Variability of Hailstorms on the South African Plateau

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ABSTRACT

Detailed climatological studies of hailstorms on the South African plateau have been made using a dense network of voluntary observers. Hailstone structures have been investigated and, since 1971, radar observations have been used to study storm characteristics. Results are given for the frequency of hailstorm occurrence, characteristics of hailfalls at a point, hail paths, types of storms, radar characteristics and hailstone trajectories. Practically all features showed great variability, the magnitude of which is given whenever possible. Application of the results to the design of a hail suppression experiment is briefly discussed.

1. Introduction

Variability is a well-known characteristic of hailstorms and it has made the evaluation of hail suppression experiments a frustrating task. Both the design and evaluation of such experiments require quantitative data on natural variability. One needs information ranging from the year-to-year changes in the number and type of hailstorms to be expected in a particular area down to small-scale effects within one storm. Variations in several hail parameters within distances of as small as 100 m were revealed by a dense network of hail sensors in Illinois (Morgan and Towery, 1975).

This paper describes certain aspects of the variability of hailstorms on the South African Plateau. The findings are based on investigations of hailstone structures and surface hailfall patterns, as well as on radar studies of storms in the Transvaal in the vicinity of Pretoria and Johannesburg. This is a region of summer rainfall with a high incidence of thunderstorms. The altitude is about 1500 m MSL. Some 3000 observers located within a rectangular area of 40 km × 70 km provide details of hailfalls. Prior to 1970 the number was about 800. The implications of some results with regard to hail prevention are discussed.

2. Frequency of hail occurrence

a. Size of observational area

The operational area for a hail prevention experiment must be sufficiently large to ensure that enough hailstorms will occur within it to allow the experiment to be completed within a reasonable period. Inevitably there will be logistic restraints which will limit the size. The relationship between hail incidence and observational area must be known in order to reach a reasonable compromise in fixing the size of the operational area.

Shands (1944) suggested that the hail frequency for any area is approximately five times the point frequency. This was more or less confirmed for a 400 km² area including Denver, Colo., during a 10-year study by Beckwith (1960). Many storms must have passed unrecorded in these studies because of the coarse networks which were used. Much higher ratios of areal to point frequencies were found by Carte (1967) when the network density was sufficient to ensure that practically all storms would be detected. Results are shown in Fig. 1. They have been subdivided according to storm severity, as defined by the size of the largest hailstones.

Fig. 1 shows the magnitude of the increase in number of hail days with area and it emphasizes the relative scarcity of severe storms, as defined above. The data were obtained during a seven-year period. A hail day was any day for which at least one hail report was received from within the particular observational area. The smallest area investigated was 2.6 km² and results from at least 19 such areas were averaged annually. Progressively fewer areas were averaged as the area became larger. Hatching indicates the spread in average values from year to year. Further details were given by Carte and Basson (1970).

The point hail frequency in Pretoria over 20 years varied between one and nine days of hail per year (Schulze, 1965), with an average value of 4.5 and a standard deviation of 1.9. A decade of results for the whole network gave an average of 69 days of hail per year (three when hailstones exceeded 3 cm in diameter), the extremes being 95 and 39 and the standard deviation 18.7. These results are shown in Fig. 1 by vertical bars. The variability in hail frequency can be seen to decrease as the size of the observational area increases: the highest and lowest point frequencies differed by a factor of 9, while the difference between the extreme values for the whole network was a factor of 2.4.
Fig. 1. Observational area as a function of the average annual number of hail days subdivided according to the size of the largest hailstones. Hatching indicates the spread over 7 years. The vertical bar on the left applies to 20 years of records of the point frequency in Pretoria, and the one at the top right to 10 years of data for the hail frequency within the network; solid points indicate extreme values; the cross bars above and below the means (circles) span one standard deviation.

More information on year-to-year changes in the number of hail days within the whole network is given in Fig. 2. The results were subdivided according to the sizes of the largest hailstones. The number of observers was increased in 1970 to about 3000 without any change of the network area. This resulted in fewer of the light hailfalls passing unrecorded.

The results in Figs. 1 and 2 illustrate that hailstones no larger than 1 cm in diameter were produced on about half of all the hail days and hailstones greater than 3 cm have been rather rare and most variable in their occurrence. These ratios do not necessarily apply elsewhere. In the Po Valley, Italy, where the hail frequency is lower than here (2.6 days per year at a point in Verona, 43 days per year within an area of tens of thousands of square kilometers) walnut-size hailstones are reported to have occurred on 30% of the hail days (Morgan, 1973).

b. Seasonal changes

Hail is generally regarded as a phenomenon of summer, although there are localities such as the highlands of Kenya where it occurs all the year round (Alusa, 1976). Most of the hail here falls during the months October to April, which include the summer. There are occasional occurrences in winter, as illustrated by the average monthly distribution in Fig. 3, which also shows the results for the years with the least and the most hail days during a decade (Held, 1973). The mean distribution for the five years from 1970–75 when there was a larger panel of observers was essentially the same as for that in Fig. 3. The vertical bars in Fig. 3 for the months October to June span one standard deviation. November is the peak month for hail, with an average of 12 days, limits of 6 and 18 and a standard deviation of 4. Severe storms tend to occur early in the season in contrast with findings for North America and Europe (Held, 1973).

The storms which produce the largest hailstones are generally those of greatest areal extent. This is reflected by the results displayed in Fig. 4 where the percentage of the total observational area covered by hail during 10 years is plotted against month. It will be noted that more than half the contribution to the average annual value came from hailstorms during October and November while not even one-third of the hail days fell into the same period.

c. Urban and orographic effects

The results up to now have been presented as though the hail frequency is uniform throughout the network.

Fig. 2. Yearly number of hail days within the network. Results are shown for the the original panel of observers from 1962–72 and for the denser network from 1970–76. The vertical bars span one standard deviation. Sizes refer to the largest hailstones.
area. This is not the case. The northern half was found to have had fewer days with hail than the southern half, which is ~300 m higher in altitude. When the results of this seven-year study were stratified according to the size of the largest hailstones it was noted that both regions experienced nearly the same number of days when only hailstones less than 1 cm in diameter fell but they differed consistently as regards the occurrence of more severe storms (Carte and Basson, 1970).

This study was extended to cover 14 years, and the data were subdivided according to the sizes of both the largest and commonest hailstones. Comparisons were made between three equal areas of 100 km², all with the same density of observers. Two areas in Johannesburg gave essentially the same results, but all averages showed that Pretoria had fewer days with hail than Johannesburg, the higher lying area in the southern half of the network. The results of one such comparison are presented in Fig. 5. It will be seen that if the analysis had been restricted to the last five years and to days when the largest hailstones were greater than 1 cm in diameter no difference between the two regions would have been apparent. (The results for 1970–71 and 1971–72 show qualitatively that this is not an effect of the increased observer density.) This finding emphasizes the caution that should be exercised in attempting to correlate hail frequencies in two different areas.

More detailed comparisons were made afterward between different parts of the network. Results are shown in Fig. 6. Urban areas experienced more occurrences of hail than adjacent rural ones. The effects of observer density were eliminated as far as possible (Held, 1974) and greater confidence was gained in the results when the isohetal pattern for the summer months closely matched the pattern of hail incidence. The occurrence of more rain and hail in Johannesburg is attributed to its altitude being 300 m above that of Pretoria. Even smaller scale influences seem likely in that more rain and hail occurred to the north of ridges in both regions than to the south. The increased precipitation in these urban areas may be due to the combined influences of urban and orographic effects, although the rather small differences in topography suggest that urban effects would be more important. The occurrence of severe storms (hailstones >3 cm in diameter) bore no relationship to specific parts of the network.

Correlation of hail incidence with gross topographical features is well known. Long-term records of point frequencies kept by the Weather Bureau show that isopleths of hail incidence conform well with the general relief of southern Africa (Schulze, 1965). Significant

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**Fig. 3.** Seasonal variation of hail days within the Pretoria-Johannesburg hail-observing network for the decade 1962–72. Vertical bars span one standard deviation. Results are also shown for the years with the most and the least hail days.

**Fig. 4.** Seasonal variation of the area covered by hail and the number of hail days per month. Results are given as percentages of the totals for the period 1962–72.

**Fig. 5.** The total number of days when hailstones exceeded 1 cm in diameter within observational areas of 100 km² in Johannesburg (solid lines) and in Pretoria (broken lines). Results are shown for the original panel of observers from 1962–72 and for the denser network from 1970–76.
3. Hailfalls at a point

a. Intermittency and duration

Several characteristics of hailfalls at a point show extreme variability with time and from storm to storm. Out of over 27,000 hail reports, 30% stated the hailfalls to have been intermittent. Up to eight bursts of hail have been recorded, but mostly only two occur. Many of the so-called continuous falls varied in intensity without complete lulls. Intermittency arises from movement of hail cells of irregular shape, repeated expansion and contraction of hail cells, and the passage of more than one cell past a given point (Carte and Held, 1972).

Average values for the durations of point hailfalls since 1970 were found to be 7.3 min for all reports, 5.8 min for continuous falls and 10.9 min for intermittent ones. All these values varied between wide limits but one remarkable fact was that average values for any one year deviated by no more than ±10% from the averages for the whole period.

b. Amount of hail

On occasions hail has accumulated to depths of more than 10 cm on flat ground but generally the amount is much smaller. Only 21% of reports have stated that there was more than enough to cover the ground. Insofar as one can generalize, there is more hail when the hailstones are large (i.e., larger masses of hail per unit area occur and hail falls over a larger area). The maximum amount does not necessarily occur at the location of the largest hailstones (e.g., Carte and Mader, 1977). Amount of hail has also been found to be related to duration (Held, 1973). Striking differences in amount can be found within one path of hail with enormous quantities occurring in some places and practically nothing in others (Carte, 1966). Perhaps the most significant finding is the small amount of hail which generally occurs (though there is more than enough to cause considerable damage). Hail generation seems to be far more efficient in the Po Valley of Italy than here. There the point frequency is less than three days per year but large depths of hail are frequently reported and the hailstones exceed the size of walnuts on 31% of the hail days, as already mentioned. Heavy hailfalls are also frequent in parts of Russia (Sulakvelidze, 1967). Most hailstorms in the Po Valley originate under frontal conditions, in contrast with the Transvaal where air mass storms predominate, and this is the likely reason for the more frequent occurrence of severe storms (as characterized by size of hailstones, amount and duration of hail) and of storms during the night (Prodi, 1974).

c. Size distribution of hailstones

It has been suggested that seeding might shift the size distribution of hailstones toward smaller sizes. Size spectra vary widely from monodisperse to broad, making such changes difficult to detect. The results in Fig. 7 show the relative frequencies of hail reports which gave the size of the largest, commonest and smallest hailstones in various size groups. The vertical bars indicate that yearly averages have deviated rela-
Progressively little from the averages for 14 years. The modal size group for every category has remained the same for every year. If the effect of seeding were to produce smaller hailstones, then this could be detected by comparing the distributions based on at least a year’s data with the results in Fig. 7.

Information on the width of hailstone size distributions and on modal size groups is presented in Fig. 8. It was derived from reports which gave estimated sizes of the largest, commonest and smallest hailstones. Certain trends are obvious: with increasing size of the largest ones, the modal size of the commonest ones increased steadily and size spectra became wider. There were occasions, but only a few, when large hailstones occurred and narrow or even monodisperse spectra were encountered. The modal size group for the smallest ones was always either the smallest or the group from 0.5 to 1 cm.

It may be inferred from the results in Fig. 8 that the commonest hailstones in a hailfall at a point are not often the smallest ones, unless only small ones occur.

This need not be the case afloat since the spatial concentration for a given size group is equal to the flux of hailstones striking the ground divided by their terminal velocity.

The results presented in Figs. 7 and 8 constitute meaningful averages in spite of the variability of hail and the subjectivity of the observations. Sufficient results have been collected from the network during 14 years to show that addition of further data is unlikely to alter the averages significantly. Differences between the results for any one year and the long-term averages are small, compared with results for individual storms, and deviations of three-year averages are even smaller. In fact, histograms for three years are distinguishable from those in Fig. 8 only for those categories with few reports, viz. when hailstones exceeded about 5 cm in diameter.

4. Hail paths

Hail from one storm may cover anything from a few square kilometers to more than 1000 km$^2$. Hail areas from sustained storms may be elongated in the direction of travel. Such long, narrow tracks (paths, swaths) may have been produced by a single long-lived cell or by a number of cells which traversed the path, each producing what Changnon (1970) called a "hailstreak." Areas on which hail fell at a particular instant may be of complex shape and they may change rapidly with time as illustrated in Fig. 9 which is from Carte and Held (1972). A very high density of observations and accurate times are required to resolve such detail. Patchiness of hail paths is a general feature and it reveals unsteadiness of the hail production process. This is also manifested by changes in size and structure of the hailstones, amount of hail, size and shape of the instantaneous hail areas, and other characteristics. Examples have been

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Fig. 7. Relative frequencies of various size groups for hailstones reported to be (a) largest, (b) commonest and (c) smallest. The period covered by the observations is 1962–76. The vertical bars indicate maximum and minimum values of yearly averages.

Fig. 8. Frequency distributions of reports covering the period October 1962 to September 1976 of (a) smallest hailstone sizes and (b) commonest hailstone sizes against size groups, the parameter being the size of the largest hailstones.
given by Carte and Held (1972), Carte and Mader (1977) and Roos et al. (1977). Admirat (1973) has reported on the characteristics of "hail cores" for which all parameters of the hailfalls reached a maximum on the ground at the same place. It is difficult to find examples here where such systematic behavior has occurred and, for instance, the maximum amount of hail has fallen after the largest hailstones have ended. Misleading conclusions are easily reached when insufficient detail is available. For example, plotted isochrones of hail onset time might fail to reveal the presence of two contiguous hailstreaks.

Fig. 9. Details of hail areas at 1 min intervals within a 10 km x 10 km square in Johannesburg on 29 September 1970. The density of points from which the hail areas for 1546 South African Standard Time (SAST) were derived is shown (lower left).

Fig. 10. Examples of areas covered by hail on six different days (hatched). Cross-hatching indicates where hailstones exceeding 3 cm in diameter fell. The solid lines enclose instantaneous hail areas and arrows show their direction of movement.
Examples of the areas covered by hail within the observing network on six days are shown in Fig. 10. A rough indication of the size of the largest hailstones and a few examples of instantaneous hail areas are given. Characteristics of 69 hail paths which occurred during 1970–75 were as follows: mean area, 150 km²; maximum area, 1125 km²; half were 50–250 km²; one-third < 50 km²; 7% > 500 km²; most were within 5–9 km in width and 10–19 km in length. Those of length greater than 20 km tended to occur in the first half of the season. The mean instantaneous hail area was 36 km², most were 11–50 km² and the largest was 250 km².

5. Types of storms and radar echo characteristics

An S-band radar with a beam width of 1.1° was operated on 447 days during four summers from 1971 to 1975. Storms within a radius of 300 km were observed on 389 days and within 100 km on 361 days. The storms included single cells, multicellular systems and linear arrays of thunderstorms that extended for hundreds of kilometers. All these were essentially similar to those reported in the literature (Marwitz, 1972; Fujita, 1955). There were differences such as discrete growth being favored on the left and the squall lines not being associated with fronts as a rule. Also noted were disorganized multicellular systems where new cells formed apparently at random, and storm zones of about 50 km×200 km, or longer, that were stationary or moved northward and within which scattered storms occurred.

Supercell storms were not found. Long-lived severe traveling storms with one main echo core were tracked but the radar structure and halffall patterns showed that continual discrete regeneration must have occurred.

The elements of squall lines generally behaved in a more predictable manner than other storms, with new growth and hail at the leading edge. The cells move to the right of the direction of travel of the line which is often from southwest to northeast. But even for this type of storm situation one finds deviations: new cells forming between old ones, or even at the rear, and movement of cells directly along the line (Held and Carpe, 1973; Held and Van den Berg, 1977).

For the 361 days when storms were within 100 km range, there were isolated storms on 39% of the days, scattered storms on 54% and squall lines on 7%.

Multicellular storms were observed on 29% of the days with isolated storms but they were much more frequent (72%) when scattered storms occurred. Multicellular systems accounted for the majority of storms on more than half of all storm days. The only significant seasonal trend which was found was that squall lines occurred more often during November to January than later in the season. Of the 27 squall lines observed during four seasons, 22 occurred during these three months.

Out of 35 hail-producing storm cells, the hail occurred in 86% of them in the region where strong reflectivity gradients were found; the hail was on the left flank in 38% and at the leading edge in 39% of them. Hail occurred occasionally from the rear of a cell.

Two-thirds of new cells formed on the equatorward side of existing storm cells, which was the general direction of the wind below cloud base (800 mb). Out of 70 cells, 26 of which gave hail, 54% formed on the left of older ones and 23% ahead of them. The average storm speed was 30 km h⁻¹. The deviation from the 300 mb winds for 86 cells was left, 57%; right, 27%; and nil or small, 16%. These findings are in contrast with those for the Northern Hemisphere where the deviation is generally to the right of the mid-level winds [e.g., in Italy (Prodi, 1976) and in North America (Marwitz, 1972)].

The relationship between echo heights and probability of hail in this region of the Transvaal plateau has been investigated in detail. No precise criterion for hail could be found because storms exhibit a wide range of behavior. Some with sustained echoes exceeding 50 dBZ gave no hail while others with the 40 dBZ contour as low as 2–3 km AGL produced hail, results which are in conformity with findings elsewhere (Held, 1978). A large sample of 181 storms was investigated, the study being confined to areas where it could be established with reasonable certainty whether or not hail fell from a particular cell. This led to the conclusion that a useful criterion for forecasting the occurrence of the ground of hailstones >1 cm in diameter is that the 40 dBZ level.

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Fig. 11. The probability of hail versus height of the 40 dBZ radar reflectivity contour for all hail cells (solid curve) and for cells for which the largest hailstones produced were >1 cm in diameter (broken curve).

Fig. 12. Tracing of PPI at 2° elevation showing radar echoes on 17 January 1975 at 1752 SAST. Contours for 23, 40, 50 and 60 dBZ are drawn. Arrows indicate direction of movement of echo cores.
should exceed 6 km AGL. The extent to which this is valid is shown by the results in Fig. 11.

Fig. 12 illustrates how the probability of hail cannot reliably be based on echo characteristics alone. An isolated storm (Storm A) traveled in an easterly direction to merge with a storm complex comprising a number of cells, which was moving northward. Shortly before the merger Storm A produced hailstones >3 cm in diameter while none of the cells in the complex gave hailstones >1 cm even though they were taller, larger in area and no less intense in reflectivity than Storm A.

6. Hailstone trajectories

The multi-layered structure of many hailstones provides a qualitative indication of heterogeneous growth environments. Quantitative estimates of ambient temperature, liquid water content and updraft speed can be derived from measurements of average crystal lengths, isotopic content and concentrations of air bubbles. Such approaches have indicated that some hailstones grew up to 3 cm in diameter while being maintained at practically the same height of 7–7.5 km above the ground. Other equally large ones from the same storm moved up and down between heights a few kilometers apart during growth. It was concluded that the updraft experienced by one hailstone pulsed with a periodicity of about 8 min. Small hailstones which grew during descent only were found (Roos et al., 1977). These findings indicate complex updraft patterns, both in time and in space, which is in general conformity with observations of surface hailfall patterns and the variability of radar structures.

Investigation of the nature of the growth centers of many hailstones has led to certain generalizations. Growth centers were classified in various ways. One was according to whether they were composed of opaque, small-crystal ice (rime or graupel) or of transparent, large-crystal ice. Frozen drops would fall into the latter category. The tendency found was that the larger the hailstone the more likely it was to have a growth center comprising rime (Carte and Kidder, 1966). The implication of this is that large hailstones tend to form higher in clouds than smaller ones. The meaning of such findings is obscure when it is noted how individual storms can behave quite differently. However, there are significant differences related to geographical locality. In the United States, Knight and Knight (1976) found more graupel growth centers in smaller hailstones than in larger ones.

7. Discussion of results

Variability of hailstones ranges from annual and seasonal differences, through differences from storm to storm down to small-scale variations within part of one storm. Significant changes may occur within 1 min and within 1 km. Unsteadiness is a more common feature of hailstorms than a steady state. Realistic models of hail growth will therefore need to take into account time and spatial variations when they can be specified satisfactorily.

These studies of hailstorms have been pursued for 14 years and significant averages have been derived for at least some of the variables. A much longer series is required before results for the rather rare severe storms reach significance. Even the urban and topographical effects are only just above the threshold for detection. Certain variables have shown remarkably little variation from year to year: instances are the mean duration of point hailfalls and the relative frequencies of the size groups for the largest and commonest hailstones.

The climatological and other investigations that have been made in the Pretoria-Johannesburg region could be applied to design a hail prevention experiment. If, e.g., 100 days with hail were considered to be necessary, then this total should be experienced during three years within an area of 10³ km² if operations were confined to the first three months of every season (October–December) when almost half of the year's average number of hail days occurs. However, it is important to know that in fact the total per year might be anywhere from about 22 to 50 with a standard deviation from the mean of 8.6. Selection of the first three months of the season would usually include the most severe storms, which can be expected at any hour of the day or night, and would tend to exclude short-lived, almost stationary storms as often occur in March. The operation would have to be designed to cope with a variety of storm types, including large complexes with new storms arising at random and squall lines where new growth would probably be hidden from above by overhanging cirrus. A hail alert based on 40 dBZ exceeding 6 km AGL would not be effective for some 50% of all hailstorms, of which more than one-third would produce hailstones >1 cm in diameter.

In practice, a more useful figure than the number of hail days would be the number of storms to be expected. The average number of storm cells per day within the confines of the 40 km x 70 km area is estimated to be greater than 7. In one day 36 cells were observed during a 3 h period. There may have been days with even more.

The small amount of hail that is so often produced naturally has two implications: 1) perhaps hail tends to be suppressed naturally and 2) the scarcity of natural hailstones might mean that the introduction of additional growth centers would simply increase the number of hailstones at the ground without reducing their size.

Effects of seeding potential hailstorms can be investigated statistically or by seeking evidence of physical changes. The differences in hail frequency that have been found here and elsewhere between contiguous areas would complicate any statistical approach. Target and control areas should be chosen with circumspection and even randomized experiments should not disregard
the effects of nonuniform hail frequency. As an example, if seeding in the Johannesburg area reduced the number of hail days with hailstones > 1 cm in diameter by one-third, this would be interpreted as an ineffective experiment if Pretoria had been the control area, unless it were known that Johannesburg normally has one and a half times as many hail days as Pretoria (as indicated by Fig. 5, results for 1962–72). Another complication is that the effects of one or a few severe storms could dominate statistical findings. The results in Fig. 4 show how relatively few days at the beginning of the season (when severe storms are most likely to occur) contribute largely to the total area affected by hail. Finally, it must be emphasized that any such comparisons would be even less meaningful if results for only one or two years were compared because of the natural fluctuations from year to year.

Effective seeding must cause physical changes in the cloud but such changes have been sought for with little success. Goyer (1975) has suggested that time-integrated values of radar reflectivity, echo-top heights, echo coverage, etc., are more likely to reveal differences than instantaneous values. Even by using these the effects of natural variability will be difficult to eliminate. Other useful measures of the effects of seeding might be those variables which have shown the least variation such as mean duration of point hailfalls.

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