1939


the ground; tables giving frequency distribution of hail sizes for India, central Europe, and the United States; temperature within hailstones, temperature of hailstones on the ground, and temperature of hailstones at certain altitudes; horizontal and vertical distributions of hail.


B-74. Boyle, P.: An Unusual Fall of Hailstones. Weather (London), vol. 1, no. 5, Sept. 1946, p. 160. Description of three types of hailstones that fell in the area surrounding Shouldham Thorpe, Norfolk, on July 2, 1946. Diameter 2.0 to 2.5 inches; as big as tennis balls when they first fell.


C.- HAILSTORMS - SINGLE CASES

PREVIOUS TO 1800


1800 - 1849


storm of uncommon violence affecting southeastern Ohio, southwestern Pennsylvania and the northern part of West Virginia. Drawings of cross sections and description of two hailstones picked up by author. Two photographs showing evidence of destruction.


1900 - 1919


C-69. Violle, J.: (A Hailstorm Followed the Course of an Electric Transmission Line.) *Comptes Rendus (Paris)*, tome 147, Aug. 17, 1908, pp. 375-377. Describes the course of a hail storm along a high voltage transmission line that had only been in use for a year. The storm extended over an area 14 kilometers by 2 kilometers. The direction of the movement of this storm was not unusual for this area.


1920 - 1929


*C-103. Cline, Joseph L.: Hailstorm at Dallas, Texas, May 8, 1926. Monthly Weather Rev., vol. 54, no. 5, May 1926, p. 216. Hail fell for 21 minutes. Size varied from 0.5 to 4 inches in diameter. Larger stones had five to eight layers and weighed 22 ounces. Damage estimated at $750,000.


1930 - 1939


C-118. Rodewald, Martin: Das Hagelunwetter in der Zone Hildesheim-Peine vom 18, Juli 1936. Wetterskizzen Nr. 11. (Hailstorm in the Hildesheim-Peine Zone on July 18, 1936. Weathersketch No. 11.) Annalen der Hydrographie und Maritimen Meteorologie (Hamburg), Bd. 64, Heft 10, Oct. 1936, pp. 447-448. (Available at the Lib. of Congress.) Synoptic conditions in connection with one of the worst hailstorms in the Hannover-Brunswick portion of Germany.


C-124. Anon.: Hailstorm in New Orleans - a Rare Phenomenon. Taylor- Rochester, vol. 29, no. 2, 1939, pp. 58-59. Details of the most destructive hailstorm in several decades which was accompanied by lightning, thunder, and high wind. Storm was result of a violent thunderstorm-type condition which covered a large area.

1940 - 1950

C-125. Little, E. W. R.: Observations on Hail. Quarterly Jour, Roy. Meteorol. Soc., vol. 66, no. 283, Jan. 1940, pp. 21-22. Brief account of two hailstorms on Oct. 27, 1939, in Durham, England, where hail is a winter phenomenon. In both cases air temperature was slightly above freezing which may have been responsible for the formation of stones resembling bundles of fibers.

C-126. Rossman, F.: Ein bemerkenswerter Hagelfall: Sehr grosse, vereinzelt fallende Hagelstein. (A Remarkable Hailfall: Very Large, Scattered Hailstones.) Meteorol. Zeitschr. (Brunswick), Bd. 57, Heft 1, Jan. 1940, pp. 43-45. 2 figures. An analytical account of a thunderstorm situation in Bavaria on May 27, 1931. The stones were formed of concentric layers and were dry. An adiabatic chart for that day made from a sounding at Friedrichshafen shows the tremendous amount of energy available for convective activity.


C-129. Anon.: L'orage a grêle du 29 Juin 1944 dans le nord du Loir-et-Cher. (Hailstorm on June 29, 1944 in Northern Loir-et-Cher.) La Météorologie (Paris), 3e série, Jan.-June 1944, pp. 111-112. Brief account of area and damage of hailstorm with stones as large as oranges.

*C-130. Conover, John H.: "Baseball" Hail from Towering Cumulonimbus. Weather (London), vol. 1, no. 7, Nov. 1946, p. 217. 2 photos. Pictures were taken at Blue Hill Observatory on July 4, 1944, while cumulonimbus was dropping baseball-sized hailstones on Taunton, Mass., which was about 20 miles away.


C-132. Anon.: Grêlons monstrueux. (Tremendous Hailstones.) La Nature (Paris), tome 75, no. 3129, Feb. 1, 1947, p. 43. Brief account of hailstorm in Sydney, Australia, on Jan. 1, 1947, in which 210 persons were hospitalized and extensive property damage incurred.


C-137. Hariharan, P. S.: Sizes of Hailstones. Indian Jour. of Meteorology and Geophysics (Delhi), vol. 1, no. 1, Jan. 1950, p. 73. (Available U. S. Weather Bur. Lib.) Account of hailstorms in the Hyderabad State of India on March 17 and 18, 1939. The largest hailstones that fell on the first day weighed 7.5 pounds each, the largest on the second day weighed 5 pounds. The storm of March 17 affected 17 villages in an area of 30 square miles.
D.- HAIL FREQUENCY AND DISTRIBUTION

1810 - 1849


1850 -1899


D-17. Abbe, Cleveland, ed.: Depth of Hail Fall. Monthly Weather Rev., vol. 25, no. 9, Sept. 1897, p. 399. Information on several storms including hailstorm of June 24, 1897, at Topeka, Kansas, where size of hailstones averaged 4 inches in diameter with a maximum of 6 inches.


1900 - 1919


D-23. Vallot, J.: (Hail and Hoar-Frost on Mont Blanc.) Comptes Rendus (Paris), tome 154, June 10, 1912, pp. 1650-1652. At this location hail is usually accompanied by a deposition of hoar-frost which is deposited on corners or sharp edges and grows in the windward direction.


1920 - 1929


1930 - 1939


D-39. Kozaroff, P.: Des chutes de grêle désastreuses en Bulgarie durant les dix dernières années. (Disastrous Hailstorms in Bulgaria during the past Ten Years.) Matériaux pour l'Étude des Calamités (Geneva), tome 32, no. 4, 1933, pp. 349-352. (Available U. S. Weather Bur. Lib.) 1 table. Hail usually occurs from middle of April to end of September with the most disastrous storms coming in June and July. Four worst storms in 10 year period took place in 1923, 1926, 1929, and 1932. These storms are described.


D-41. Paoloni, P. D. Bernardo M.: Circa una Prossima Pubblicazione Sulla Distribuzione e sui danni della Grandine in Italia. (About a Recent Publication on Hail Distribution and Damage in Italy.) La Meteorologia Practica, tomo 16, no. 5-6, Sept.-Dec., 1935, pp. 244-252. (Available U. S. Weather Bur. Lib.) Table of frequency of hail disasters in 4,000 communities for years 1925-1935 arranged by provinces. Number of disasters in a large number of communities, monthly frequency of disasters, data of most disastrous storm and insurance odds are given.

D-42. Kunze, G.: Die Räumliche Verteilung der Hagelwetter in Schlesien. (The Areal Distribution of Hailstorms in Silesia.) Meteorol. Zeitschr. (Brunswick), Bd. 53, Heft 3, March 1936, pp. 102-105. 6 figures. Hail damage frequency is given for each of the years from 1930 to 1934. The author claims that analysis of the data shows no relation between orography, temperature, wind direction, or air masses and hail frequency, and a slight correlation between air pressure, wind speed or short-wave reception, and hail damage. Results agree with those found in a similar study for East Prussia. Methods of analysis not too sound.


D-47. Hrudíčks, B.: Die Hagelverhältnisse in Böhmen. (Hail Conditions in Bohemia.) Meteorol. Zeitschr. (Brunswick), Bd. 55, Heft 3, March 1938, pp. 111-112. 1 figure, 9 references. After reviewing the sources of data and early studies on hail distribution in Bohemia (Kreil, 1865), the author presents data for various parts of the country along with a chart showing the probability of hail according to five class intervals ranging from 1 to 4 percent. Extreme maximum probability of 10 percent is in South Bohemia where the thunderstorm frequency is least. In the north where hail damage probability is least, the maximum rainfall amount and thunderstorm frequency prevails.

*D-48. Ramdas, L. A., Satakopan, V., and Gopal Rao, S.: Frequency of Days with Hailstorms in India. Indian Jour. of Agric. Sci. (New Delhi), vol. VIII, Dec. 1938, pp. 787-805. 2 tables, 14 figures. (Available U. S. Dept. Agric. Lib.) The figures and tables showing the frequency of hail in India are based on 38 years of records at the majority of the stations, but the tables are all computed to a 100-year basis.

*D-50. Anon.: Thunderstorms. UAL Meteorology Circular No. 6, Meteorology Dept., United Air Lines Transport Corp. (Chicago), June 15, 1939, pp. 1-6. A detailed analysis was made of 136 hailstorms where the hailstones were the size of walnuts or larger, between 1931 and 1938. Five tables on hail distribution are included.


1940 - 1950


*D-57. Shands, A. L.: The Hail-Thunderstorm Ratio. Monthly Weather Rev., vol. 72, no. 3, March 1945, pp. 71-74. Gives mostly reasons for the wide variance of hail-thunderstorm ratio throughout the country. Makes reference to charts in "Climate and Man." Concludes that climatic summaries seem to indicate that hail usually occurred in a state, on more than 20 percent of the days on which there were thunderstorms. The 25-year period from 1915 to 1940 was used to determine how many days there were thunderstorms in the state of Iowa and in the Maryland - Delaware - District of Columbia area.

D-58. Anon.: Estudios Superiores, Seccion de Investigaciones Meteorologicas. Observacion de la frecuencia e intensidad del granizo en todo el territorio de la Republica. (Observation of the Frequency and Intensity of Hail in the Entire Republic.) Boletin de Meteorologia (Montevideo), Ano 2, no. 2, 1944, pp. 9-10. (Available Lib. of Congress.)


D-68. Champion, Donald L.: The Seasonal Distribution of Hail in Great Britain. Weather (London), vol. 3, no. 7, July 1948, pp. 201-205. 4 figures, 1 plate, 1 table. Analysis and compilation of records made throughout Britain for 10 years (1937-1946) indicate greater frequency of hail at coastal stations than in interior, although greater incidence of thunderstorms in interior places. Inverse relation to thunderstorms with maximum in summer and minimum in midwinter. Conclusion is that hail is a convergence phenomenon along coast line, whereas thunderstorms are more often of convective origin.


D-70. Philippson, Alfred: Das Klima Griechenlands. (The Climate of Greece.) Ferd. Dummlers, Bonn, 1948, pp. 120-121. (Available Harvard Univ., Blue Hill Observatory Lib.) 1 table. Reference is made to annual hail frequency data for 26 stations, and monthly frequency for 10 stations. Range is very great; seven days a year in Crete to 1 day a year or less at Lamia.


D-72. Harrison, H. T., and Beckwith, W. B.: A Re-examination of Hail Patterns over Western United States. UAL Meteorology Circular No. 35, Meteorology Dept. United Air Lines, Inc. (Chicago), March 1950, 27 pp., 15 figures, 17 references. Geographical distribution of hail; damage to aircraft aloft; local observations of hail and synoptic patterns for hail at Denver; problems of hail forecasting; pilots' responsibility for avoiding hail.
E.- HAIL FORMATION THEORIES AND FORECASTING

1822 - 1849


1850 - 1899


E-8. Smith, Spencer: An Hypothesis Concerning the Formation of Hail. Trans. Acad. Sci. St. Louis, vol. I, 1856-1860, pp. 297-300. (Available Lib. of Congress.) The theory is advanced that the passage of a current of electricity through the atmosphere would cause a rapid expansion and thus cause cooling. The small hail first formed, being tossed about in this cold current, would, on coming in contact with each other, be quickly congealed together, thus deriving the aggregated form.


1900 - 1929

E-23. Arton, A.: (Formation of Hailstones.) Electricita (Milan), tomo 19, Nov. 3, 1900, pp. 690-692; discussion by L. Bombicci, tomo 20, Jan. 19, 1901, pp. 34-37. Artificial hailstones were produced by the rotation of an insulator in a partially insulating fluid medium when subjected to an electrical field.


*E-32. Humphreys, W. J.: The Uprush of Air Necessary to Sustain the Hailstone. Monthly Weather Rev., vol. 56, no. 8, Aug. 1928, p. 314. Supports the theory that updrafts are necessary for the production of large hailstones. Table based on wind-tunnel experiments shows speed of updrafts necessary to sustain various sizes of hailstones.


1930 - 1939


*E-36. Grimminger, George: The Upward Speed of an Air Current Necessary to Sustain a Hailstone. Monthly Weather Rev., vol. 61, no. 7, July 1933, pp. 198-200. 1 table, 7 equations, 7 references. Shows the development of formulas for computing the vertical velocity to sustain a hailstone. Furthers Humphrey's paper on the same subject. (See E-32.)


E-39. Kunze, G.: Sind Hagelschläge Luftelektrisch Bedingt? (Do Hailstorms Depend on Atmospheric Electricity?) Meteorol. Zeitschr. (Brunswick), Bd. 53, Heft 1, Jan. 1936, pp. 32-33. 2 figures, 4 references. Correlation found between days with good short-wave radio (10m) transmission and days without hail. The conclusion is that good radio reception occurs when subsiding air masses prevail; a condition unfavorable for hail occurrence; and that poor reception occurs where air masses with convective activity prevail.

E-40. Kunze, G.: Rhythmische Wiederkehr von Hagelschlägen am Gleichen Ort. (The Rhythmical Recurrence of Hail at the Same Place.) Meteorol. Zeitschr. (Brunswick), Bd. 53, Heft 5, May 1936, pp. 191-192. 1 figure. Analysis of hailstorms for North Germany for 1932, 1934, and 1935 to prove that there is a $\frac{1}{2}$-day cycle in hail occurrence in a given region. Also correlates between hail occurrence and poor radio reception. Periodicity may be found mathematically significant, but since there is so much variation in length of periods, and so many periods skipped, such data would have little or no forecast value.


E-42. Stoye, Karl: Hagel und 10m-Hörbarkeit. (Hail and 10m Radio Reception.) Meteorol. Zeitschr. (Brunswick), Bd. 53, Heft 9, Sept. 1936, p. 346. A severe criticism of the conclusions presented by Kunze (E-39) showing that many hailstorms occurred at times of maximum short wave reception. Author states that short-wave radio reception is a function of ionospheric, not tropospheric, conditions.

E-43. Kunze, Gerhard: Hagelhäufigkeit und Kurzellenausbreitung. (Hail Frequency and Short Wave Propagation.) Meteorol. Zeitschr. (Brunswick), Bd. 54, Heft 1, Jan. 1937, pp. 27-28. A rebuttal to the article by Stoye, defending the author's previous article (E-42) about the $\frac{1}{2}$-day periodicity in the occurrence of hail and short-wave reception.


E-47. Frey, H.: Zur Entstehung des Hagels. (Formation of Hail.) Beiträge zur Geophysik (Leipzig), Bd. 50, Heft 2-4, 1937, pp. 216-222. (Available Lib. of Congress.) 3 figures, 19 references. By observation of hailstones, an analysis of conditions favorable for the formation of hail and the internal structure of the cloud was conducted. For producing hail a labile air layer, supersaturated with water vapor and with strongly supercooled water drops at about 4000 meters is assumed. Tiny drops are formed by the falling in of snowflakes, and with emission of latent heat of crystallization they are shot upwards. A premature disturbance of the labile equilibrium opposes the formation of hail.


E-49. Gabran, O.: Verfahren zur Abscheidung von Aerosolen aus Schnee und Hagel. (Process for Separation of Aerosols from Snow and Hail.) Meteorol. Zeitschr. (Brunswick), Bd. 55, Heft 3, March 1938, pp. 112-113. A technique for catching fresh snow or hail in a 2-liter jar containing pure petroleum at subfreezing temperature, allowing the impurities to be separated and examined microscopically or spectroscopically in order to determine the nature of the condensation nuclei.


E-54. Rossmann, F.: Blitz und Hagel (Über die Elektrische Natur des Gewitters). (Lightning and Hail (On the Electrical Nature of Thunderstorms.)) Meteorol. Zeitschr, (Brunswick), Bd. 56, Heft 10, Oct. 1939, pp. 372-378. 2 figures, 17 references. Based on 3 years of observations at Feldberg (Schwarzwald) and on reports from flights through thunderstorms and rainshower clouds, the author presents a schematic picture of the structure of the two types of cumulus clouds (water clouds and ice clouds), showing the zones where ice particles, snow, graupel, hail, melting snow, and rain occur, and the electric field in the vicinity of the cloud. A theory on the relation of hail to lightning is presented, with numerous quotations from literature dating back to the 18th Century. Hail and lightning are less frequent when the zero isotherm is high, than (as in Aug. to May) when it is low, and also less frequent in the tropics than the temperate zone, and in midday than at night.

1940 - 1950

E-56. Rossmann, F.: Über die Bildung und Auflösung des Hagels. (On the Formation and Release of Hail.) Annalen der Hydrographie und Maritimen Meteorologie (Hamburg), Bd. 68, Heft 3, March 1940, pp. 89-93: discussion by W. Findeisen, Bd. 68, Heft 8, Aug. 1940, pp. 281-282. Dynamic and thermodynamic conditions necessary for and attending the formation of hail are considered. Special attention is paid to the conditions of supercooling in the cloud tops, the thickness of cloud and the velocity fields necessary to form and support hailstones several inches in diameter.


*E-61. Buell, C. E.: The Occurrence of Hail in Thunderstorms. Jour. of Aero. Meteorology (Kansas City), vol. 1, no. 3, April 1945, pp. 120-128. 17 figures, 2 tables, 7 references. Discusses hail formation theories, reviews the factors showing thunderstorm intensity, considers the geographical distribution of thunderstorms and hail in the United States, and concludes that thunderstorms in the central United States during spring, fall, and winter usually produce hail.


E-69. Ludlam, F. H.: The Composition of Coagulation-Elements in Cumulonimbus. Quarterly Jour. Roy. Meteorol. Soc., vol. 76, no. 327, Jan. 1950, pp. 52-58. 3 figures, 1 table, 7 references. Calculations are made from which it appears that the rate of loss of heat from ice particles growing by coagulation in dense supercooled clouds may be insufficient to allow all the acquired water to freeze. The larger coagulation-elements within cumulonimbus clouds may therefore have liquid skins at levels where the temperature has fallen to -20° or -30° C. The effect may be important in the production of ice nuclei by "splinter" formation and in the generation of thunderstorm electricity.

E-70. Workman, E. J., and Reynolds, S. E.: Electrical Phenomena Occurring during the Freezing of Dilute Aqueous Solutions and Their Possible Relationship to Thunderstorm Electricity. Physical Rev. (New York), vol. 78, no. 3, May 1, 1950, pp. 254-259. The discovery of an electrical effect accompanying the orderly freezing of dilute aqueous solutions is reported. Potential differences as great as 230 volts are measured across the water-ice interface during the freezing process. Application of this effect to the formation of hail and thunderstorm electricity is discussed.
F. - HAIL DAMAGE AND PREVENTION

1826 - 1849


1850 - 1899


1900 - 1919


F-9. Sigaux, J.: Hail Showers and Cannonades. Revue Scientif (Paris), tome 14, Oct. 13, 1900, pp. 461-464. A report on the First Conference on Weather Shooting held in 1899. There were at this time 16,000 hail reporting stations in Italy. The guns used in the prevention of hail were mounted perpendicularly. Since the hail generally moves from the southwest, the guns were discharged in that direction first. Discharges were made twice each minute.


F-13. Shaw, W. N.: Hailstorm Artillery. Nature (London), vol. 64, June 13, 1901, pp. 159-161. Gives an account of the methods used in the prevention of hail by the use of cannon. Shows how their use has spread from Italy to other parts of Europe in recent years.


1920 - 1929


F-50. Hummel, Alfred: Die Beurteilung von Hagelschäden. (The Valuation of Hail Damage.) Reichsnährstand Verlags (Berlin), 1936, 49 pp. (Available Lib. of Congress.) 41 figures. Illustrations and descriptions of types of hail damage to various grains. Suggests precautions to be taken in evaluating damage in respect to insurance.

F-51. Hrudicka, B.: Über Hagelschlag in Mähnten-Schlesien. (On Hail Damage in Moravian Silesia.) Meteorol. Zeitschr. (Brunswick), Bd. 54, Heft 7, July 1937, pp. 265-267. 2 figures. Based on records of hail damage for the years 1926-1935, the frequency of hail in various parts of Moravian Silesia, and the hail damage "quotient" or probability is calculated and shown in two charts.


F-53. Piersig, W.: Gewittertätigkeit und Hagelwetter in Südbayern, am 27. Juli 1936. (Thunderstorm Activity and Hailstorms in South Bavaria on July 27, 1936.) Meteorol. Zeitschr. (Brunswick), Bd. 55, Heft 2, Feb. 1938, pp. 48-54; discussion by Franz Zimmer, Bd. 55, Heft 4, April 1938, p. 153. 8 figures, 3 tables, 8 references. Synoptic and upper air analyses of conditions before and during an outbreak of cold air into Bavaria, which resulted in severe thunderstorms, heavy rain, and widespread hail damage along a strip 15 kilometers wide and 180 kilometers long. Crops were 70 to 100 percent destroyed. This storm was not the most severe in Germany - (the one of July 8, 1927, in the East Erzgebirge killed 146 people).


F-57. Allix, André: L'étude de la grêle par avion et le système de défense du Beaujolais. (The Study of Hail by Airplane and the System of Defense of Beaujolais.) Revue pour l'Étude des Calamités (Geneva), tome 2, no. 5, March-April 1939, pp. 89-100. (Available U. S. Weather Bur. Lib.) 4 figures. Explanation of hail defense system used in Beaujolais where damage to vineyards has been extensive. Bombs are dropped on portion of thundercloud where hail is forming, and these are supplemented by mobile ground batteries. Success is claimed.

1940 - 1950


F-69. Anon.: Daños producidos por el padrisco y medios para evitarlos.  
(Damage Produced by Hail and Methods for Preventing It.)  
Calendario Meteorofenológico 1949, Sección de Climatología,  
Servicio Meteorológico Nacional (Madrid), 1948, pp. 104-114.  

of the activity of the Crop-Hail Insurance Actuarial Association  
and its meteorological-statistical research program.  Method of  
collecting statistical information, determination of crop-hail  
insurance rates, and manner of adjustment in case of damage.

Pedrisco, Particularmente en Mendoza.  (The General Problem of  
Small and Large Hailstones, Particularly in Mendoza.)  Boletín  
de Estudios Geográficas (Mendoza), vol. 1, no. 2, first quarter  
Between 1929 and 1948, one-fourth of damage to vineyards by  
weather disasters was caused by hail.  Methods of hail protection,  
negative results.  One table gives percentage of damage to vine-  
yards from all causes and one for damage from hail only.

*F-72. Anon.: Report of Impact Test on Metal Wing Sections and Propeller  
Dome with Artificial Hailstones.  Memorandum Rep., Aircraft  
Development Div., Structures Section, CAA Tech. Development  
Experimental Station (Indianapolis), May 1949, 12 pp., 10 figures.  
Hailstones less than 0.75 inch in diameter caused no damage to  
DC-6 and DC-3 aircraft wing sections at speeds between 200 and  
300 miles per hour.  Pictures show extent of damage by hailstones  
of 0.75, 1.25, and 1.88 inches in diameter.

*F-73. Anon.: Hail Damage to Simulated DC-6 and Convair Leading Edges  
under Laboratory Conditions and Development of a Suitable Hail  
Catcher.  Tech. Note No. 10, Operational Development Branch,  
Flight Engineering, American Airlines System (New York), May 3,  
1949, 17 pp.  (including a 6 page supplement).  4 graphs,  
2 tables; 6 figures in supplement.  Description and results of  
hail impact test of metal wing sections carried out by CAA Tech.  
Development Experimental Station.

*F-74. Anon.: Description of Circuitry for Erasing Video Signals above a  
Selected Threshold Level and a Flap Attenuator for Automatically  
Measuring Its Performance When Connected to the Output of an Air-  
borne Radar.  Tech. Note No. 12, Operational Development Branch,  
Flight Engineering, American Airlines System (New York), May 23,  
1949, pp. 1-3.  Includes two graphs on the reflectivity of radio  
waves with respect to hail diameters and rainfall rate.

*F-76. Ayer, R. W., White, F. C., and Armstrong, L. W.: The Development of an Airborne Radar Method of Avoiding Severe Turbulence and Heavy Precipitation in the Precipitation Areas of Thunderstorms and Line Squalls. Final Rep. on Task No. 1 of Navy BuAer Contract NO a(s)-9006, Operational Development Branch, Flight Engineering, American Airlines System (New York), Sept. 15, 1949, 35 pp. 15 figures. Only small hail was encountered during the test flights made on this project. Description is given of the hail encountered and the pilot's reaction. Pictures of the hail catcher are included. Hail flight avoidance possibilities are discussed.

*F-77. Richards, Leverett G.: They Really Do Make Rain. Country Gentleman (Philadelphia), vol. 120, no. 7, July 1950, pp. 19, 60, and 61. Also condensed form in the Readers Digest (Pleasantville), vol. 57, no. 339, July 1950, pp. 63-67. Description of the widespread interest in artificial rain making and the successful results of several independent groups in the United States and Hawaii. Hail control is also explained and illustrated by the activities of the Rogue River Valley Traffic Association in southern Oregon.
G.- RELATED SUBJECTS

1784


1800 - 1899


1900 - 1929


1930 - 1939

*G-14. Lange, K. O. (J. Vanier, trans.): Measurements of Vertical Air Currents in the Atmosphere. NACA TM 648, 1931, 9 pp, 9 figures. Extensive research was conducted with balloons, sailplanes, and light airplanes at the Research Institute of the Rhon-Rossitten Society of Germany. The results reveal that the vertical velocities of the air are primarily dependent on the vertical temperature distribution. Effect of local terrain, sky conditions, wind, and so forth, are discussed.


*G-17. McNeal, Don: Ice Formation in the Atmosphere. Jour. Aero. Sci. (New York), vol. 4, Jan. 1937, 14 pp. Discusses, (a) the condensation of water vapor, (b) the existence of undercooled water, and (c) the freezing of undercooled droplets in the atmosphere.


1940 - 1950


*G-27. Anon.: Pre-Coldfrontal Squall Lines. Meteorology Circular No. 16, Meteorology Department, United Air Line Transport Corp. (Chicago), March 1, 1941, 12 pp., 3 figures, 2 tables. A good discussion of the squall lines that develop east of the Rockies and the results of a study of all squall lines occurring near the Cheyenne-New York airway between April 1939 and May 1940.


*G-30. Brancato, George N.: The Meteorological Behavior and Characteristics of Thunderstorms. Hydrometeorological Sections, U. S. Weather Bur., April 1942, 16 pp. Because some thunderstorms cause flooding, the Hydrometeorological Section of the U. S. Weather Bureau was assigned the problem of determining the depth-frequency-elevation relationship and areal extent of the thunderstorm. As a result of this study, it became possible to form conclusions concerning other thunderstorm characteristics. This paper discusses the conclusions reached and compares them with the conclusions reached by Humphreys, Petterssen, and Shaw.


*G-37. Kaster, R. B.: Lightning Strikes and Static Discharges. UAL Meteorology Circular No. 24, Meteorology Dept., United Air Lines, Inc. (Chicago), March 1, 1944, 3 pp. Brief description of the sequence of events leading up to a lightning discharge, including radio static, coronal discharge, turbulence, precipitation, and so forth. Points out the best methods of avoiding lightning strikes.


Weather Radar Research Dept. of Meteorology, M.I.T. (Cambridge),
Dec. 31, 1946.

G-46. Ryde, J. W.: The Attenuation of Centimeter Waves and Echo
Intensities Resulting from Atmospheric Phenomena. Jour. Insti-
tution of Electrical Engineers (London), vol. 93, pt. III A,
1946, pp. 101-103.

Meteorol. Soc., vol. 72, nos. 312-313, April-July 1946,
pp. 235-250. 11 figures. Equations of motion for air-currents
flowing at an angle to the horizontal are derived. From these,
an equation is developed relating the veering or backing of the
wind with height to the rate of ascent of the air and the local
rate of rise of temperature.

Feb. 1947, p. 93. Research activity supports Humphreys theory
on hail formation.

Meteorology, vol. 4, no. 3, June 1947, pp. 91-94. 6 figures,
1 table, 4 references. A theoretical analysis of convective
cloud formation is presented; the fundamental hypothesis being
that the ascending current in a cloud entrains air from its
surroundings.

*G-50. Langmuir, Irving: Summary of Results Thus Far Obtained in Arti-
Project CIRRUS, General Electric Research Lab. (Schenectady),
July 15, 1947, pp. 4-11. Includes discussion of the evaporation-
condensation theory of the growth of small droplets and describes
their study of ice crystal growth within clouds.

*G-51. Schaefer, Vincent J.: Properties of Particles of Snow and the
Geophysics Union (Washington), vol. 28, no. 4, Aug. 1947,
pp. 537-614. 8 tables, 16 figures, 18 references. This paper
describes studies of the physical properties of snow crystals
including their electrical characteristics. Measurements of
falling velocity, quantity and sign of electric charge, mass,
range in quiet air, variety of crystal forms, and other proper-
ties of single crystals are given.


*G-55. Findeisen, W., and Schulz, G.: Experimental Investigations Relating to the Formation of Ice Particles in the Atmosphere. Translation No. 387, U. S. Air Force, Dec. 5, 1947, 45 pp. From Forschungs und Erfahrungsberichte des Reichsivetterdienstes (Berlin), 1944. Direct measurements of temperature, water content, and ice content made in various cloud formations and laboratory tests, showed that ice formation in a cloud is a gradual process. The first solid particles form on a certain class of nuclei when a critical temperature is reached. As the temperature is further reduced, more and different atmospheric impurities act as nuclei. This first ice formation is a direct sublimation of the water vapor to a solid. The vertical velocity of the cloud mass determines the critical temperature required.


28 research reports which may be classed under the following general topics: (a) the relation of icing to the synoptic weather situation, (b) studies of the statistical expression of underlying physical relationships among the factors affecting icing, (c) development and evaluation of instruments and instrumental techniques in the measurement of icing phenomena, (d) physical characteristics of icing clouds and ice accumulations.

*G-59. Smith-Johannsen, Robert: Some Experiments on the Freezing of Water. Occasional Rep. No. 3, Project CIRRUS, General Electric Research Lab. (Schenectady), June 1, 1948, 7 pp. Water samples were frozen in a special container arranged in such a way that no air-solid interface below 0°C was in contact with the liquid. The surface of the liquid was exposed to the air. Under these conditions, it was found that water normally freezes at approximately -20°C. However, water which had been exposed to ultrasonic radiation froze in one case at -38.5°C.

*G-60. Byers, Horace R., and Braham, Roscoe R., Jr.: Thunderstorm Structure and Circulation. Jour. Meteorology, vol. 5; no. 3, June 1948, pp. 71-86. 23 figures, 16 references. Analysis of the data obtained from the thunderstorm project show that the thunderstorm is composed of several distinct cells and that each cell has a three-stage life cycle. Entrainment of air into these cells, combined with convection, results in lapse rates in the updraft and downdraft regions that approximate the lapse rates of the environment.

*G-61. Vonnegut, Bernard: Occasional Rep. No. 5. Project CIRRUS, General Electric Research Lab. (Schenectady), July 15, 1948, 12 pp., 6 figures. Discusses (a) production of ice crystals by the adiabatic expansion of gas, (b) nucleation of supercooled water clouds by silver-iodide smokes, and (c) influence of Butyl alcohol on shape of snow crystals formed in the laboratory.


*G-63. Weickmann, H. (M. G. Sutton, trans.): The Ice Phase in the Atmosphere. (Die Eisphase in der Atmosphäre.) Library Translation No. 273, Royal Aircraft Establishment, Ministry of Supply, Millbank, (London), Sept. 1948, 95 pp. 42 figures, 50 plates, 68 bibliography. Reports the results of 6 years of research on the formation, appearance, occurrence, and growth of the ice
phase in the laboratory, on the ground, and in the atmosphere up to altitudes of 32,500 feet. The most important result is the theoretical and experimental proof that no sublimation nuclei exist and that down to cirrus temperatures crystals form on freezing nuclei via the state of water saturation, or at least at ice supersaturation humidities.

*G-64. Blanchard, Duncan C.: Observations on the Behavior of Water Drops at Terminal Velocity in Air. Occasional Rep. No. 7, Project CIRRUS, General Electric Research Lab. (Schenectady), Nov. 1, 1948, 13 pp. Gives (a) experimental setup and results obtained, (b) size of drop and suspension times, (c) maximum drop diameter before breakup, (d) drops subjected to sudden change in air velocity, (e) drop deformation, (f) breakup fragments of individual drops, (g) aerodynamic effects as a cause of drop collision, (h) drop breakup by collision effects.


*G-66. Cunningham, Robert M., and Miller, Robert W.: Five Weather Radar Flights: Measurements and Analysis. Tech. Rep. No. 7, Weather Radar Research, Dept. of Meteorology, M.I.T., Dec. 1, 1948, 54 pp. 81 figures, 19 references. Since microwave radar is a radically new tool for the meteorologist, the Army Signal Corps initiated the Weather Radar Project at M.I.T. in 1946, with the broad objective of accurate measurement of weather conditions aloft. This report covers only observations where airborne measurements were accurately coordinated in space and time with ground radar observations and measurements. Five cases were selected illustrating five different types of weather situations. The report includes a description of the instruments and radar system used and the observational procedures by which the data were obtained. Exceptionally well illustrated with graphs, diagrams, maps, photographs, and so forth. Hail occurs infrequently in the Boston area where the data were obtained and is only mentioned briefly in figures 7 to 9.


*G-71. Schaefer, Vincent J.: The Possibility of Modifying Lightning Storms in the Northern Rockies. Occasional Rep. No. 11, Project CIRRUS, General Electric Research Lab. (Schenectady), Feb. 15, 1949, 12 pp. A study of cumulus clouds was made at the Priest River Forest and Range Experiment Station of the U. S. Forest Service. This location is in the center of a cloud breeding area where intense thunderstorms are frequent. The direct relation of cloud supercooling, ice-crystal concentration, thunderstorm intensity, lightning, and cloud modification by seeding are discussed.


*G-73. Byers, Horace R., and Hull, Edwin C.: Inflow Patterns of Thunderstorms As Shown by Winds Aloft. Bull. Am. Meteorol. Soc., vol. 30, no. 3, March 1949, pp. 90-96. 9 figures, 9 references. The thunderstorm project over Florida found that in the early stages of development, inflow or horizontal convergence is present at the ground as well as all heights reached by the cloud. In the mature stage, outflow or horizontal divergence was observed under the cloud base and again in the uppermost levels. Relationships to rainfall and to cloud entrainment of environmental air are shown.

*G-75. Heverly, J. Ross: Supercooling and Crystallization. Trans. Am. Geophysics Union (Washington), vol. 30, no. 2, April 1949, pp. 205-210; discussion by John C. Johnson and the author in vol. 31, no. 1, Feb. 1950, pp. 123-126. 3 figures, 21 references. Crystallization experiments were conducted in a laboratory, and the supercooling of water droplets was quantitatively studied under simulated atmospheric conditions. The spontaneous freezing point is presented in a graph as a function of droplet size.


*G-79. Press, E., and Thompson, J. K.: An Analysis of the Relation between Horizontal Temperature Variations and Maximum Effective Gust Velocities in Thunderstorms. NACA TN 1917, 1949, 11 pp., 4 tables, 1 figure. Results indicate that the relation when extended to include frontal conditions appears useful for forecasting the intensity of turbulence for thunderstorms in temperate regions.


*G-86. Mason, B. J.: The Nature of Ice-Forming Nuclei in the Atmosphere. Quarterly Jour. Roy. Meteorol. Soc., vol. 76, no. 327, Jan. 1950, pp. 59-74. 1 figure, 1 table, 31 references. During the last decade many experiments have been designed to investigate the initial processes of ice formation in the atmosphere. The results of these experiments are examined for clues as to the identity of the responsible nuclei and the following tentative conclusions are reached: (a) The nuclei which cause freezing
between 0° C and -32° C are mainly solid, insoluble particles which are melted by water and produce ice crystals by the freezing of water drops. (b) The nuclei which become operative in the range -32° C to -41° C consist of droplets of sea salt solution, ice and salt crystallizing out on contaminating foreign particles. (c) The nuclei effective at just below -41° C consist of droplets of "pure" salt solution and possibly of "gaseous" nuclei formed industrially or by the action of ultraviolet light on gases of the upper atmosphere.

*G-87. aufm Kampe, H. J.: Visibility and Liquid Water Content in Clouds in the Free Atmosphere. Jour. Meteorology, vol. 7, no. 1, Feb. 1950, pp. 54-57; correction in vol. 7, no. 2, April 1950, p. 166. 6 figures, 15 references. Koschmieder's formula is verified by experimental data obtained on Mt. Washington and is used to determine visibility in clouds from measurements of the scattering coefficient. Knowing the visibility and drop size, it is possible to calculate the liquid water content by applying the Trabert formula. The average water content in large cumulus clouds is approximately 2.5 g/m³, in fair weather cumulus 0.5 g/m³ and in stratus 0.2 g/m³.

*G-88. Langmuir, Irving: Progress in Cloud Modification by Project CIRRUS. Occasional Rep. No. 21, Project CIRRUS, General Electric Research Lab. (Schenectady), April 15, 1950, 25 pp., 2 figures. Part I describes the effects of various seeding techniques on the growth modification of large cumulus clouds. Part II discusses the equation for determining the probability that a shower will occur at a definite place and time. The author shows that controlled seeding increases the probability of rainfall in New Mexico.
NACA TN 2734
National Advisory Committee for Aeronautics.
SUMMARY OF AVAILABLE HAIL LITERATURE AND THE EFFECT OF HAIL ON AIRCRAFT IN FLIGHT.
Robert K. Souter and Joseph B. Emerson.
September 1952. 162p. diags., photos., 6 tabs. (NACA TN 2734)

Available information on the hail phenomenon affecting aircraft in flight has been examined. This paper attempts to coordinate the present knowledge of hail with the effect of hail on aircraft in flight and includes (1) a digest of the literature on the physical properties, the occurrence, and the formation of hail; (2) a survey of the hail effect on aircraft in flight from analyses of 57 cases of airplanes damaged by hail; (3) a résumé of hail information for the benefit of pilots, forecasters, and ground operational personnel; and (4) an annotated hail bibliography of 552 articles for use of research personnel.

Copies obtainable from NACA, Washington