Crop-Hail Intensities in Central and Northwest United States

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ABSTRACT

Information on hail intensity is not readily available on a national or local scale. As a result, a study was made to obtain general estimates of the mean areal patterns of hail intensity in the central and northwestern continental United States. Although the results of the study are based on indirect measures of hail intensity developed from crop-insurance data, the results provide useful estimates of a phenomenon heretofore unmeasured. Intensity measures derived from crop-insurance data available for 19 states revealed that summer hailfalls at points in the lee of the Rocky Mountains were 5 to 15 times more intense than those in the Middle West. A good correlation was found for the mean intensity indices of states and the mean hail-day frequencies, suggesting that the widely available climatological data on hail frequency could provide useful estimates of hail intensity in other states.

1. Introduction

One of the primary unanswered questions in many hail studies involves hail intensity. The intensity or total impact force of hail has never been accurately or directly measured, and yet reliable information on hail intensity is of importance to the building industry, agricultural interests, insurance companies, and now to meteorologists attempting to design and evaluate hail modification efforts. The only widely available hail data existing in long-term weather records are those for hail days.

The need for information on the climatology of hail has recently become sufficiently great to warrant research to obtain measurements, albeit indirect, of the areal variability of intensity. Since hail intensity over wide areas has never been measured directly and systematically, questions relating to the natural space variability of hail intensity have remained largely unanswered.

The purpose of this study was to obtain or develop statewide intensity values that could be used to measure the macroscale variations of hail intensity. The only data available that could provide even indirect measurements of hail intensity for several states were crop-insurance records. Crop-hail insurance data for 19 major grain-producing states in the central and northwestern United States were analyzed for wheat and corn crops to develop empirical measures of intensity as reflected in the monthly crop-damage statistics. Individual storm-day data for each month were used to select a median storm-day loss value, which could be considered a measure of the damage capability of an 'average' hailstorm or as an index of hail intensity. These resulting crop-hail intensity indices for each state became the basis for the study of areal variations in hail intensity. The state intensity values were also correlated with statewide mean frequencies of hail days. This statistic is readily available for all states and offers a means to evaluate hail intensity in states other than the 19 in this study.

2. Data and analysis

Insurance statistics on crop losses for individual states were provided by the Crop-Hail Insurance Actuarial Association, and these data were used to develop empirical measures of hail intensity. These insurance data represent approximately 75% of all crop-hail insurance coverage in the United States. The Association provided lengthy listings of the individual storm-day loss cost values for all dates in the 1957–1964 period for 14 major wheat states and 9 major corn states.

Loss cost is a number that represents the total storm-day losses divided by the liability for the area with loss, the ratio being multiplied by $100. Thus, a storm causing $100,000 in losses in an area with $100 million in liability would have a loss cost of $0.10. This ratio computation permits comparison between states with variable amounts of liability. In each state and for each month a median storm-day loss cost value was determined for either corn or wheat or both, and these were defined as intensity indices. The median loss cost values for months with eight or more storm days ranged from a low of $0.0001 to a high of $0.0270. To simplify these median loss cost values, which are also considered the measure of hail intensity, the dollar designations were removed and they were multiplied by 10^4. Thus, the median monthly loss cost of $0.0270 became a monthly hail intensity index of 270. Monthly intensity indices were computed for the available data on corn and on wheat, which resulted in a set of monthly indices for wheat and a set for corn. In those states

TABLE 1. Monthly data on hail damage to wheat, 1957–1964.

State	Apr.		May		June		July		Aug.		Sept.	
	a*	b*	a*	b*	a*	b*	a*	b*	a*	b*	a*	b*
Texas	8	42	24	100	25	146	5	5	0	0	0	0
New Mexico	0	0	5	204	10	260	3	15	0	0	0	0
Oklahoma	11	17	25	113	22	36	3	4	0	0	0	0
Kansas	8	5	26	36	29	80	14	6	0	0	0	0
Colorado	0	0	13	68	21	234	20	121	4	6	0	0
Nebraska	2	3	19	41	28	90	24	42	4	2	0	0
Wyoming	0	0	2	62	11	240	14	270	4	77	0	0
North Dakota	0	0	3	2	23	25	29	107	25	20	6	3
South Dakota	0	0	6	15	23	78	28	110	15	15	1	2
Minnesota	0	0	1	2	13	40	20	40	13	10	2	3
Montana	0	0	2	3	20	26	25	161	20	30	4	3
Oregon	0	0	1	6	3	38	4	17	3	14	1	2
Washington	0	0	2	8	4	30	4	10	2	14	0	0
Idaho	0	0	1	8	7	19	8	31	10	30	4	6

*a**: Average number of storm days.
*b**: Intensity indices (altered median loss cost values).

with loss-cost data for both crops, two sets of monthly intensity indices were developed.

Intensity indices can be considered useful measures of regional variations in hail intensity, but they cannot be used in seasonal comparisons of intensity. Crop losses from hail are a function of hail intensity and the crop's susceptibility to damage, and the susceptibility of most crops to hail damage varies considerably during the growing season (Hail Insurance Adjustment and Research Association, 1955). Much of the seasonal variation shown by the intensity indices has been found to result from seasonal differences in a crop's susceptibility to damage (Changnon, 1966). Crop susceptibility also varies somewhat regionally, since row crops in the Great Plains are not planted as thickly as those in the Middle West. Hence, plants in the Great Plains do not protect themselves from wind-blown hail as well as crop stands in the Middle West. The intensity indices do have insurance applications since a single integrated measure of seasonal intensity and susceptibility differences is useful in developing hail rates (Changnon, 1966).

The intensity indices can be used to make regional comparisons of crop-hail intensity if the indices compared are for months when the stages of crop growth are similar. Such indices were calculated for corn and wheat in those states where these crops were relatively heavily insured.

3. Results for wheat

Insurance loss data pertaining to wheat crops in 14 states are presented in Table 1. It should be realized that these statistics are affected by the extent of insured area in each state, and therefore, interstate differences in the values may partially be a result of sampling vagaries. The storm-day frequencies reveal that many more storm days occur on the average in the states in the middle and upper Great Plains than elsewhere, a result also shown by Lemons (1942).

Table 1 also presents the wheat intensity indices. Most states have their highest intensity indices in either June or July although in Oklahoma May indices rank first. Temporal variations in the wheat indices are illustrated for selected states in Fig. 1. Comparison of of the monthly values obtained for Kansas reveals that the value in June is more than twice as great as

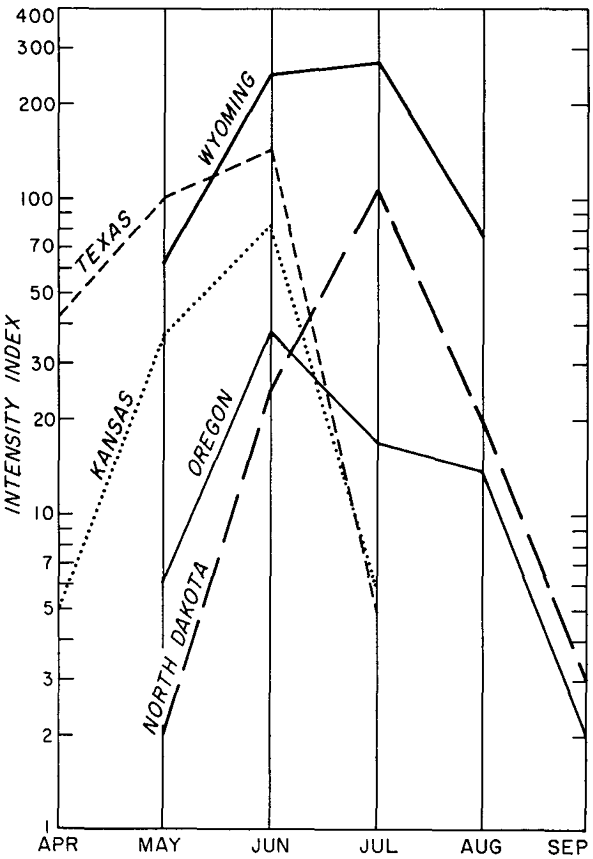

FIG. 1. Seasonal variations in storm intensity-crop susceptibility indices for wheat in selected states.

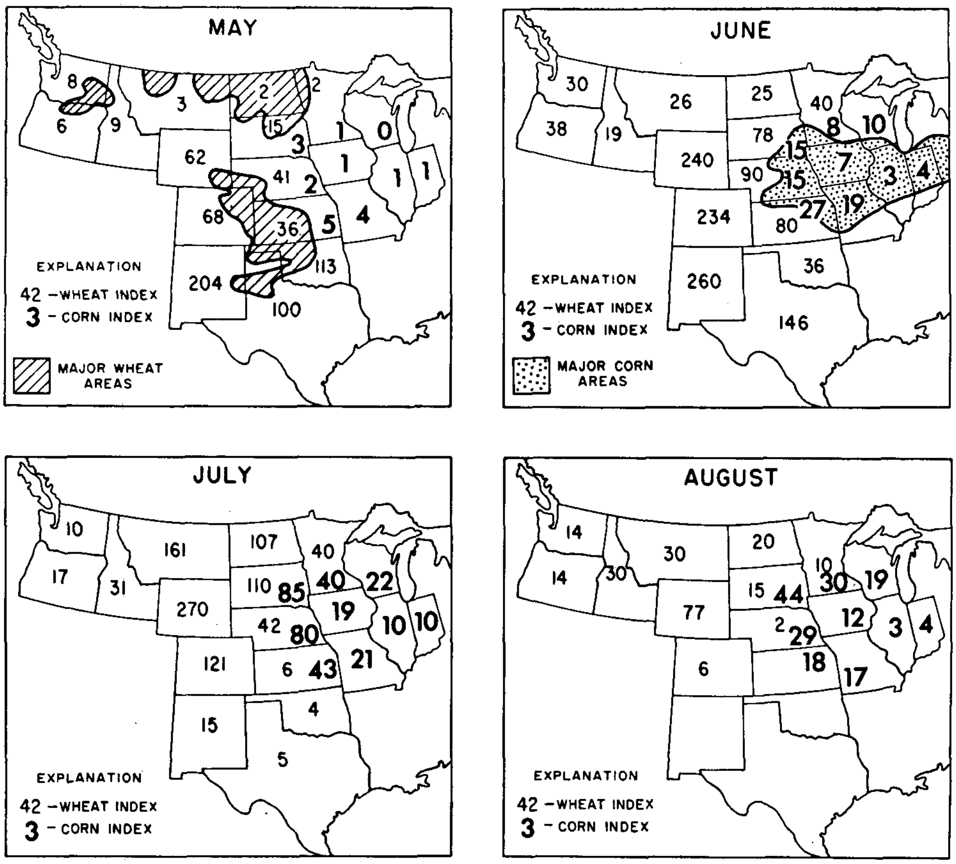

FIG. 2. Monthly patterns of intensity indices for wheat and corn.

that in May, and the June intensity, or susceptibility to damage, value is about 15 times greater than those in April and July. Thus, in Kansas the average June hailstorm day causes 15 times more wheat damage over the state than the average April or July hailstorm day.

Regional variations in the state wheat indices are shown in Fig. 2 for the four major damage months. These patterns reveal that Wyoming hailstorms in June, July and August are considerably more damaging to wheat than those in most other states. May and June storms in New Mexico are also exceptionally damaging, although the number of damage days is small (Table 1). The high indices in New Mexico, Colorado and Wyoming (Fig. 2) to some extent may be caused by the smaller insured areas in these states even though the storm loss values in all states were adjusted to liability in the area of loss. However, inspection of the arrays of storm data from these three states does not indicate that a larger sample would produce significantly lower monthly indices.

The northward shift of the higher intensity indices from May through August is more likely a reflection of the latitudinal shift from winter wheat to spring wheat, and hence in the susceptibility of wheat to damage, rather than a shift in hail intensity. However, values for nearby states can be compared for given months when susceptibility to damage is similar. In May (Fig. 2) the median hailstorm in New Mexico is shown to be about twice as intense as those in nearby Oklahoma and Texas. During July, which is the peak of the damage season of spring wheat in the northern Great Plains, the median Wyoming hailstorm is shown to be about 2.5 times as intense as those in nearby South Dakota and North Dakota. Furthermore, the median hailstorms in the Dakotas during July are about twice as intense as those in Minnesota. The monthly intensity indices in Washington, Oregon and Idaho are generally less than the indices east of the Continental Divide. In any given month, the hail intensity values in the more mountainous states, including New Mexico, Colorado, Wyoming and Montana, are greater than those in adjacent states to the east. Since research in Illinois (Changnon, 1966) and South Dakota has shown that crop-hail damage is largely a result of wind-blown hail, these results suggest that hail-producing storms in the lee of the Rockies also produce strong surface gusts with the hailfalls.

Due to the great geographical disparity in the locations of the wheat states, comparable stages of wheat

Table 2. Comparison of maximum monthly wheat intensity indices in each state with that of Washington.

State	Maximum index	Month	Given state index / Washington index
Washington	30	June	1.00
Idaho	31	July	1.03
Oregon	38	June	1.27
Minnesota	40	June–July	1.33
Kansas	80	June	2.67
Nebraska	90	June	3.00
North Dakota	107	July	3.56
South Dakota	110	July	3.66
Oklahoma	113	May	3.76
Texas	146	June	4.86
Montana	161	July	5.36
Colorado	234	June	7.80
New Mexico	260	June	8.70
Wyoming	270	July	9.00

growth occur in different months which makes it difficult to compare the hail intensities of all 14 states. However, an estimation of these regional intensity differences can be gained by comparing the intensity indices for the peak month of intensity by assuming that the wheat crop is at about the same damage susceptibility level in these months. Washington's peak monthly index of 30 in June is lower than the maximum values of all other states, and the ratio of the maximum for each state to the Washington value is shown in Table 2.

Inspection of these ratios suggests the existence of five general classes or groups of intensities. Hail intensities reflected by wheat in Minnesota, Idaho, Washington and Oregon are similar and much less than that in other states. Kansas and Nebraska have hail intensities that are comparable and about 3.0 times as great as those of the first group of states. North Dakota, South Dakota and Oklahoma form a third group with hail intensities about 3.5 times those in the first group. The Texas and Montana hailstorms on the average are approximately 5.0 times more intense than those in Washington, and those in Colorado, New Mexico, and Wyoming are about 8.0 times more intense on the average.

Interestingly, the states in these groups tend to be juxtaposed so that each intensity group occurs in identifiable geographic entities. The northwest states are largely the low intensity group; the central Great Plains states compose the slightly higher intensity group; the eastern portions of the Upper Great Plains are the third group; and the states in the two highest intensity groups are either in the southern Great Plains or in the western portions of the Upper Great Plains. In general, the regional comparison of the maximum monthly wheat indices suggests that, on the average, the hailstorms in the more mountainous states are much more intense at a point than those in the central plains and in the northwest.

4. Results for corn

To provide information on regional intensity variations in states east of the Wheat Belt, similar indices were developed for corn from insurance loss cost data. In the Corn Belt states there is less seasonal difference in the corn crop's susceptibility to damage than is found in the more widespread wheat states. Thus, for any given month reliable regional comparisons of intensity indices of all the states can be obtained for corn.

Monthly data on the average number of hailstorm days producing damage to corn and the median storm-day corn intensity indices are shown in Table 3 for nine major corn states. The data for Illinois show that the peak intensity index of 10 (loss cost of $.0010) occurs in July. Comparison of this value with the other Illinois monthly values reveals that the average July hailstorm day is about three times more damaging to corn at a point than is the average storm in June or August.

The lack of significant geographical variability in the month of maximum corn damage is revealed by the data in Table 3 and Fig. 3. All states have their highest index in July and their lowest indices in May and September. In more southerly states (Kansas and Missouri), the June indices are greater than those in August, but in the more northerly states August intensity ranks ahead of that in June.

The frequency of corn-damaging hail days, as shown in Table 3, is least in Indiana, Kansas and Missouri, and greatest in Nebraska and Iowa. Regional variations in the corn-hail intensity indices are also revealed in Fig. 2. In most months the indices indicate a longitudinal variation in intensity with the lowest values in the east and the highest in the western states of the Corn Belt. Regional comparisons of hail intensity in the Corn Belt states were made using the indices for July, the peak month of intensity-susceptibility. The lowest intensity value was 10 in Indiana and Illinois. The intensities in Iowa, Missouri and Wisconsin were about twice those in Illinois and Indiana; those in Minnesota and Kansas were 4 to 5 times greater; and those in Nebraska and South Dakota

Table 3. Monthly data on hail-damage to corn, 1957–1964.

State	May *a**	May *b**	June *a**	June *b**	July *a**	July *b**	Aug. *a**	Aug. *b**	Sept. *a**	Sept. *b**
Illinois	3	1	12	3	17	10	13	3	4	1
Indiana	1	1	6	4	9	10	6	4	2	1
Iowa	5	1	21	7	26	19	23	12	11	1
Missouri	3	4	8	19	10	21	6	17	2	4
Kansas	4	5	4	27	7	53	5	18	2	11
Nebraska	4	2	19	15	27	80	26	29	13	3
South Dakota	1	3	12	15	21	85	23	44	6	5
Minnesota	2	1	11	8	21	40	21	30	6	3
Wisconsin	0	0	2	10	6	22	5	19	2	2

*a**: Average number of storm days.
*b**: Intensity indices (altered median loss cost values).

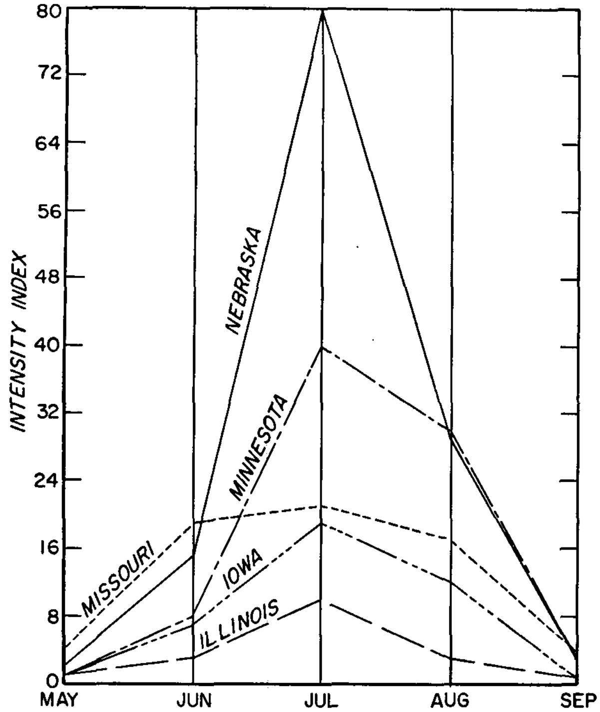

FIG. 3. Seasonal variations in storm intensity-crop susceptibility indices for corn in selected states.

were about 8 times greater than the median intensity of July hailstorms in Indiana and Illinois.

5. Regional variations in hail intensity

To measure the areal variability of hail intensity across the entire 19-state area required joint utilization of the corn intensity indices and the wheat indices since neither of these indices was available for all the states. To combine the intensity indices from the two crops required 1) proof of a close relationship between indices, and 2) a mathematical procedure for equating the indices.

Degree of relationship between wheat and corn indices. The wheat and corn intensity indices for the four states (Minnesota, South Dakota, Nebraska and Kansas) with both crops were compared. The states were paired and compared using ratios based on the maximum monthly intensity indices calculated for wheat and corn. For instance, the Kansas maximum monthly wheat index of 80 (Table 2) was divided by the Minnesota maximum wheat index of 40 resulting in a ratio of 2.0 shown in Table 4; and the Kansas maximum monthly corn index of 53 (Table 3) was divided by the maximum Minnesota value of 40 to get a corn ratio of 1.4 (Table 4).

Thus, comparison of the corn indices indicated that hail in Kansas was 2.0 times as intense as that in Minnesota, whereas comparison of the two states using their wheat indices indicated that the hail intensity in Kansas was 1.4 times that in Minnesota.

TABLE 4. Wheat and corn intensity ratios for pairs of states developed using maximum monthly intensity indices for each crop.

Pairs	Ratios Wheat	Ratios Corn
Kansas/Minnesota	2.0	1.4
South Dakota/Minnesota	2.7	2.1
Nebraska/Minnesota	2.2	2.0
Nebraska/Kansas	1.2	1.5
South Dakota/Kansas	1.4	1.6
South Dakota/Nebraska	1.2	1.1
Means	1.8−	1.6+

The resulting intensity ratios calculated for the six possible pairings of the four states with wheat and corn data are shown in Table 4. Although none of the paired ratios were exactly equal, they were approximately the same which meant that the maximum monthly intensity indices developed for corn could be combined with those for wheat to obtain a reasonably accurate basis for comparing the crop-hail intensity among the 19 states.

Procedure for combining wheat and corn indices. As a first step, the maximum monthly intensity index for corn in each of the states was divided by 10, the Illinois and Indiana maximum corn intensity indices, because this was the lowest of the state maximum indices. Thus, these maximum intensity indices for Illinois and Indiana became 1.0, and these reduced values were defined as "adjusted intensity indices." Similarly, the South Dakota maximum corn intensity index of 85 became an adjusted intensity index of 8.5 which meant that the July hailstorms in South Dakota on the average were 8.5 times more damaging to a corn crop than those in Indiana and Illinois. These adjusted intensity indices, as calculated for corn, were plotted

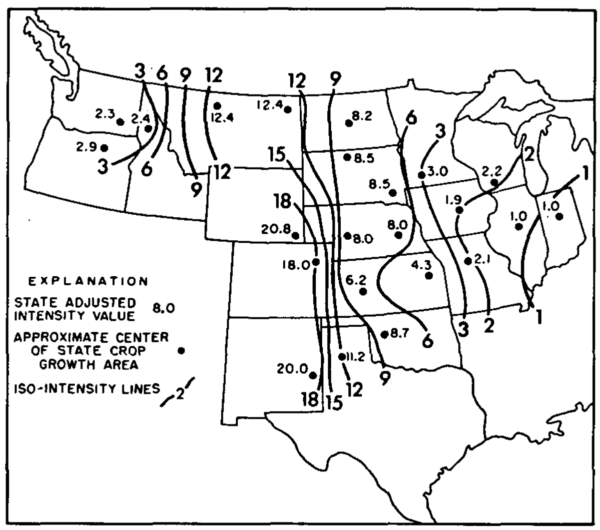

FIG. 4. Pattern of hail intensity as determined for peak month (June or July) of wheat-corn damages.

near the center of the principal corn growth area in the nine corn states (Fig. 4). Two adjusted intensity values appear in those states where corn and wheat values could be developed and where the corn growth region was distinctly separate from the region of wheat growth.

South Dakota data were then chosen to develop a relation between the wheat indices and those for corn. For each of the 10 wheat states which had no developable corn indices, a ratio of the maximum monthly wheat intensity index to that for South Dakota was calculated. This ratio for each state was multiplied by the South Dakota adjusted corn intensity index of 8.5 to obtain an adjusted intensity index for each of the wheat states. For instance, the ratio of the peak Montana wheat intensity index of 161 (Table 2) to the South Dakota value of 110 was 1.46, and multiplication by 8.5, the South Dakota adjusted intensity value, produced an adjusted intensity index of 12.4 for Montana. These state adjusted intensity indices were determined for each of the wheat states and were plotted at the center of the major wheat areas in each state (Fig. 4).

Results. The areal variations in hail intensity, as measured by the adjusted indices developed from the maximum crop damage months (either June or July), are revealed by the iso-intensity lines on Fig. 4. The crop-hail intensity in midsummer decreases rapidly eastward from the Rocky Mountain states. Midsummer hail in the central and eastern portions of the Great Plains states that border the mountain states is only about 20–40% as intense, on the average, as that in mountain states. The hailfalls in the next north-south line of states (Missouri, Iowa and Minnesota) on the average are only 25–50% as intense as those in the adjacent states on their western borders. The most eastern states analyzed, Illinois and Indiana, have average hail intensities that are 50% of those in the adjacent states to the west. Hail intensities in Idaho, Oregon and Washington are comparable with those in the Middle West.

6. Relationship between crop-hail intensity and hail occurrences

Hail intensity values similar to those derived from the crop-insurance data for the 19 states cannot be obtained for most other states because of the lack of extensive crop insurance in many areas. Thus, a national climatological portrayal of hail intensity and its areal-temporal variations is not available.

The only widely available climatological data on hail are for the number of days with hail as recorded at U. S. Weather Bureau first-order stations (U. S. Weather Bureau, 1947) and at cooperative substations. If a relationship exists between hail-day frequencies and hail intensity, the frequency data offer a means for estimating hail intensity throughout the nation. As a consequence, the hail-day frequencies and insurance intensity indices were compared to measure the degree of relationship.

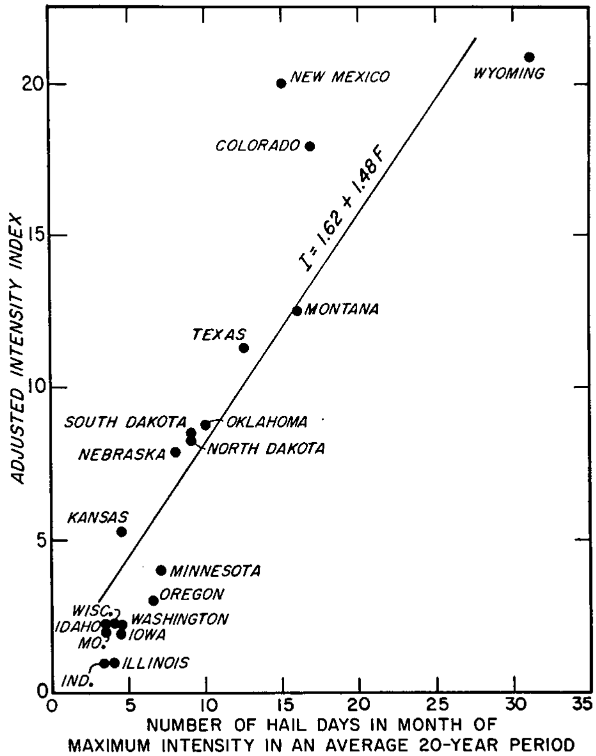

FIG. 5. Comparison of average point hail-day frequencies and adjusted hail intensity indices.

A comparative analysis was made using the intensity and frequency data for the 19 states with identified intensities (Fig. 4). Since the adjusted intensity indices selected for these comparisons were based on months of maximum intensity, this hail frequency-intensity comparison was based on data for these same months. In most states the month of maximum intensity was June or July (Tables 2 and 3). For each state an average point hail-day value for the maximum intensity month was calculated using data from the first-order stations located in and on the periphery of the state.

The intensity-frequency data for the 19 states are shown plotted on Fig. 5. A line was fitted to the 19 data points by the method of least squares and the regression equation is presented on Fig. 5. The standard error of estimate for the scatter around the regression line was 2.98. The correlation coefficient computed for the intensity-frequency values was +0.89 which indicated that the average hail-day values explained 79% of the variation in the hail intensity.

Comparative studies of summer hail frequencies and annual amount of crop loss in Illinois also indicated a relationship between hail-day frequencies and crop losses (Roth, 1961). Changnon (1960) found that the annual amount of crop-hail loss in Illinois correlated well with the extent of area experiencing more summer hail days than could be expected to occur once in ten years. In this instance, relatively more hailstorms over large areas of Illinois were associated with more total damage, indicating the existence of a correlation between frequency and intensity, if the degree of damage is a measure of intensity.

7. Conclusions

The insurance-derived intensity indices for each state indicated that the point intensity of hail near the Rocky Mountains is much greater than that in the northwest, Great Plains and Middle West. Hail intensity in the peak intensity-crop damage months, June and July, decreases rapidly and steadily eastward from the Rocky Mountains. Hail in Illinois and Indiana is only 5–10% as intense on the average as that in the mountain states. Evaluation of seasonal differences in intensity using the insurance indices was inconclusive because the indices strongly reflect temporal changes in the susceptibility of crops. The maximum intensity-susceptibility values occur in June in the southern wheat states and in July in the more northern wheat states and in all the Corn Belt states.

Damaging storm days are most frequent, on the average, in Kansas, Nebraska and the Dakotas, and damage days are least frequent in the mountain states (wheat) and the eastern Middle West (corn). Thus, in the mountain states where hail intensity at a point is greatest, storm days are less frequent than those in the Great Plains. However, the intensity indices were found to be well correlated with the mean frequency of total hail days at a point, suggesting that the widely available hail-days data offer a means for estimating intensity throughout the nation.

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REFERENCES

Changnon, S. A., 1960: Relations in Illinois between annual hail loss cost insurance data and climatological hail data. Chicago, Crop-Hail Insurance Actuarial Association Research Report 3, 18 pp.

——, 1966: Summary of 1965 hail research in Illinois. Chicago, Crop-Hail Insurance Actuarial Association Research Report 30, 38 pp.

Hail Insurance Adjustment and Research Association, 1955: Corn hail loss survey sheet instructions. Chicago, 8 pp.

Lemons, H., 1942: Hail in American agriculture. *Econ. Geography*, **45**, 363–378.

Roth, R. J., 1961: Some applications of research report 3. Chicago, Crop-Hail Insurance Actuarial Association, 11 pp.

U. S. Weather Bureau, 1947: Thunderstorm rainfall. Vicksburg, Hydrometeorological Report 5, 311 pp.