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A Radar Analysis of Hailstorms Over the Peking Region in 1964

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A RADAR ANALYSIS OF HAILSTORMS OVER THE PEKING REGION IN 1964

1964年北京地区降雹过程的雷达分析

by

Ge Run-shang (Ko Jun-sheng 葛润生) et al

CH'I-HSIANG HSÜEH-PAO
气象学报
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A RADAR ANALYSIS OF HAILSTORMS OVER THE PEKING REGION IN 1964*

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Ge Run-shang et al**

ABSTRACT

This paper presents a radar analysis of 12 hailstorms over the Peking region in 1964 with particular emphasis on the four most intense ones. The study was supplemented by surface observations and is mainly concerned with the evolutionary characteristics of the radar echoes. In addition, the shape and intensity of the echoes from hail clouds, the vertical distribution of the various parameters affecting the reflectivity of radar waves, the hail regions in clouds and the topographical influence on the formation of hailstones are discussed.

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I. INTRODUCTION

In 1964 the frequency of occurrence of hail over Peking was higher than normal, and the storms affected a wide area with great intensity. In the course of the year there were 12 occasions of hail of which 6 occurred in June, 4 in July and 2 in August. The area of the hail region, the intensity of hail precipitation and the resultant damage to agricultural products were much smaller in scale in July and August than in June. The 4 cases of severe damage all occurred in June (on 10th, 11th, 19th and 24th).

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** Ye Zong-xiu (Yeh Tsung-hsiu) of the Lanchow Institute of Geophysics and Meteorology, Academia Sinica, and several other colleagues at the Meteorological Observatory, Central Weather Bureau have participated in this study.

During the period 10 - 12 June hailstorms occurred on three consecutive days. In the first two days hail fell intermittently over a belt of more than 200 km in length stretching from Yenching and Kupeikou in the north to Tientsin and Tangku in the south. Severe hailstorms with hailstones as large as an egg were recorded in Shun-I, Tunghsien, Hsiangho and the adjacent regions on 10th, while peach-size hailstones were observed in Miyun on 11th, resulting in severe damage to agricultural products. The area affected by hail on 19th was comparable to that on 10th, but the incidence was less intense on 19th with hailstones of about 2 cm in diameter. The hailstorm on 24th was different from the above cases in several respects and was restricted to the southwest region in the vicinity of Tahsing and Fangshan. The area affected was relatively small but the intensity was great. Severe hailstorms covering an area of 4.5 km by 3 km occurred southwest of Hsiaohungmen in the suburban area of Peking and almost all agricultural products were damaged. The maximum size of hailstones measured up to 5 cm in diameter in general and reached 10 cm in some places where they did not melt completely until noon on the following day.

Radar observations were made on all the 12 hailstorms except the case on 12 June. This paper presents an analysis of the observed radar echoes as a manifestation of the hail processes with particular emphasis on the antecedent conditions for the purpose of obtaining some useful predictors. The formation and development of the hail elements and their characteristics are also examined.

II. SYNOPTIC CONDITIONS DURING HAIL DEVELOPMENT

In general, the 12 cases of hailstorms are found to be associated with a variety of synoptic situations. The hail precipitation on 15 July occurred along a pre-frontal squall line, while the storm on 24 June did not seem to be due to any synoptic system detectable on the weather map. However, the evolution of the radar echoes shows that the storm might be associated with the passage of a cold front some 200 km distant over the northern part of Peking. In the other 10 cases, cold fronts or active upper-troughs were detected and PPI radar pictures reveal close agreement between the precipitation bands and these systems. Hail clouds generally form and develop in the warm air regime ahead of cold fronts or upper troughs. This is confirmed by surface as well as by radar observations which reveal that echoes from hail clouds seldom lie inside the frontal zone. For example, the cold front lying along a line across Chihcheng, Kuanting and Pingtingshan at 1400 hours (local time) on 10 June moved at a speed of about 25 km/hr, and hail fell at 1340 hours in Yenching, at 1510 hours in Huaijou and at 1517 hours in Mentoukou. These places were 20, 90 and 50 km respectively ahead of the front. On 11 June the system became quasi-stationary and dissipated near the hilly region to the northwest, but radar echoes from hail precipitation were found to spread far toward the southeast. The situation on 19th was similar to that on 10th. Convective and conditional instability with a large amount of latent energy were noted from the surface to the 700-mb level on each day of hail. At times, unstable conditions were observed in the morning with towering cumulus as early as 0800 hours. However, instability is not a sufficient criterion for the occurrence of hail since other dynamic factors relating to the large-scale synoptic systems may also be involved.

The evolution of the synoptic process associated with the occurrence of hail for three consecutive days on 10 - 12 June may be summarized as follows: The 700-mb flow shows an area of low pressure moving slowly eastward across western Hailar. From this area minor troughs developed and moved eastward and then southward in succession. The axis of each trough was found tilted forward along the vertical so that the 500-mb system lay ahead of that at 700 mb. Weak cold air advection was noted over Peking at 700 and 500 mb, and became intense at higher levels. The surface cold front was not active and dissipated in the vicinity of Peking on 11 June. The hail incidence in the three consecutive days was accompanied by the southward excursion of cold air which continued until the 700-mb low had moved well to the east. The synoptic situation on 19th was similar to the above, the only difference noted being that the depression was located further to the east and moved with a higher speed. Rain occurred on 20th but there were no reports of hail.

The hailstorm on 24 June seemed to be a local process in the region of warm and moist air, because the incidence was not apparently associated with any large-scale synoptic systems. The trough line to the northwest did not affect Peking until 25th and a cold front passed through the hilly region of Peihou in the afternoon of 24th. Since the southern edge of the frontal zone was more than 200 km away, it did not seem likely to have any direct influence on the weather over Peking. However, an examination of the evolution of the banding arrangement of radar echoes reveals that the vigorous development on this occasion was definitely related to the activities of the cold front to the north. It therefore seems difficult to obtain a clear picture of the actual process involved by means of the existing techniques in synoptic analysis.

III. CHARACTERISTICS OF THE EVOLUTION OF RADAR ECHOES DURING HAIL PRECIPITATION

The three types of synoptic configurations associated with hail precipitation over Peking during June, July and August are found to possess certain distinct characteristics in terms of the evolution of the radar echoes. Hail rarely occurs with a squall line which generally passes through Peking with relatively high speed reaching 60 - 70 km/hr. The passage is also seldom accompanied by precipitation, but winds with gusts to gale force are often observed. However, convection is pronounced during the first stage when the line moves slowly over the hilly regions in the northwestern part of Peking, resulting in precipitation. The evolutionary characteristics of the radar echoes associated with this type of synoptic situation will not be described in the present paper, but the other two types associated with hail precipitation are analyzed in the following sections.

The evolution of the radar echoes observed in hailstorms associated with cold fronts and upper troughs is distinctly different from that in other forms of precipitation. In general, precipitation echoes resulting from a cold front are usually oriented northeast-southwest which is basically in alignment with the position and orientation of the system. On occasions, several lines are observed and are almost parallel to the cold front moving with the same speed as the latter. However, in the case of hail precipitation, additional echoes are noted in the form of discrete lines ahead of the cold front and subtending an angle of 60° to 90° with it. This configuration is referred to as "rows" in the present study. Individual cells of intense development observed in these rows are found to be associated with hail precipitation. Under such circumstances, the frontal bands are usually weak and at times too feeble to be detected. Figure 1 shows that the echoes on 2, 11 and 19 June and on 27 August are characterized by a significant "row" structure, which may vary from one to three in number. On 10 June the appearance of many individual cells with intense development masked the row configuration. However, a comprehensive analysis reveals that even the echoes with vigorous development tend to align themselves in rows.

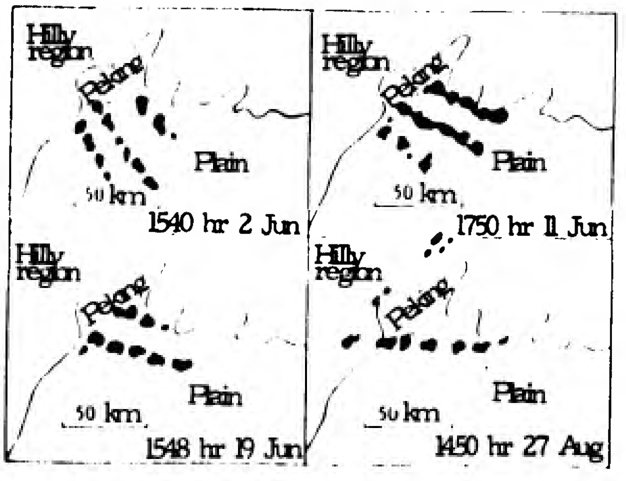


Figure 1

Some radar echo patterns of hailstorms.

It is noted that the above configuration usually appears before the onset of hail precipitation. The storm on 19 June is a typical example, when such a configuration was noted at 1145 hours (see Figure 2a) before the onset of hail precipitation at 1400 hours. A similar phenomenon was observed on 10 June. When the hailstorm was still far away in the hilly regions to the north, two rows of echoes with an east-west orientation appeared with an indistinct frontal band just to their west (see Figure 2b).

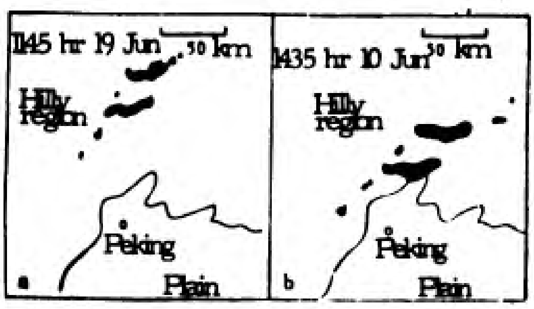


Figure 2

Radar echo patterns during the development period of hailstorms.

Following the southeastward displacement of the cold front, the echo bands extended from the northeast to the southwest along the frontal zone. After reaching the plain region, they intensified vigorously along several sections, forming the so-called "row" configuration. According to radar observations, the formation process may be described as follows:

Several "source" regions first develop in the vicinity of the frontal zone. New echoes then appear one after another in these regions, move downstream along the 700 - 500 mb flow, grow in size and intensity to form individual bands and finally attain a "row" configuration. Two to three rows are often observed separated by distances of the order of 30 - 50 km and echoes seldom appear in the space between the rows. Hail occurs principally in the individual cells with vigorous development within each row.

Since hail precipitation in the presence of a cold front is characterized by the appearance of echo bands making an angle of 60° - 90° with the frontal zone, the early configuration of radar echoes may be used as a clue to the prediction of hail. However, the search for an explanation of the observed characteristics in terms of the synoptic situation, air-mass properties and the effect of topography is beyond the scope of the present study.

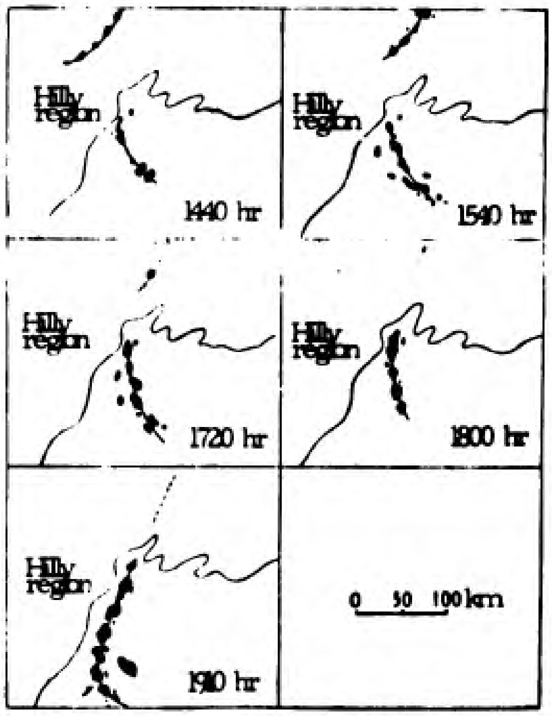


Figure 3

The evolution of radar echo patterns for the period 1440 - 1910 hr, 24 June 1964.

The situation on 24 June was different from the above. The echoes were similar to those in air-mass thunderstorms during the initial stage. The scattered cells only gradually assumed a banded structure to resonate with the passage of the cold front. The bands then rotated in a clockwise direction (Figure 3) and subsequent intensification gave rise to hail precipitation in the vicinity of Fangshan and Tahsing. The displacement of the individual cells was different from other cases. They spread northeastward along the low-level southwesterlies to form rows of echoes, which showed a clockwise rotation subsequent to the intrusion of cold air from the northwest (along the trailing portion of the cold front). This was accompanied by a continuous generation of fresh echoes ahead of the rotating band (i.e., the right front side of the advancing old echoes). Further development and rotation brought the band to alignment with the passing cold front in the north, forming an apparent continuation of the latter. Thereafter, the band moved southeastward, while the individual cells travelled along the band toward the northeast. Finally the whole system left the Peking region by 2000 hours. It may be noted from the evolution of radar echoes in this case that under the condition of pronounced thermal instability, even a very weak intrusion of cold air may give rise to severe weather. This phenomenon should receive more attention in weather forecasting.

IV. ECHO CHARACTERISTICS FROM HAIL CLOUD

An analysis of the structure, formation and development of radar echoes from individual hail clouds reveals the following characteristics.

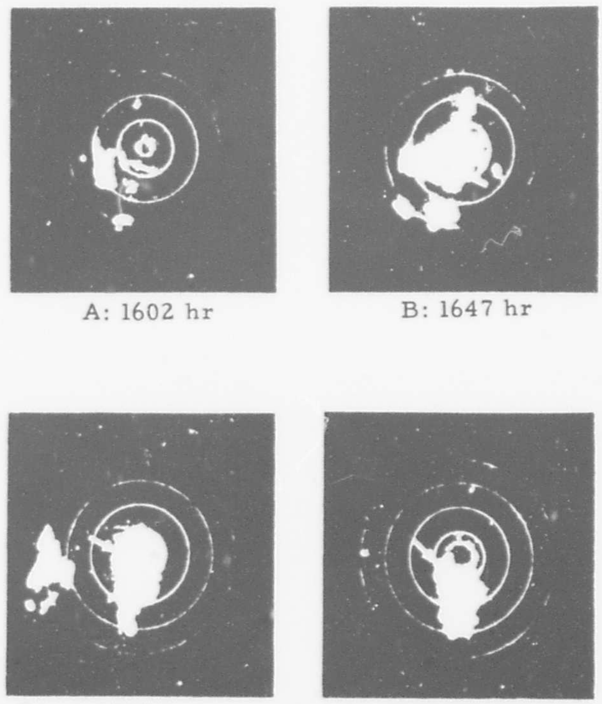
(a) Formation of Hail Clouds

The situations accompanying the formation of hail clouds in relation to large-scale developments may be classified into three types:

(1) The first type is characterized by the appearance of several patches of echoes over a region at the beginning, of which one develops to great intensity while the others weaken and dissipate. The severe hailstorm of 24 June over the suburban area in the vicinity of Hsiaohungmen belongs to this type. It may be seen from Figure 4 that the cells which only covered a relatively small portion of the precipitation echo at 1602 hours (Figure 4 A) became fully developed by 1720 hours (Figure 4 D), giving rise to large hailstones of 5 cm in diameter. At this time, all other echoes approached the stage of dissipation. However, it is not yet possible to forecast the region favorable for vigorous development.

(2) In the second type, the hail echoes ahead of the cold front often start in a few source regions along the frontal zone. After they have broken away from the front, they are steered by the upper winds and develop into a row of cells. Thus hailstorms may affect a particular region one after another in succession. For example, in the afternoon of 11 June the hailstorms over Peking consisted of three separate spells. Echoes were first observed to form near Fengtai and Mentoukou to the northwest and then moved into Peking. Figure 5 A shows no echoes in the northwest quadrant. However, a fresh echo was seen close to the city 40 minutes later. Hail clouds budded off from the source region one after another giving rise to the well-known

phenomenon that hailstorms come in discrete spells, described in folklore as "Hailstorms jump like frogs".



A: 1602 hr

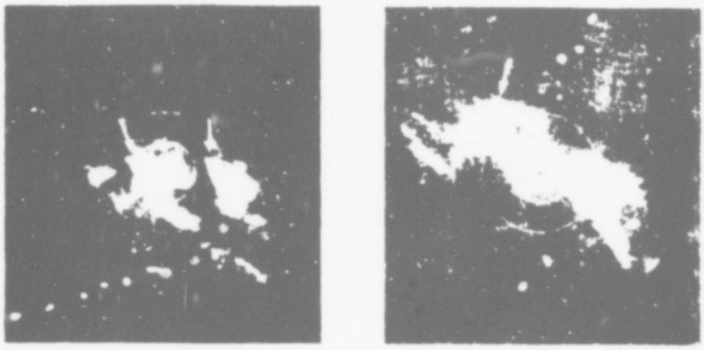
B: 1647 hr

C: 1710 hr

D: 1720 hr

Figure 4

The evolution of radar echoes from hail clouds on 24 June 1964.
(Arrow points at the hail echoes.
Range markers at 20 km in A & B and at 10 km in C & D.)

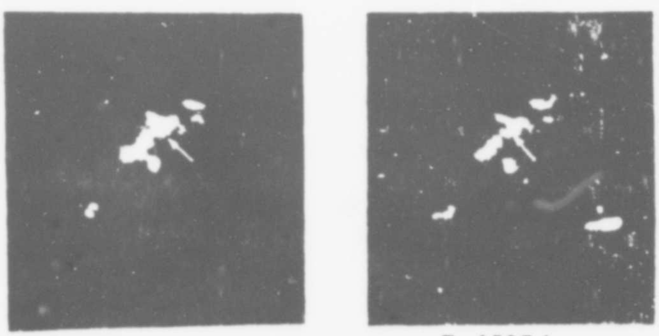


A: 1535 hr B: 1615 hr

Figure 5

Formation and movement of new echoes
from hail clouds on 11 June 1964.

(Arrow points at birthplace of hailstones. The echoes over the station in Chart A move eastward to appear as echoes east of the station in Chart B, in which new echoes appear northwest of the station. Range markers at 10 km.)



A: 1457 hr B: 1507 hr

Figure 6

The amalgamation of two echoes (shown by arrow) as an indication
of hail formation on 10 June 1964.

(Hail precipitation reaches ground at 1510 hr.
Range markers at 30 km.)

(3) In the last type, hail precipitation occurs after the amalgamation of two cells into one. An example of this is the severe hailstorm near Huaijou on 10 June. (Hailstones of 4.7 cm in diameter weighing 9.4 gm were reported by the Huaijou Meteorological Station.) It is noted that there was no precipitation of any form before the two cells merged into one. However, violent hail precipitation occurred as soon as they came close together to form a larger cell.

(b) Echo Intensity of Hail Clouds and Its Vertical Distribution

Measurements of the echo intensity have been made in many investigations in foreign countries. Donaldson [1] has conducted detailed measurements of the radar reflectivity factor (Z) in thunderstorm cores. Such a study of the vertical distribution of Z in relation to the structural characteristics of hail clouds offers useful clues for investigations on the mechanism of the formation of hail. In the present study similar measurements have also been made and the results reveal that the vertical extent and the intensity of a hail cloud are greater than those of a thundercloud. The target cloud top in the former reaches about 10 km on average and 12 km in some cases, and the intensity is usually above 10^5 mm^6/m^3 and exceeds 10^6 mm^6/m^3 in extreme cases; whereas in the latter, the height of the echo usually lies between 5 and 6 km and seldom exceeds 9 km and the intensity is below 10^5 mm^6/m^3.

The vertical distribution of the reflectivity factor in hailstorms is also different from that in thundery showers. In Figure 7 the broken line depicts the variations of the mean values of core intensity with height for 3 hailstorms. It is known that in thunderstorms, Z acquires its highest value of about

5.4×10^4 mm^6/m^3 at the lower level and decreases rapidly above 3 km. The profile for hailstorms presents a great contrast. In this case, Z begins with more or less the same value as in thunderstorms at the lower level, but increases rapidly with height with the maximum value at about 4 km and then decreases sharply with increasing height. It may be noted that Z is almost constant between 3 to 5 km and that at 5 km its value for hailstorms is about 2 orders of magnitude higher than the corresponding value for thundery showers.

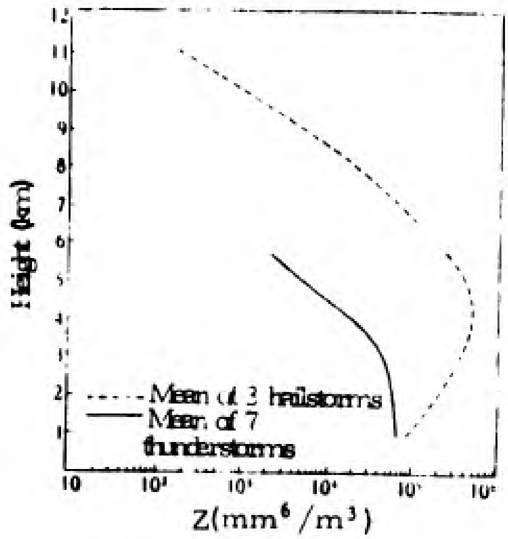


Figure 7

The vertical distribution of the radar reflectivity factor for thunderstorm echoes over Peking during June - July 1964.

The vertical distributions of Z have also been evaluated before and after the onset of hail precipitation in the same hailstorm. Because of the short duration of hail precipitation and the relatively long interval between observations, it is not easy to obtain suitable data for analysis. As a result, only one hailstorm was analyzed during 1964. Figure 8 shows the vertical distributions of the Z value 17 minutes before and 8 minutes after the onset of hail precipitation on 10 June in the vicinity of Mentoukou. The storm lasted 31 minutes and the largest hailstone collected was 2 cm in diameter. Figure 8 indicates that the profiles of Z are similar before and after the onset of hail precipitation except that a higher maximum value is found at the lower level ahead of the storm.

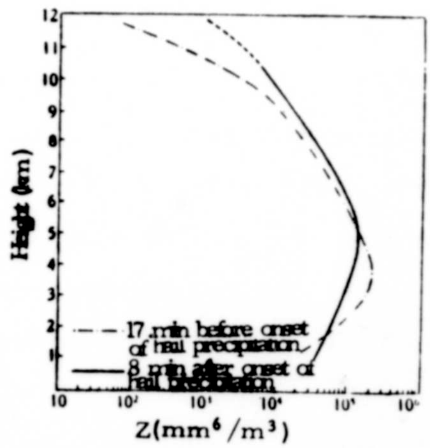


Figure 8

The vertical distribution of the radar reflectivity factor from echoes of hail clouds on 10 June 1964.

(c) Position of the Hail Regime as Revealed by Echoes from Hail Clouds

The results presented in the foregoing sections indicate that the occurrence of hail is not evenly distributed in a large band of echoes. Although hailstones are known to be generated in the region of vigorous development, the location of the maximum concentration in a cloud system is still not yet known with any degree of certainty and there are discrepancies among the results of various investigators [2 - 4]. In the present study, radar echo patterns have been correlated with observations collected from a network of meteorological stations, communes and survey teams to determine the position of hail occurrence.

During the four intense hailstorms of 10, 11, 19 and 24 June, a total of 37 radar echo patterns from hail clouds was obtained. However, in more than half of the cases, the position of hail centers could not be determined with sufficient confidence because of operational limitations such as incomplete meteorological data, small echo area or echoes being too far away from the radar station.

In the three cases associated with cold fronts, hail mainly occurs in the right rear quadrant relative to the forward movement of the cloud system. An analysis of the relatively complete records of 18 hail clouds during a three-day period shows that 78% of the hail incidence occurs in the rear portion and 61% in the right portion. However, the situation on 24 June is completely different from the above, because in this case hail occurs in the left front quadrant relative to the forward movement of the hail cloud.

Thus the expression of position relative to the forward movement of the target cloud does not seem to be the most appropriate delineation, and it appears that the effect of the flow configuration at the lower and upper levels should also be considered. In the above 4 cases, hail incidence occurs most frequently in the northwest quadrant, and may be due to the presence of a zone of maximum shear between the upper northwesterlies and the low-level southwesterlies over the region which is favorable for convective development. The echoes of the target cloud are often steered by the low-level southwesterlies if the flow aloft is weak and significant synoptic systems are absent. The difference noted between the hailstorm of 24 June and other cases may be accounted for in this way.

(d) Characteristic Echo Shapes from Hail Clouds

If it is possible to identify the occurrence of hail by an examination of the shape of the individual cells, interpretation would become a rewarding exercise. However, there is considerable variation in the characteristics of radar echoes from hailstones according to the findings of various investigators [5 - 7] in foreign countries. Hitschfeld is of the opinion that echoes with a feather-like structure are associated with the formation of graupel (soft hail) while the appearance of "protruding finger" in the echoes is suggestive of the presence of destructive hailstones. On the other hand, "boot-like" echoes are considered as an indication of hail occurrence. In the present study, we have attempted to discriminate hail precipitation through the interpretation of echo shapes, but the efforts to find a useful predictor were unsuccessful. Feather-like characteristics and "protruding finger" configurations were observed in this study, but it is found that each hail cloud generally gives rise to a particular echo shape, which can be recognized only after the onset of hail precipitation. Thus the use of the shape of echoes to determine the presence of hail has little practical value as a predictor.

In the above analysis we have found that on many occasions the presence of hail is located in the "convex" portion of the echo-cell. The echo over the northwest quadrant of Peking in Figure 5B is a typical example. The arrow head points at the position of hail occurrence. However, it should be pointed out that not all "convex" portions of the echo-cell are indications of the presence of hails. We have also noted cases in which the echo-shapes between hail clouds and thunderstorms are similar and it would seem extremely difficult in practice to distinguish the echoes between these systems.

(e) The Hail Cloud of 24 June in Relation to the Wind Field

On 24 June the region of severe hail was located in the vicinity of a meteorological station. Two upper-air ascents were, therefore, made before and after the onset of hail precipitation in order to obtain wind data to describe the flow field both outside and inside the hail cloud. The first balloon was released 40 minutes before the onset of hail precipitation about 5 km in front of the approaching hail cloud and went in cloud at approximately 9 km above M. S. L. The trajectory of the balloon relative to the hail cloud is shown in Figure 9. The second ascent was released when hail precipitation ceased to reach the ground, but the balloon was shot down by falling hailstones at 1.3 km above M. S. L. As a result, only upper winds in front of the cloud were obtained. Radar observations of the vertical structure of the hail cloud are shown in Figures 10 and 11. Figure 10 A shows a vertical section of the hail cloud in the direction of its movement and Figure 10 B another vertical section perpendicular to its displacement. The wind field relative to the cell is separated from the observed wind data by differential combination with the 1300-hr observations to obtain the appropriate components for the two cross-sections. Figure 11 shows that the low-level flow in front converges strongly into the hail cloud with divergence aloft. However, this type of convergence and divergence does not give rise to a simple circulation model, but forms a rather complicated pattern resulted from the superimposition of small-scale disturbances on a large-scale flow field. Furthermore, the probing on this occasion reveals the flow configuration outside the hail cloud only, while the circulation pattern may be far more complicated inside.

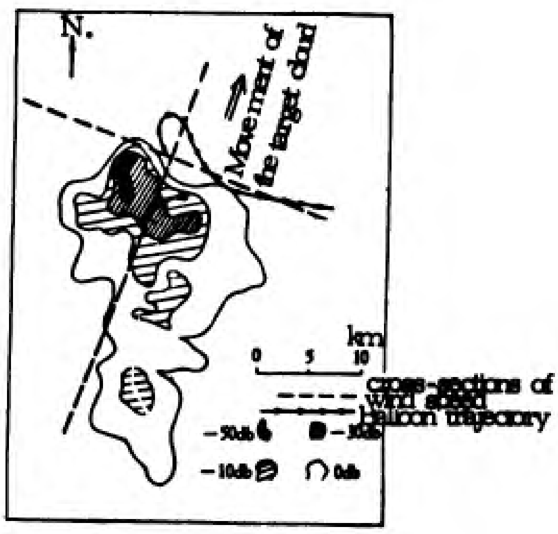


Figure 9

The balloon trajectory relative to the target cloud.

V. THE EFFECT OF TOPOGRAPHY ON HAIL OCCURRENCE

In the course of our analysis, it was noted that the topography in the Peking region exerts a pronounced effect on hail occurrence. A summary of some features revealed by radar echoes is presented in this section.

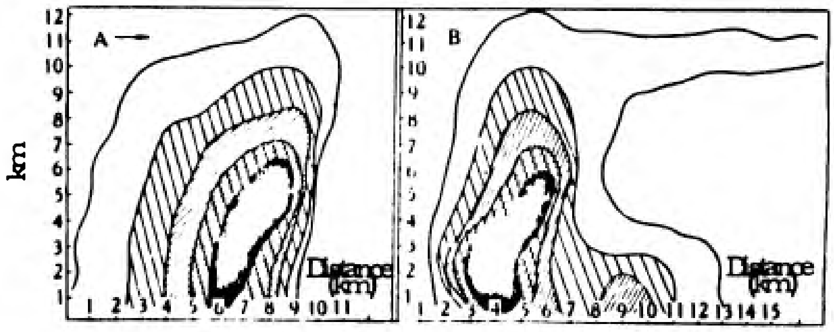


Figure 10

Cross-sections of hail echoes on 24 June 1964.

A: Along the target movement.
B: Perpendicular to the target movement.

(Legend of echo intensity same as Figure 9.)

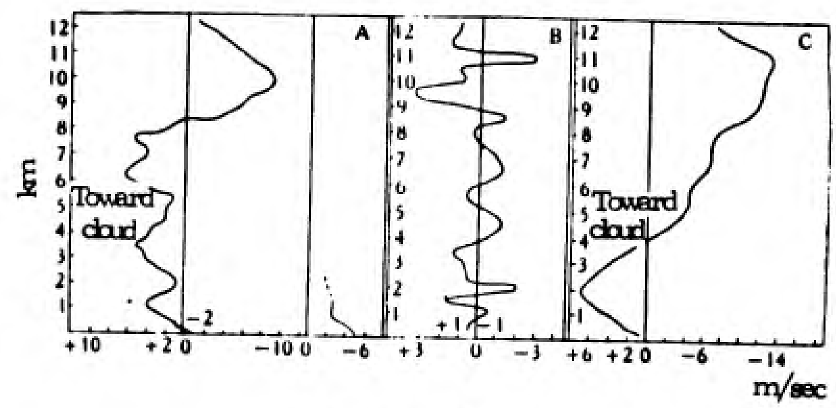


Figure 11

Wind flow around the hail cloud on 24 June 1964.

A: Advection along the target movement.

(+ denotes convergent flow into cloud and - divergent flow from cloud.)

B: Vertical component of flow.

(+ denotes upcurrent and - subsiding current.)

C: Advection perpendicular to the target movement.

(Legend same as A.)

(a) Hailstorm Tracks

Hail clouds often move along the same path. The observational evidence in the previous sections suggests that after the passage from the hilly region to the plain the "echo rows" travel along several typical tracks with active development. This is also borne out by surface observations. The folklore "Hailstorms strike along trodden paths" is nothing but a resume of this phenomenon and implies that the individual hail cells travel along more or less the same typical path one after another as in the case of a "relay" racing. It is, however, important to note that the whole path is not covered by one single cell. "Hailstorms jump like frogs" similarly describes the same characteristics of their trajectories.

Figure 12

A schematic diagram of the tracks of hailstorms on 10, 11 and 19 June 1964.

(--- 10th; -·-·- 11th; —— 19th)

Figure 12 depicts the tracks of three hailstorms associated with cold fronts. It may be clearly seen that cells of the hailstorm of 10 June are basically concentrated along two tracks. One starts from Miyun and Huaijou across Shun-I and Tunghsien to Hsiangho, Wuching and Tientsin while the other stretches from Mentoukou and Fengtai across Tahsing to Kuan. Although other hailstorms moved along different courses from these two, they generally followed two or three basically parallel tracks, which were closely related to the 500-mb flow. Another point of interest is that hailstorms originating from the same source region may take different paths. In the above example, it is obvious that one source region lies near Miyun and Huaijou while the other is located in the vicinity of Mentoukou and Fengtai.

(b) Topographical Influence

It is noted from the analysis of radar echoes and surface observations that topography also plays a part in affecting the development of hailstorms. For example, hail was reported at Yenching in the northwestern hilly region during all the storms examined in the present study. Radar observations also indicate that the echoes seldom move away from this region. An examination of the local topography reveals that this phenomenon may be related to the east-west orientation of the hills and valleys. Similarly, the frequent hail incidence over Miyun and Huaijou may also be related to the northeast-southwest orientation of the adjacent ranges. In this locality, orographic lifting of the low-level flow over the western slopes is favorable for convective development. Hailstorms in the vicinity of Mentoukou and Fengtai are also i[illegible]enced by the underlying topography to some extent.

VI. CONCLUSION

In 1964 there was more hail incidence in Peking and less in Laiyuanhsien in Hopeh, which lies 170 km southeast of the Capitol. In the past years hail incidence had been more frequent over Laiyuanhsien than Peking. The cause of the anomaly is not yet clearly understood. Climatological consideration may produce some important and meaningful results in this connection.

The known characteristics of the evolution and arrangement of radar echo patterns in relation to hail precipitation and the typical hail tracks may be used to predict the occurrence of hailstorms, which will be useful in short term forecasts. In a rainy situation on 7 July 1965, we have analyzed the characteristics of the arrangement and evolution of radar echo pattern and estimated that hail precipitation was possible. This was verified by the occurrence of hail in the vicinity of Haiting and Fengtai 3 - 4 hours later. The accuracy of the predictors discussed above has to be assessed in further verifications. In addition, it is necessary to conduct studies on the evolution of radar echo patterns in relation to upper-air and synoptic systems.

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