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On forecasting hailstorms by the method of vectorial wind changes

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ABSTRACT. The conditions leading to the occurrence of a number of hailstorms over northwest India have been investigated. The method of assessment of convergence by using 24-hour vectorial wind changes was found in these situations to be superior to the conventional methods and of definite prognostic value. The border region between cyclonic and anticyclonic wind shear patterns was found suitable for thunderstorm development whenever the cyclonic shear appeared in a moist air stream, notwithstanding the unfavourableness of the winds and of the thermal structure aloft. Strong upper winds and a pronounced vertical shear are found to promote transformation of the thunderstorms so formed into hailstorms. The direction of the associated squall, if any, lies close to that of the isallobaric wind.

The variety of shapes and sizes of hailstones in the same or in different storms is attributable to the simultaneous occurrence of elementary hailstones characterised by concentric shells together with larger stones formed by the compounding together of two or more elementary stones. Compound hailstones possess a single common glazed-ice envelope and breed just above the freezing level. Their jaggedness results from non-uniform accretion of supercooled water. The maximum size attained by hailstones is related to the severity of turbulence in a storm only if the specimen examined is of the elementary variety.

1. Introduction

A number of hailstorms occurred over Rajasthan, Punjab (I) and west Uttar Pradesh during the period 18 to 20 March 1957. Considerable damage to crops and structures is reported to have been caused by these storms. In the hailstorm at Jodhpur on 18 March some damage was also inflicted on aircraft kept parked and moored in the open. The prevailing synoptic and thermodynamic situation over northwest India during the above period did not furnish sufficient clues for anticipating these storms. Reviewing the methods of thunderstorm forecasting, Beers (1945) has opined that there is no reliable method of recognizing in advance a thunderstorm that would produce large hailstones. An attempt by the authors to understand the physical processes leading to the above hailstorms by assessment of convergence using vectorial wind changes with time, following the method described recently by Roy and Rai Sircar (1955), has yielded fruitful and encouraging results. Similar situations at Jodhpur leading to hailstorms on earlier occasions have also been examined. The results of these investigations are reported in the present paper.

2. Description of the hailstorm situations

Hailstorms are rather unusual at Jodhpur, the annual frequency given in the *Climatological Tables of Observatories in India* (1953) being 0·5 only. During the past six years, three hailstorms were experienced at Jodhpur in 1952, 1956 and 1957, all of them in the month of March. A brief description of the wind and weather conditions leading to these as well as other hailstorms, which affected Agra and Delhi during the period 18 to 20 March 1957 is given below.

2.1. *Hailstorm at Jodhpur on 31 March 1952*

On 31 March 1952, a shower of big raindrops commenced rather suddenly at 2130 IST, preceded by thunder. After a minute, a brisk hailshower commenced and lasted for two minutes. The hailstones varied in size from small pellets of 3 to 4 mm in diameter to larger stones 25 mm across. Unlike the smaller ones, the bigger stones were rugged and oblong in shape and measured about 25 mm along the longer axis and 15 mm along the shorter one. They generally had two layers around an opaque core, and the bigger ones were composed of two stones cemented together along their longer axis. This hailstorm occurred under the influence of a low induced over west Rajasthan by a western disturbance as a result of which an occlusion of the warm front type, preceded by an upper cold front, traversed Jodhpur towards the late evening on that day. The upper winds at Jodhpur at 0730 IST were mainly southwesterly with a speed of 20-25 kts upto 2 km and of about 35 kts aloft upto 3 km.

2.2. *Hailstorm at Jodhpur on 21 March 1956*—On 21 March 1956, a thunderstorm cell approached the station from the northnorthwest at 1800 IST. It caused a shower of big-sized rain drops at 1830 IST together with graupel, 3-4 mm in diameter. No big-sized or composite hailstones were, however, received from this thunderstorm. A northnorthwesterly squall of 25 kts was also associated with the hailstorm. This hailstorm had occurred under the influence of a western disturbance, which moved northeastwards across northwest India. The upper winds at 0730 IST on this day were mainly westnorthwest, 15-20 kts upto 3 km while cloud observation data showed the prevalence of a westerly wind of 38 kts at the altocumulus level. The 1430 IST ascent of this day actually showed westerly winds in the 3 to 6 km layer which rose in speed with height from 30 to 65 kts. No realisable energy was revealed by the latest available tephigram, which was constructed from the sounding at 2045 IST of 20 March 1956.

2.3. *Hailstorm at Jodhpur on 18 March 1957*—Although the tephigrams and the upper winds at Jodhpur were unfavourable, two cells developed close to each other on the western horizon at about 1530 IST. During the next hour they towered up rapidly with well defined anvil tops. As well marked vertical wind shear prevailed at the time, the upper portions of the clouds appeared to drift overhead by 1700 IST even prior to the arrival of the lower part. From accoustically identifiable lightning flashes, the basal parts of these clouds could be estimated to be at a distance of about 5 miles from the station at 1725 IST. By this time, an extensive layer of mammato-cumulus spread across the sky. At 1745 IST hailstones commenced to fall out of these clouds without any perceptible rainfall. Rain commenced one or two minutes later when the hailstones also waxed in size. The majority of the hailstones were spheroidal in shape having diameter ranging from 13 to 20 mm. After about 10 minutes, the size of the stones became conspicuously large and their shape highly irregular. It was found on dissection of a large number of these stones that they displayed generally three distinct concentric layers alternately of glazed ice and rime around the opaque cores. Out of eleven well-formed spheroidal stones dissected by the authors, all except two had a uniform core diameter of 8 mm, the other two being of 7 and 9 mm respectively. In all cases, this core was enveloped by a transparent shell, 1 mm thick; surrounding this, was a shell of rime 13 mm in outer diameter. Although the shape as well as the thickness of the outer glazed coat varied from one specimen to another its diameter was generally about 18 mm in every case.

One of the many specimens studied showed as many as seven concentric layers, alternately glazed and white, with a core diameter of 4 mm and an outer shell diameter of 13 mm. This, however, was rather the exception than the rule. The relevant measurements on this stone are shown in Table 1.

By 1755 IST, the stones became larger in size and irregular in shape and presented a jagged appearance. These were generally 35 mm along the larger axis and 20 mm along the shorter one. The cross-section of one such typical stone is illustrated in Fig. 1. These stones were apparently the result of the cementing together of pairs of the elementary stones described earlier. They revealed on dissection a core diameter of 8 mm with three layers around each. In contrast to the geometrical pattern displayed by the inner shells, the exterior surface of the glazed ice envelope was very irregular. All the bigger samples collected and dissected by the authors revealed the same structure. A few cases of even bigger stones in

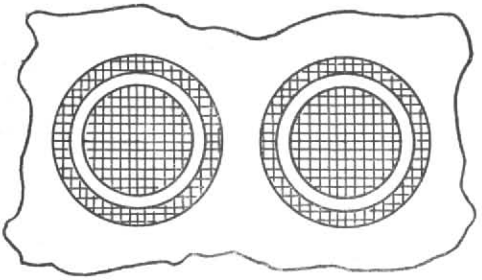

Fig. 1. Structure of a typical binary hailstone collected at Jodhpur on 18 March 1957

which three elementary stones became cemented together, have also been reported by I.A.F. meteorological personnel stationed at Jodhpur, from another locality near the airfield.

The hail ceased falling at 1800 IST and was followed by rain and squall till 1810 IST. The surface wind which was westsouthwest about 10 kts changed to southsoutheast during the squall. Surface temperature fell from 30°·7 to 23°·7 C. This hailstorm occurred under the influence of a well marked trough of low pressure extending from north Baluchistan to Punjab (I) on the morning of 18 March 1957. Under its influence, considerable influx of moist air took place into northwest India. The upper air charts of 19 March showed merely an extended area of cyclonic circulation over West Pakistan and neighbourhood, together with a well marked anticyclone with its central region over the Deccan.

The upper winds at Jodhpur were 220°/240° at all levels upto 10·5 km at 0830 IST of 18 March 1957. The speed was 10-20 kts upto 1·5 km increasing to 20-25 kts upto 4 km, 40-50 kts upto 6 km, 50-65 kts upto 9 km and to about 120 kts at 10·5 km. The subsequent pibal ascent at 1445 IST and the nephoscope observations showed more or less a persistence of the same vertical wind shear.

The tephigram of 18 March at 0830 IST showed a practically moist adiabatic lapse rate from the ground upto 725 mb as also aloft above 640 mb with a thin layer of dry adiabatic lapse rate sandwiched in between.

TABLE 1

Structure of a large sized elementary hailstone

Element	Appearance	Diameter (mm)
Core	White	4
1st layer	Transparent	6
2nd layer	White	7
3rd layer	Transparent	8
4th layer	White	9
5th layer	Transparent	11
6th layer	White	12
7th layer	Transparent	13

2.4. *Hailstorm over Agra and Gwalior districts on 19 March 1957*—Fairly widespread hailstorm activity was reported on the evening of 19 March 1957 from the western parts of Agra district and the adjoining parts of Gwalior district. At Agra itself, the hailstorm occurred at 2310 IST and lasted for 10 minutes during the course of a thundershower, which commenced at 2250 IST and lasted till 0015 IST of 20th. A westnorthwesterly squall of 35 kts was also reported. Hailstones are said to have been generally of small size about 3 to 5 mm in diameter. This hailstorm occurred in association with the passage across Punjab-Kumaon hills of the low pressure trough which, as already described, extended on 18 March 1957 from north Baluchistan to Punjab (I). The morning pibal ascent at Gwalior showed fairly strong northwesterly winds reaching a speed of 30-35 kts aloft upto 3 km.

2.5. *Hailstorm at Delhi on 20 March 1957*—Between 1828 and 1910 IST on 20 March 1957, a hailstorm accompanied by northwesterly squall of 69 kts passed over Delhi. Hailstones and raindrops are reported to have occurred simultaneously but the hail was in the nature of graupel with a diameter varying from 3 to 5 mm. Strong northwesterly winds reaching 40 kts continued till about 1910 IST.

The upper winds at Delhi on the morning of this day were southeasterly 5-10 kts upto 1·5 km veering to south and increasing in speed to about 20 kts at 3 km and southwesterly about 40 to 50 kts at 9 km. The tephigram of 0800 IST of 20 March 1957

TABLE 2

Winds, weather and related particulars concerning the hailstorms

	31-3-1952 Jodhpur	21-3-1956 Jodhpur	18-3-1957 Jodhpur	19-3-1957 Agra	20-3-1957 Delhi (Palam)
Time of occurrence (IST)	2030	1830	1745	2250	1828
Associated squall	NW 37 kts	NNW 25 kts	SSE 34 kts	WNW 35 kts	NW 60 kts
Upper winds at 15000 ft					
at (*i*) 0730 IST	..	..	240°/45 kts		240°/37 kts
(*ii*) 1430 IST	..	270°/55 kts	..		250°/36 kts
Cloud observation					
(*i*) Time (IST)	..	0830	1130 1430	0830	
(*ii*) Type of cloud	..	*Ac*	*Ac* *Ac*	*Ci*	
(*iii*) Direction	..	270°	270° 230°	250°	
(*iv*) Speed (kts)	..	38	38 44	83	
Nature of hailstones					
(*i*) Elementary	Graupel, spherical 3-5 mm in diameter	Graupel, spherical 3-5 mm in diameter	Small spherical stones 18 mm in diameter	Graupel, 3-5 mm in diameter	Graupel, 3-5 mm in diameter
(*ii*) Compound	Large ragged stones 25 mm long and 15 mm thick	..	Large ragged stones 35 mm long and 20 mm thick	..	..

did not reveal any realisable energy even on the basis of the anticipated maximum temperature of the day. The air was relatively dry upto 800 mb but some moistness was in evidence aloft upto 600 mb.

The synoptic chart on the morning of this day showed that a 'high' had established itself over Kashmir and adjoining Pakistan in the wake of the low pressure trough, which had moved off across the Punjab-Kumaon hills earlier.

The data describing the times of occurrence of the various hailstorms, the associated squalls and nature of hailstones are summarised in Table 2.

3. Method of analysis

It will be seen from the description of the synoptic and thermodynamic situations, which preceded the hailstorms, that the customary methods of prognosis of convective phenomena were inadequate for anticipating them. As convective phenomena are the result of occurrence of updraughts in the lower troposphere, the only other way, in which assessment of the magnitude of these updraughts could be made, is either by computation of convergence or of the vertical component of absolute vorticity. As Das (1951) has found, after his investigation into convergence charts over the Indian regions, the construction of convergence charts involves the preparation of four different charts, which occupies a considerable time. Preparation of sufficiently fresh convergence charts on a routine basis for forecasting thunderstorms or hailstorms sufficiently ahead of their occurrence is impracticable. Das has also shown that the error in computation of divergence in extreme cases is of the same order of magnitude as the divergence itself. The construction of each of the component charts involves, in addition, subjective uncertainties.

Pre-monsoon thunderstorms in India are of air mass type and the results of organised convection of the lower moist air mass. A simple method for estimating the growth or decay of cyclonic vorticity in a wind stream has recently been suggested by Roy and Rai Sircar (1955) in their study of some atmospheric disturbances. This method involves the computation of vectorial wind changes during given periods of 24 hours or less. These charts are capable of speedier

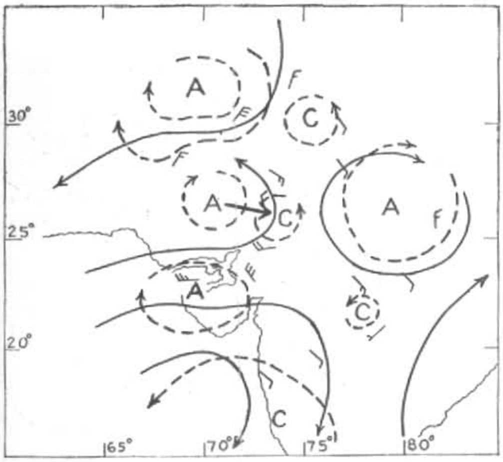

Fig. 2. 31 March 1952

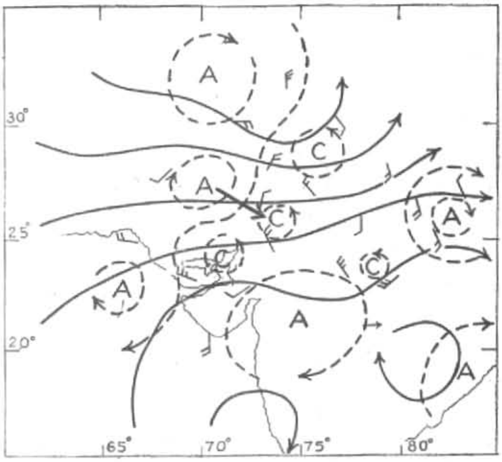

Fig. 3. 21 March 1956

Vectorial wind changes at 1.5 km a.s.l. for 24 hours ending 0730 IST

– – – – Vectorial wind changes ——— Stream lines at 1·5 km a.s.l at 0730 IST

construction than convergence and vorticity charts and are quickly available for forecasting use. As there is a simple and direct relation between wind and pressure tendency, such charts are representative of the isallobaric patterns. On the wind change charts based on the fairly good network of pilot balloon stations in India, even minor areas of isallobaric changes at the higher levels such as are associated with localised weather phenomena are discoverable.

The authors have constructed vectorial wind shear charts for the 1·5-km level for the 24-hour period preceding 0730 IST on the days of occurrence of hailstorms described above. On the charts have also been superimposed the streamlines at the 1·5-km level in order to bring out the peculiarities of vorticity development within the wind streams.

4. Discussion

4.1. *Wind shear and streamline patterns preceding the hailstorms at 1·5 km a.s.l.*

4.1.1. *Hailstorm at Jodhpur on 31 March 1952*—The streamlines at 1·5 km a.s.l. on 31 March 1952 as well as the wind shear patterns for the preceding 24-hour period are reproduced in Fig. 2. It will be seen from this illustration that a well marked cyclonic circulation lay over west Rajasthan centred at Jaisalmer. To the right of this, centred about 70 miles to the northnortheast of Jodhpur appears a localised region of cyclonic wind shear. Lying to its northwest is an area of anticyclonic wind shear. The katallobaric centre suggested by the region of cyclonic wind shear implies a northeastward displacement of the low pressure centre at the 1·5-km level. An isallobaric wind flow from a northwesterly direction towards the katallobaric centre may, therefore, be anticipated during the course of the next few hours. Into this region of cyclonic wind shear is maintained a steady inflow of moist Arabian sea air, as evidenced from the streamline pattern.

Vigorous localised cyclonic vorticity can, therefore, reasonably be expected to develop in the vicinity of Jodhpur. The thunderstorm, which occurred at 2030 IST is, therefore, the natural consequence of the development of such vorticity augmented by insolation, notwithstanding the strong upper winds associated with a marked wind shear.

4.1.2. *Hailstorm at Jodhpur on 21 March 1956*—The wind shear charts pertaining to this hailstorm shown in Fig. 3 reveal a region of cyclonic shear in the close proximity of Jodhpur and centred to its southeast, together with a region of anticyclonic shear

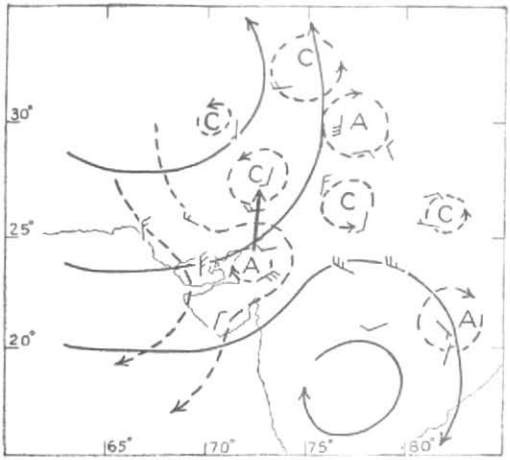

Fig. 4. 18 March 1957

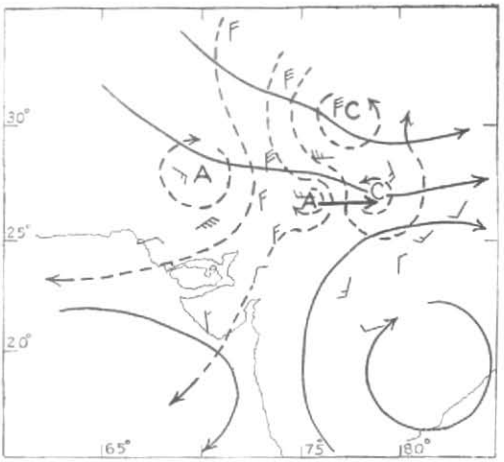

Fig. 5. 19 March 1957

Vectorial wind changes at 1·5 km a.s.l. for 24 hours ending 0730 IST

- - - - Vectorial wind changes ——— Stream lines at 1·5 km a.s.l. at 0730 IST

towards its northwest. The disposition of these vortices is suggestive of an isallobaric wind flow towards Jodhpur from the northwest. The streamlines show the influx of moist air from the Arabian sea into this region of cyclonic vorticity.

4.1.3. *Hailstorm at Jodhpur on 18 March 1957*—The wind chart for this day is illustrated in Fig. 4. The development of a narrow region of cyclonic vorticity to the north of Jodhpur skirted on the south by a small area of anticyclonic shear is evident from Fig. 4. This cyclonic vortex is also embedded in a moist current from the north Arabian sea. These vortices show the development of a southerly isallobaric wind towards Jodhpur.

It is of interest to mention that in association with the cyclonic vortex bordering on Amritsar and the contiguous anticyclonic vortex to its southeast, a hailstorm is also reported to have occurred on the evening of 18 March 1957 at Amritsar.

4.1.4. *Hailstorm at Agra on 19 March 1957*—Fig. 5 displays the streamlines and wind-shear patterns, which preceded this hailstorm. The streamlines show the appearance of a well-marked cyclonic vortex to the southeast of Gwalior. To its west is seen a region of anticyclonic vorticity yielding a westerly isallobaric wind over the western portion of the district of Agra. The cyclonic vortex lay in the field of a westerly moist stream originating over the Bay of Bengal and circulating around an anticyclone centred near Kanker.

4.1.5. *Hailstorm at Delhi on 20 March 1957*—The wind conditions on this day are portrayed in Fig. 6. A region of vigorous cyclonic vorticity which is inferable from the easterly shear of 55 kts at Delhi, is situated in juxtaposition with a well marked anticyclonic vortex to its northwest. As already stated, the air over the station was relatively dry upto 800 mb at 0800 IST on that day, although the cyclonic vortex is embedded in maritime air of Bay of Bengal origin. It is quite conceivable that moist air got eddied into this vortex by the evening when the hailstorm developed.

4.2. *The causes for occurrence of hailstorms*

From the discussion in the preceding paragraphs, the following generalisations emerge.

4.2.1. Hailstorms have visited only such stations as lie in the border regions between cyclonic and anticyclonic vortices.

4.2.2. A strong upper wind field which normally inhibits the development of convective phenomena, is invariably associated with hailstorm development.

4.2.3. The velocity profile in the vertical displays an increasing wind-shear with height.

4.2.4. The direction of the squall associated with every hailstorm is almost coincidental with the direction of the isallobaric wind towards the station.

A study of the vectorial changes in a seemingly or nearly translatory wind field enables a more accurate determination of the area where local convective storms of the intra-mass type are likely to occur. While such a feature is a necessary condition for the growth of vigorous convective cells, certain other conditions such as those mentioned in 4·2·2 and 4·2·3 above have also to be satisfied in order that the convective processes may culminate in a hailstorm.

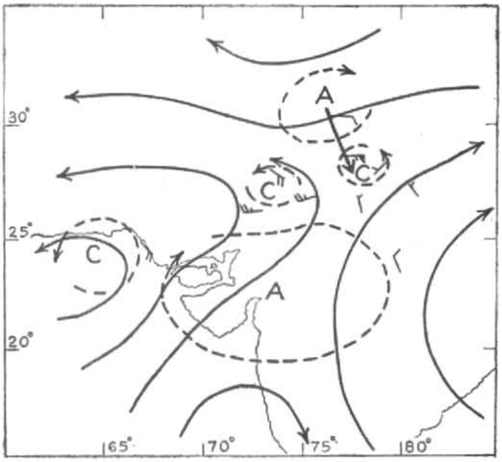

Fig. 6. Vectorial wind changes at 1·5 km a.s.l. for 24 hours ending 0730 IST of 20 March 1957

- - - - Vectorial wind changes

——— Stream lines at 1·5 km at 0730 IST

When the intensity of the convection is of the normal character, a strong upper wind field tends to shear the tops of towering cumuli and thereby inhibits the development of convective phenomena like thunderstorms. When the intensity of convection is nevertheless vigorous enough to overcome the shearing effect of such a wind field, the thunderstorm that develops tends to transform into a hailstorm. The reason for such transformation appears to be that the horizontal stresses due to strong upper winds tend to deform the growing cell as the latter is composed of sizeable water drops and ice pellets. As Riehl (1954) has pointed out, cumulus congestus and cumulonimbus in the tropics commonly reach into strata with a wind structure differing radically from that at the low levels. These clouds display a twisted shape for their upper portions. Broadly speaking, the axis of a thunderstorm cell tends to deviate from the vertical in conformity with the velocity profile. The conclusion arrived at from the work on the *Thunderstorm Project* (Byers and Braham 1949) that graupel and hail have been noticed only in 5 per cent of the project thunderstorms cannot receive acceptance as it is based on the visual observations on the windscreens of reconnaissance aircraft and as soft hail is liable to be mistaken for snow under such conditions of observation. That these observations are undependable and that thunderstorms have a region of hail formation immediately above the freezing level has been stressed by Browne, Palmer and Wormwell (1954) and also by Wexler (1954).

The turbulent middle portion of a thunderstorm cloud containing graupel and hail is thus liable to suffer displacement with respect to its base when it is embedded in a wind field characterised by marked vertical shear. The vertical component of the updraft sustaining the hailstones would, therefore, progressively decline with increasing relative displacement of the central portion of the cloud. Under such conditions, the hailstones would tend to drop out in increasing numbers from the upper regions of the thunderstorm clouds. Vigorous turbulence in the central part of the cloud may sometimes lead to the ejection of hailstones over a station in advance of the arrival of the warmer part of cloud as the region of turbulence is also a region of pronounced vertical wind shear. Hailstones of 10 to 20 mm diameter, experienced by pilots *in clear air* in the vicinity of thunderstorm clouds (Houghton 1951) are also presumably discharged from the clouds as a result of pronounced wind shear in the region of turbulence. An instance in point is the case of the hailstorm, which occurred at Jodhpur on 18 March 1957. It may, therefore, be inferred that in cases where hail occurs as a result of the weakening of the vertical component without any appreciable tilt of the axis or where the tilt of the axis is only slight, rain and hail may occur almost synchronously. But when the axial tilt is pronounced and turbulent ejection of hail takes place, hailstones may precede rain.

It is of interest to discuss in this context the meteorological conditions which preceded the devastating hailstorm on the island of Zind Beveland in the southern part of the province of Zeeland in the Netherlands on 19 June 1954 recently described by Feteris (1955). The upper air sounding at a neighbouring station at de Bilt at 1300 GMT on this day showed a large amount of realisable energy. The upper winds above the friction layer were 210/220° upto 350 mb. The speed, however, rose from 17 kts at 800 mb to 26 kts at 600 mb. There was a sharp increase in velocity in the 600 to 500 mb layer from 26 to 41 kts. The speed continued to increase aloft upto 350 mb where it reached 56 kts. The maximum wind shear had, therefore, occurred in the middle part of this thunderstorm between the levels 600 and 500 mb where the temperatures were —6·4°C and —11·1°C respectively. The transformation into a severe hailstorm of the thunderstorm which developed under these unfavourable wind conditions can be pictured in the light of the foregoing generalisation as a natural consequence of the pronounced wind shear in the supercooled water region of the thunderstorm. Feteris also states that while duration of the hail at a station should not have exceeded 6 minutes, judging from the wind data and the aerial extent of the storm, it actually lasted in one continuous spell for 10 minutes. The only explanation he can offer for such prolonged duration of the same shower is the possibility of a succession of hailstorm cells having passed over the station in exactly the same track. Such an explanation, however, appears rather unacceptable as hailshower of the same intensity without any intermission could not have been caused by the joint action of two separate but contiguous cells. The correct explanation for this observation seems indeed to lie in the tilt of the axis of the hailstorm that would have been caused by the pronounced vertical wind shear. As a result of such a tilt the projection on the ground of the hailstorm below the freezing level would necessarily have taken a longer time to move across a point on the ground, the greater the tilt with respect to the vertical, the longer being the duration of the hail at the point.

4.3. *Forecasting the direction of squalls in thunderstorms*

The directions of the surface squalls, which were associated with the hailstorm under study display a remarkable coincidence with the directions of the isallobaric wind. The authors have examined a number of similar situations and have found this coincidence in every such case. It is of great interest to note that the isallobaric wind directed towards a station as early as 10 to 15 hours in advance of the occurrence of the squalls provides so dependable a forecasting clue. Further study of this aspect of thundersqualls is in progress.

4.4. *Sizes and shapes of hailstones*

As already stated hail, graupel and snow occur in the upper portions of cumulus congestus and cumulonimbus clouds in the tropics. It is generally presumed that these are supported within the cloud by strong updraughts till, by repeated excursions into the supercooled water and snow regions, they grow too large for these currents to balance. According to Humphreys (1940), a stone, one inch in diameter, with a density of 0·8 gm/cc would require an updraught of 59 mph for support. The concentrically-layered structure of the typical hailstone has lent belief to the supposition that the enlargement of the hailstone size is the consequence of vertical oscillations of graupel across the strata of supercooled water and snow. Following Houghton (1951), the growth of hailstones is the result of accretion of supercooled water as the stones fall relative to the cloud in an irregular manner through regions of varying liquid water content. While high vertical velocities doubtless contribute to the growth of large-sized hailstones, it is problematic whether the size of hailstones is indicative of the magnitude of the vertical updraughts (Ludlam 1951). A study of the reports of hailstones in India (Agarwala 1950) reveals that almost all big-sized stones are irregular in shape. Such of these as have been dissected reveal an irregular transparent outer coat, within which are localised regions of opacity (Rao 1952). The biggest stones are not built up concentrically around a central core but are apparently the result of fusion into each other of two or more of the elementary ones, exhibiting concentric shells. Battan and Braham (1956) have shown that there is a relative abundance of large-sized supercooled liquid drops having diameters exceeding 100 μ in tropical cumuli within the temperature levels of —5°C and —10°C. This part of the cumulonimbus cloud is characterised by extreme turbulence also. Elementary hailstones are apparently brought into impact with each other in this turbulent region and envelop themselves in a common supercooled water jacket which solidifies and seals them up together. The subsequent history of the compound hailstone so formed is simple to visualise. Further accretion of supercooled water from big drops takes place over its surface resulting in an unsymmetrical growth of the outer glazed ice envelope. The shape of the final glazed ice jacket seems to be determined by the varying availability of supercooled drops over different portions of its surface. The ruggedness of the compound stones is thus the result of non-uniform accretion of supercooled water around centres of homogeneity during the descent of the hailstones through a thick stratum of supercooled water.

The absence of common envelopes for the compound hailstones implies that coalescence and bonding together of elementary stones take place only in the ultimate stage of emergence of the elementary stones through the stratum of supercooled water but not in the earlier formative stages. In every well-developed hailstorm yielding a broad spectrum of sizes of hailstones, both elementary and compound stones are liable to be intermingled, the former possessing distinctly concentric rings right upto the external cover, while the latter form into stones of varying sizes and shapes due to fusion of varying numbers of the elementary stones. It follows that the maximum size attained by hailstones in individual storms is not related to the severity unless the specimen examined in each case is an *elementary* and not a compound stone.

4.5. *Peculiarities of the damage due to hailstones*

In the series of hailstorms which affected north India during 18 March 1957 to 20 March 1957, severe damage to standing crops and structures has been reported by the press. At Jodhpur, a few aircraft kept parked in the open were damaged in the hailstorm on 18 March 1957, the fabrics of the controls of such aircraft having got ruptured due to the sudden impact of the hailstones. Much of this destruction is attributable to the large terminal velocities of impact of big-sized hailstones. Weickmann (1953) has shown that this velocity is given by the relation $v = 200\sqrt{D}$

where v is the terminal velocity of the stone in cm/sec and D is the diameter in mm.

In the case of the elementary stones of 18 mm received at Jodhpur, the terminal velocity yielded by the above relation is 8·5 m/sec. For stones compounded of three such elementary hailstones and enveloped by an approximately spherical cover, D will be of the order of 34 mm which gives a terminal velocity of 12 m/sec. For binary stones, one might, therefore, expect the terminal velocity to lie between the limits of 8·5 and 12 m/sec. It is understood from the authorities of the

Hindusthan Aircraft Limited that the fabric of the controls of Dakota aircraft are prestressed to withstand a pressure of 25 lbs sq.inch. It may, therefore, be inferred that the compound stones, which reached the ground, might have come into impact with objects on the ground with a high pressure of this order on 18 March 1957.

5. Conclusion

The results of this study lead to the following conclusions —

5.1. Although thunderstorms may not develop in a strong wind field, such of those which do so, tend to transform into hailstorms.

5.2. The conditions to be fulfilled for the development of thunderstorms in an unfavourable wind field are the conjunction at a place of two vortices of cyclonic and anticyclonic character, the cyclonic vortex being embedded in a moist air stream.

5.3. Under the above conditions, thunderstorms do develop notwithstanding an unfavourable thermodynamic situation also.

5.4. The direction of the squalls associated with such thunderstorms is predictably close to the isallobaric wind disclosed by earlier wind-shear charts.

5.5. Hailstones other than graupel are of two types, *viz.*, elementary and compound. Elementary stones possess a single central core surrounded by a varying number of symmetrical layers of glazed ice and rime. Compound stones are formed by the cementing together just above the freezing level of varying numbers of the elementary hailstones. These have a single common glazed ice envelope.

5.6. The severity of a hailstorm bears no relation to the largeness of size attained by the stones produced by it, as the size depends only on the magnitude of the prevalent turbulence and the liquid water content of the cloud in the proximity of the freezing level.

5.7. The ruggedness of the outer jacket of the compound hailstones is a consequence of non-uniform accretion of supercooled water droplets over different parts of its surface.

5.8. Hail and rain may occur synchronously when the tilt of the axis of the hailstorm is slight. Hail precedes rain in cases of pronounced axial tilt.

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