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Mesoscale study of summer Thunderstorms in Delhi area

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ABSTRACT. A pilot scheme to study the mesoscale structure of the summer thunderstorms in Delhi area and their effect on the surface weather was put into operation during the months of June, July and August 1961. A network of seven stations with autographic charts was established round Delhi. Some interesting results on surface squalls and pressure and temperature changes associated with the thunderstorms were obtained from this study and are presented.

1. Introduction

The meteorological systems which cause weather at a place constitute a size spectrum with the cells of the general circulation at one end and the small local convective phenomena like the dust devils at the other. There appears to be no discernible gap in the spectrum. Both the largest and the smallest systems have their contribution to the weather. It is the work of the meteorologist to assess the influence of each of these factors and arrive at final conclusions.

The grosser synoptic systems indicate the general areas of weather development. But within these areas, pronounced local variations are noticed, which cannot be satisfactorily explained in terms of the synoptic features. The tornado has a horizontal diameter of the order of a few hundred metres, the airmass thunderstorm, of a few kilometres and the frontal squall line, a few hundreds of kilometres. These are some of the mesoscale systems, which have been studied in recent years.

The 'Thunderstorm Project' of U.S.A. (1948) can be considered as the first major project of mesoscale studies. Fujita (1955) applied the mesoscale technique to a study of the squall line structure of cold front thunderstorms. The activity in the field of mesoscale studies has increased considerably in recent years and a large number of projects have been taken up.

2. Importance of mesoscale studies

The problem of forecasting small scale but important meteorological phenomena like the speed and direction of the squalls accompanying an air mass thunderstorm, highly localised heavy rainfall, etc has always been a matter of considerable difficulty to the forecaster. The speed and direction of the thundersqualls vary so considerably even in small areas like a town or city, that their successful forecasting for a spot like an aerodrome is impossible on purely synoptic considerations. For example, a severe squall struck Safdarjung airport on the evening of 7 March 1960 with a speed of 90 knots. Lodi Road Observatory, about 6 furlongs away, recorded only 65 knots and the northern parts of Delhi experienced only gusty winds. Hence a detailed study of the structure of the squalls associated with thunderstorms would be of help in accurately forecasting the speed and direction of squalls at least in short range forecasts like Airfield Warnings, Landing Forecasts etc.

The small eddies and lows along the west coast during the southwest monsoon season pointed out by George (1956) are slightly bigger mesoscale systems which could just be detected by the existing synoptic network. It may also be mentioned that similar small lows and troughs are occasionally observed in other parts of India with pronounced associated weather activity. It is natural to speculate whether the small areas of localised heavy precipitation, that occur in the monsoon season, are also caused by smaller mesoscale systems, which accentuate the bigger (and favourable) synoptic conditions in that particular locality.

3. Network chosen for Delhi project

Delhi experiences duststorms and thunderstorms during the summer months. Often such storms are accompanied by squalls at the surface, some of which can be very severe. With a view to study the structure of these storms and their effect on the surface weather, a pilot scheme of limited extent was set up in the summer of 1961.

Fujita and Brown (1960) have suggested networks in three densities —

α — Coarse — with stations about 30 miles apart

β — Medium — with stations about 5 miles apart

γ — Fine — with stations about 1 mile apart

The network chosen for Delhi Project falls into

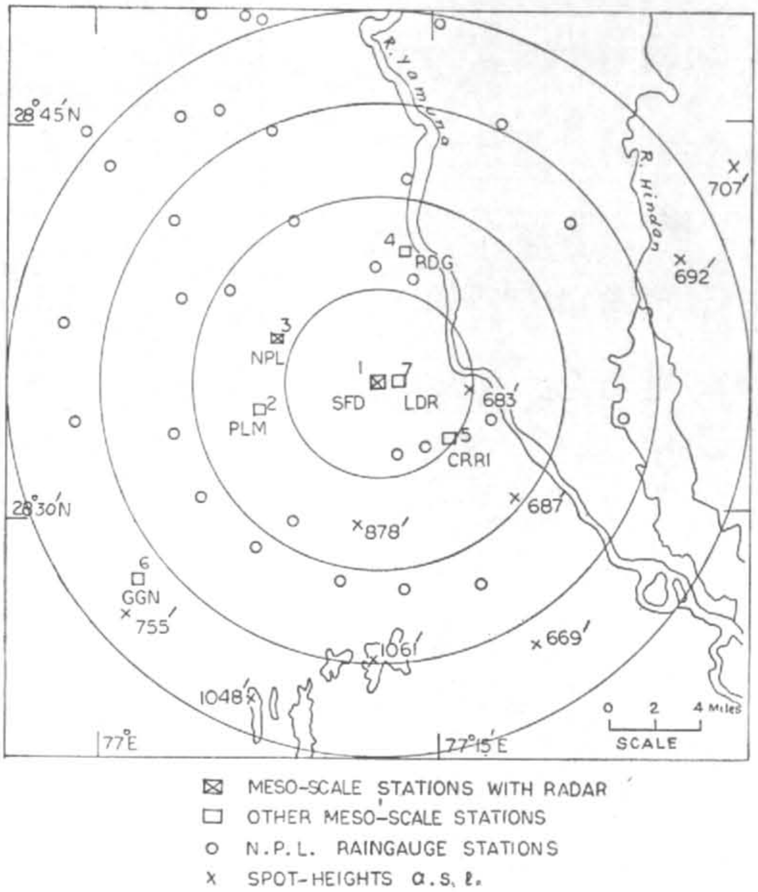

Fig. 1. Location of observatories and radar units

Station Nos. (1) SFD — New Delhi MMO (Safdarjung), (2) PLM — Palam MMO, (3) NPL — National Physical Laboratory, (4) RDG — Ridge Observatory, (5) CRRI — Central Road Research Institute, (6) GGN — Gurgaon Observatory and (7) LDR — Lodi Road Observatory

category β according to the above classification.

There are 3 meteorological observatories within the limits of the municipal areas of New and Old Delhi; in addition four more observatories in Delhi and neighbourhood were specially set up for the project. Fig. 1 shows the location of all these observatories along with the location of the two radar units, whose observations were utilised in the scheme. All the observatories were equipped with autographic instruments for pressure, rainfall, wet and dry bulb temperatures and relative humidity. Stations Nos. 1 and 2 recorded current weather observations throughout 24 hours while stations 3, 4, 5 and 6 were manned between 1100 and 1700 IST, the hours of watch being extended beyond 1700 IST in case of continued bad weather at the station. No current weather watch was maintained at station No. 7.

Thus altogether autograph charts from seven stations, current weather observations round the clock from two stations (MMOs Safdarjung and Palam) and current weather observations from four stations for limited period during day-time were available for analysis. The scheme was a modest one and was intended only as a pilot project to assess the nature of the problem.

Apart from the above autographic instruments, there are three Dines P.T. anemographs situated at Palam, Safdarjung and Lodi Road observatories. Radar observations from two of the stations, *viz.*, Safdarjung and National Physical Laboratory were available for the study.

4. Chief features of summer thunderstorms of northwest India

Dry continental air generally prevails over northwest India during the pre-monsoon months. Due to the high insolation, adiabatic or super-adiabatic lapse rates are invariably present in the lower layers of the atmosphere upto about 700 mb. Occasionally under the influence of eastward moving weak low pressure areas, incursion of moisture takes place into this region, resulting in violent convective activity. The thunderstorms generally start developing around 1300 or 1400 IST and reach a peak towards dusk. On some of these occasions only duststorms result, because of the

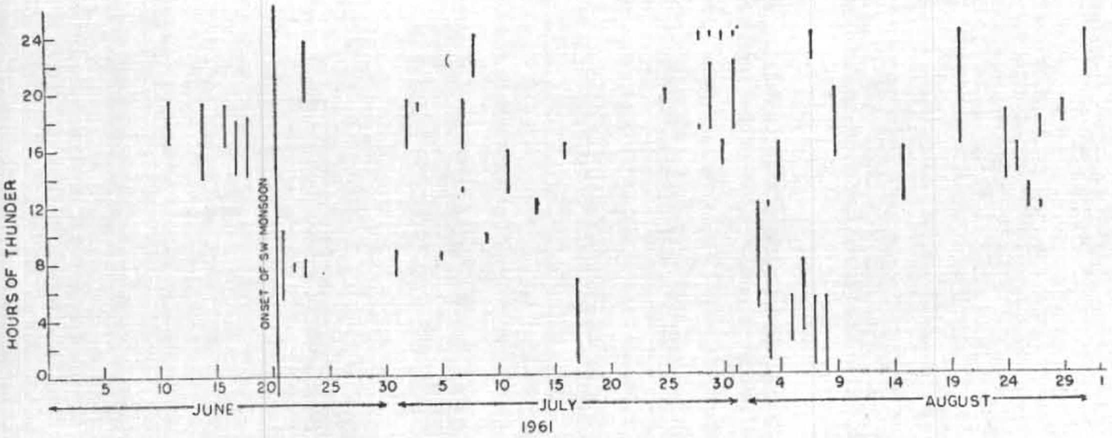

Fig. 2. Times and duration of Thunderstorms in Delhi during June to August 1961

low moisture content and the dry dusty grounds over which they pass. As the turbulent winds accompanying the thunderstorm strike the ground, they lift up the layers of fine dust and thus a duststorm is formed. When the moisture feed is sufficiently high, light to moderate showers can be expected. These storms are invariably accompanied by squalls.

After the southwest monsoon is established over the area, the airmass is humid and is conditionally unstable. During this season, the thunderstorms can be expected during all hours of the day or night. The above feature can be seen in Fig. 2 which shows the times and duration of thunderstorm activity in the Delhi area during the months of June, July and August 1961.

Most of the rainfall in Delhi area during the southwest monsoon season is from showers. Thunderstorms are as frequent in this season as in the pre-monsoon season. But the squalls are less violent and their frequency is low. Whereas every thunderstorm in the pre-monsoon season can be expected to cause moderate to severe squalls with little or no rain, the monsoon thunderstorms often give moderate to heavy rain with light or no squalls. However, when the monsoon is weak and the surface temperatures are above normal, stronger squalls occur even in the monsoon season.

5. Some synoptic features associated with pronounced thunderstorm activity

Since this paper is concerned with mesoscale phenomena, only a very brief description of the more marked synoptic situations which accentuate the airmass thunderstorm activity is given here.

In the pre-monsoon months, any system which can check the dry northwesterly flow and give a southerly component to the winds in the lower layers is a favourable condition for active thunderstorm activity. This occurs generally in association with low level troughs or low pressure areas which move eastwards across northern parts of India, and go by the name of western disturbances. Superimposed on this a high level divergence above six kilometres a.s.l. is the most favourable condition for pronounced thunderstorm activity.

During the southwest monsoon season, the low level monsoon trough is normally located near Delhi, more often to the south of it. The heaviest downpours, however, are found to occur only when a pronounced high level divergent system is superimposed over the low level trough, which has moved over Delhi.

6. Mesoscale features

(a) *Radar echoes*

Delhi has two powerful weather radar units within 8 km of each other. The Raytheon Radar*, which is situated near Safdarjung Airport, has operational commitments to aviation interests. Hence special observations could only be taken during its free time. As far as possible, PPI-scope photographs at 15-minute intervals were taken whenever *Cb* clouds were observed within 25 miles of Delhi. Secondly, the situation of the radar at the centre of the network has proved to be a handicap, as the echoes from the nearby cells (within 10 – 15 km) were rendered indistinct due to ground clutter. Thirdly, unfortunately the radar became unserviceable by about the middle of August 1961. The radar of the Cloud Physics Unit of the National Physical Laboratory† has its own programme of work. They had taken quite a large number of pictures at short intervals on many days during the project period. These were kindly loaned to us for supplementing the data of the Raytheon Radar.

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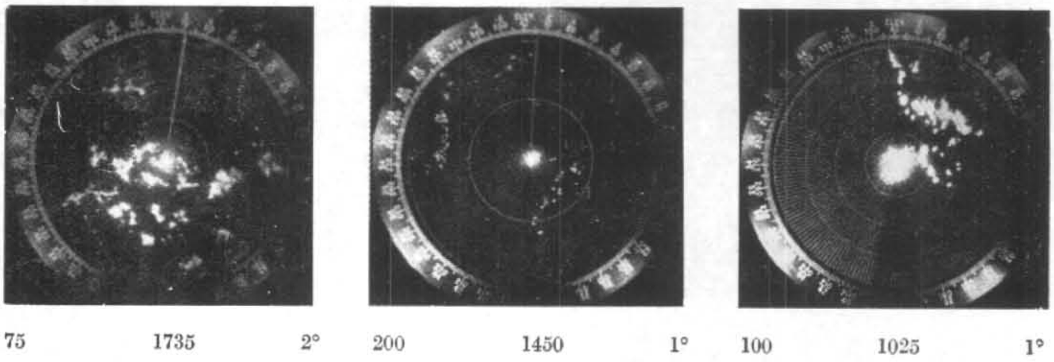
*Specifications : Type AN-CPS 9, X-Band, Wavelength 3·2 cm, Peak power 250 KW, 1° conical beam

†Specifications : NMD-451A, X-Band, Wavelength 3·2 cm, Peak power 225 Kw, 1·2° conical beam



75 1735 2° 200 1450 1° 100 1025 1°

(a) Formation of patches (b) Line type echoes (c) Wall type echoes

Fig. 3. Safdarjung radar pictures (4 August 1961)

The figures below the photographs (from left to right) indicate total range in miles, time in IST and elevation in degrees. The range markers is 25 miles in each case

In spite of the limitations mentioned above, several hundred photographs were available for study. Careful study of these pictures has revealed the following features of the cumulus and thunderstorm echoes.

The echoes from initial cumulus cells are oval or circular in shape with diameters of the order of a kilometre. Only a few of these grow in size. Cells which are close to each other often merge and form patches. Fig. 3 (a) gives a good example of such merger taking place. The resultant patch is generally less regular in shape than the primary cells. A well-developed isolated thunder cloud is represented on the PPI-scope as a patch formed by the merger of a few primary cells, which can no longer be distinguished individually. Usually, the horizontal extent of the individual patches of isolated thunderstorms in the Delhi area is of the order of 5 to12 km in the pre-monsoon season and 8 to 18 km in the southwest monsoon season.

On many occasions, further merger of even these patches takes place and as seen on the PPI-scope, the resultant large patches are highly irregular in shape. Such patches can grow to any size. In the pre-monsoon season, these patches grow to about 50 km and even to 80 km on rare occasions. In the southwest monsoon season, the echo patches are generally bigger and can extend laterally to 150 km or more on some occasions. Once such large patches form, it is practically impossible to locate the active portions of the cloud mass (the large *Cu* and *Cb* with great vertical development which have their individual life cycles) from the auxiliary portions, both of which compose the patch, from the ordinary PPI pictures of 1° elevation. Pictures taken at high elevation angles of scanning (3° or 5°) and of low gain are very useful in locating the active areas of convection. REI or RHI pictures taken at close intervals of azimuth are the best to get a clear three dimensional structure of the cloud mass represented by the echo patch on the PPI-scope.

Another technique used in the present study to obtain details about the relative concentrations of precipitation particles within a large patch was to project the negatives of the PPI-scope photographs on a screen using a Strip Film Projector. By this method enlargements upto 50 to 100 times could be got and a wealth of detail could be seen on the screen. Areas of strong concentration of water droplets could be clearly distinguished and on most occasions these were either oval or circular in shape, thereby pointing out the primary active cell area of convection.

Apart from the merging of individual cells into patches, and these into larger ones, there is a general tendency for the echoes to form along lines. These lines can have comparable gaps between the echo patches or can form into continuous wall. Figs. 3 (b) and 3 (c) show examples of the two types respectively. The lines generally stretch across the line of propagation.

(b) *Life span of a thunderstorm*

As is well known, a thunderstorm usually has a life span of 2 to 3 hours. However, this is only a mean of a wide range. In the present study, *Cb* clouds which caused minor squalls were found to have a life as low as one hour from their first detection to their final dissipation on the radarscope. On the other hand, thunderstorm echoes having a longer life of even 6 to 8 hours and travelling over long distances have also been recorded. For example, a severe thunderstorm was observed on 13 April 1961 as a well-developed oval-shaped

TABLE 1

Movement of thunderstorms

Date	Prevailing surface wind		Height of top of *Cb* cloud (ft)	Mean wind between 5000 ft and top of cloud		Cloud movement		Remarks
	Dir.	Speed (kt)		Dir.	Speed (kt)	Dir. from	Speed (kt)	
11 Jun 61	ESE	15	45000	280°	14	WNW	20	
14 Jun 61	NW	15	35000	276°	15	W	15	
16 Jun 61	WNW	15	40000	307°	19	WNW	15	
17 Jun 61	WNW	15	25000	275°	12	W	—	
18 Jun 61	Var.	05	25000	311°	15	WNW	08	
2 Jul 61	ESE	08	40000	150°	08	ESE	—	
3 Jul 61	SE	10	35000	120°	11	E	10	
5 Jul 61	ESE	05	18000	060°	12	NE	—	Large *Cu* only
11 Jul 61	ENE	05	40000	360°	01	Stationary		
13 Jul 61	ENE	05	35000	055°	08	NE	10	
17 Jul 61	SE	05	40000	115°	14	SE	—	
25 Jul 61	ESE	05	40000	105°	07	SE	08	
31 Jul 61	ESE	04	45000	256°	03	SW	05	
4 Aug 61	W	10	45000	346°	09	N	10	
9 Aug 61	E	05	25000	ESE	10	E	10	

echo patch of extent of about 80 km by 40 km at 1530 IST situated at a distance of about 250 km to the west of Delhi. It travelled fast in a northeasterly direction and was over Karnal town at about 1930 IST. It had travelled a distance of 240 km in roughly 4 hours. The associated squall of about 50 knots bent and uprooted several electric poles and caused severe damage to standing crops along its track in the Karnal area.

It was generally noticed that the bigger the patch, the longer is it able to retain its identity. Strictly, the life span of a patch cannot be treated as the life span of a thunderstorm as it usually contains several individual *Cb* clouds. But again even a *Cb* cloud of the conventional shape, contains many turrets, which are the prime convective cells, and so it is difficult to draw distinct lines between a cell, a cloud and a cloud mass containing several closely packed *Cu* and *Cb*. This complicated nature of the convective clouds adds further to the difficulties in correlating the surface weather phenomena with the cloud echoes on the radar screen.

(c) *Movement of thunderstorms*

The speed and direction of movement of thunderstorms is of fundamental importance to the forecaster. While the general direction of movement of the echoes on the radar screen is often easily determined, it is extremely difficult to compute the speed and direction of movement of individual echoes or patches due to the growth and dissipation processes which are continuously going on during all the stages of a thunder cloud.

The limitations of the available radar data have already been discussed under section 6 (a) above. However, it was possible to compute the movement of the thunderstorms on a few occasions with a fair degree of confidence, after giving due allowance for the overall changes in the cloud mass. The results are given in Table 1.

The two features brought out by the table are —

(*i*) The direction of movement of clouds is invariably from a westerly direction in June, whereas it is often from an easterly direction in July and August.

(*ii*) The speed of movement is much greater in June than in the months of July and August.

An attempt was also made to correlate the movement of clouds with the winds at different levels. There was a fair degree of correlation between the direction of movement of clouds and the wind direction at 6 km. But the correlation between the speeds was not so good. The best correlation was got between the storm movement (direction and speed) and the mean wind in the layer 1·5 km to the top of the cloud. The mean wind data are also given in Table 1.

As is well known, all the echoes on the radar screen do not move with the same velocity. This is natural because of the variations in the heights of the different clouds. In fact, relative motion between different parts of the same echo patch has also been noticed. Such an example is given in Fig. 4. The figure shows two PPI pictures taken at an interval of 9 minutes. The northeastern and southeastern parts of the cloud patch moved away much faster than the central and western parts, resulting in a rapid change in the general shape of the echo patch.

Such variations in the movements of different echoes and also the changes in the movement of the same echo are noticed particularly on the days when large vertical wind shears are present. This more or less confirms the view that prevailing winds at all levels from the base to the top of the cloud contribute to its movement.

(d) *Wind field beneath thunderstorms*

Surface wind field undergoes many rapid changes during the life cycle of a thunderstorm as the changes in the vertical movements of air in the convective cell are reflected in the horizontal movement of air beneath it.

A careful and detailed study of the autograph charts from three anemographs and the spot observations from the other stations has been made and the results are discussed in the following paragraphs.

The first point noticed was that the effect of convegence/divergence associated with convective clouds during their different stages, on the surface winds are very localised (in space), highly variant (in time) and transient (in duration), so much so that the grid of observatories of the present project and the frequency of the radar pictures have proved inadequate to bring out detailed analyses of the wind field as affected by the convective clouds. As such the results discussed below can be taken as tentative.

During the cumulus stage, if the surface wind is moderate (10 knots or more), the convergence beneath the cloud was seen as a decrease in the surface wind on the downwind sector and a freshening of the wind on the upwind sector. Sometimes the prevailing wind completely dies down giving rise to a 'calm before the storm'. The P. T. anemogram section shown in Fig. 5 is a good example of such a 'blocking' of the prevailing surface wind.

On days when the prevailing wind is light, the wind direction changes and a direct inflow was observed. When a large number of cells in different stages of development are present in close proximity, the surface winds in the area become highly variable. An instance of such conditions is shown in Fig. 6. The figure gives the sketch of the radar echoes at 1735 IST on 14 June 1961 as seen on the PPI scope of the Raytheon radar and the surface winds at 1730 IST recorded at the different mesoscale stations.

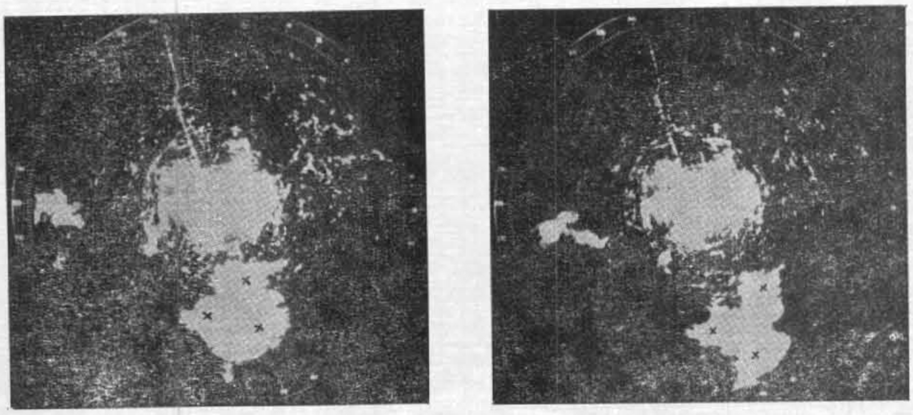
Spectacular changes of surface wind field are caused by the downdrafts of mature thunderstorms. However, these intense changes are confined to a small area in the vicinity of the downdrafts and are found to occur during a very limited period.

The chief feature of the divergence at the surface associated with the downdrafts is its asymmetry. The Thunderstorm Project of U.S.A. has this to say," .... in relatively slow moving storms, the outflow is almost radial .... In most instances however the outflow field is asymmetrical with the winds on the down stream side substantially higher than those on the up stream side. This is due to reinforcement or cancellation as the case may be of the radial outflow by the prevailing air movement in the lower layers .... As the relatively higher horizontal momentum characteristic of the upper levels is transported downwards, surface outflow wind speeds in the direction of the cloud movement are reinforced while those in the opposite direction are retarded."

The present study has indicated that the wind field is highly asymmetrical even in the case of slow moving storms. In the pre-monsoon season, the storms are generally fast moving. In July and August, the movement is generally slow. But marked asymmetry has been invariably noticed in the case of almost all the outflow fields associated with the *Cu* or *Cb* downdrafts.

As regards the transport of high horizontal momentum from the upper levels to the ground layers, even though it does seem to play a part, the observed asymmetry of the divergent wind fields cannot easily be explained by the vectorial compounding of the wind strength of the upper levels and an assumed radial outflow. For example, in the present study, the maximum squall speed of 58 knots from a westerly direction was recorded at Palam at 1716 IST on 7 July 1961. On this day, even though the upper winds had a westerly component between 2 and 12 km the speeds were small (5 to 15 knots). The winds in the lower layers were also unfavourable for any reinforcement on the 'down stream' side (Surface — Light and variable, 1500 m — 090°/07 kt).

The study of Dines P.T. anemograms also confirms the above view. Even though the three anemographs were in close proximity, none of the charts showed any evidence of a uniform radial flow or a flow anywhere near it. Most of the



20 1548 2·5° 20 1557 2·5°

Fig. 4. N.P.L. radar pictures (18 June 1961) — Relative motion between parts of the same patch of cloud

The figures below the photographs (from left to right) indicate
total range in km, time in IST and elevation in degrees
General direction of movement — WNW to ESE

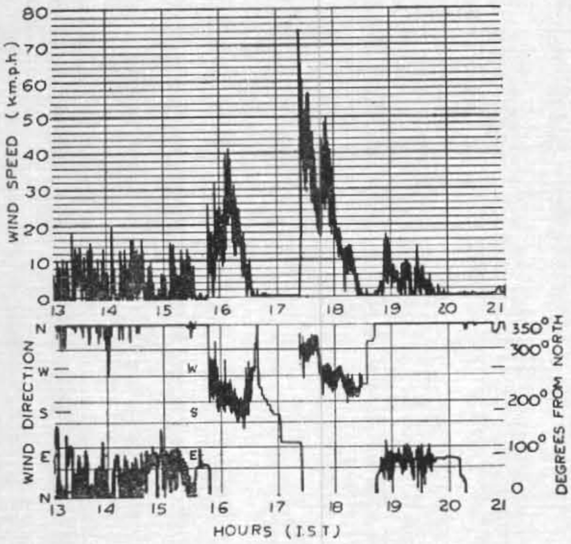


Fig. 5. P.T. Anemogram showing 'Blocking' of prevailing surface wind

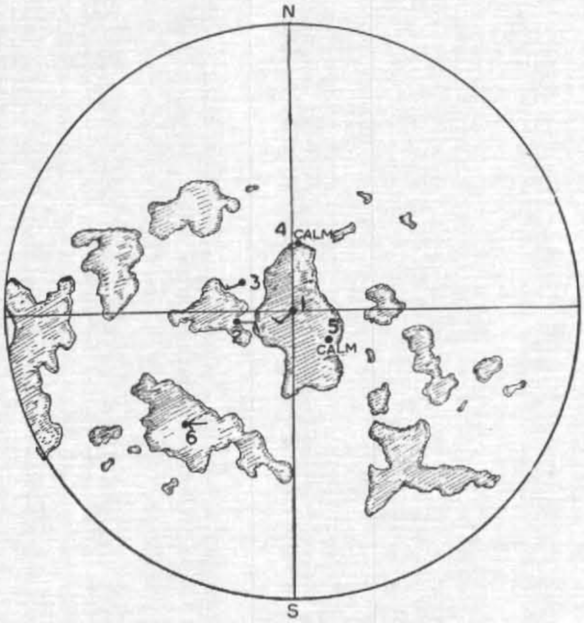


Fig. 6. PPI of Safdarjung radar (14 June 1961)
Surface winds — as affected by multiple cells
Time — 1735, IST, Elevation — 2°, Radius — 25 miles

squalls and gusts were followed either by a gradual dying out of the wind or by a calm followed by a weak wind from the direction of the cloud which has passed over the station. In Fig. 7, the anemograph chart of Safdarjung for the period 1100 to 1900 IST on 7 July 1961 is given. On this day, convective activity was vigorous and a number of downdrafts of varying intensities affected the surface winds of the station. The mean wind direction in the layer between 1·5 and 7·5 km was northerly and between 1·5 and 15 km was westnorthwesterly. These are shown as thick lines in the chart. As can be seen most of the gusts were from directions which lie within 90° of the north. In fact winds from a southerly direction were practically absent.

Direct evidence of the asymmetric nature of the outflow field of the downdrafts was available on a few occasions. One such instance is shown in Fig. 8. The figure shows the radar echoes as seen on the PPI scope of the Raytheon radar at 1413 IST on 4 August 1961 along with the surface winds recorded at the different stations at that time. The general direction of movement of the clouds was from north to south. The prevailing surface wind was light westerly. Earlier a number of cells had

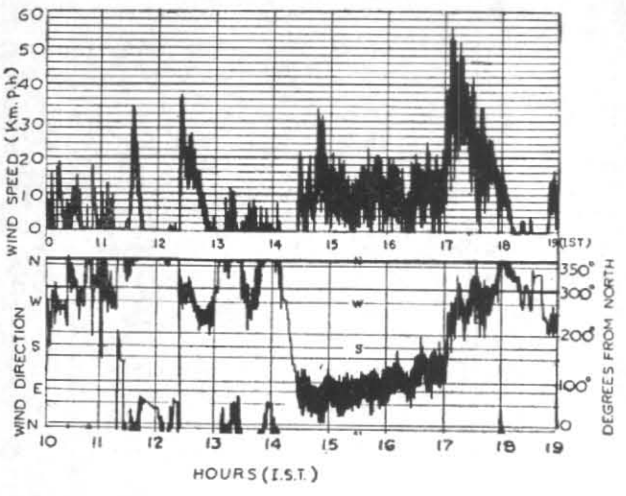


Fig. 7. P.T. Anemogram showing a number of squalls
Station — New Delhi (Safdarjung)
Date — 7 July 1961

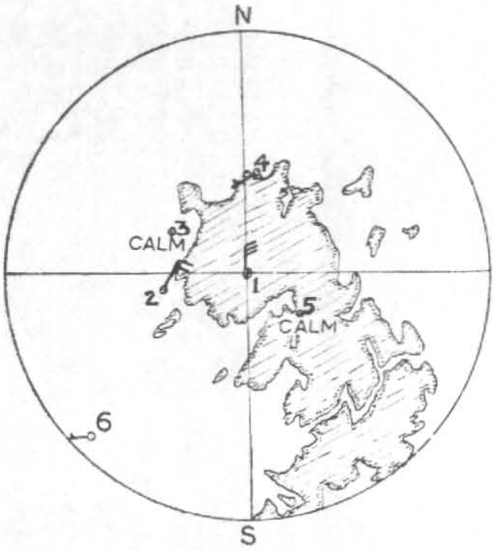


Fig. 8. Asymmetric distribution of winds — Safdarjung radar PPI
Date — 4 August 1961, Time — 1413 IST, Radius — 15 miles
Elevation — 3°, Movement of cloud — N to S

passed southwards to the east of Safdarjung (station 1) and at 1413 IST a cell had just passed over station 5 (CRRI). Another major cell lay between Safdarjung and station 4 (RDG). The striking contrast between the winds in the foreward and rear sectors of the cloud can be readily seen in this picture. The squall at Safdarjung, the unaffected prevailing wind at station 4, and the calm at station 3 (NPL) where the peak lateral outflow is opposed by the prevailing surface wind— all point out the asymmetric distribution of the outflow field of the downdraft. The 'calm' at station 5 was apparently due to the combined influence of the distant cell affecting station 1 (SFD) and the nearer cell which has just passed over. Such cases are discussed in a later paragraph.

Further evidence of the asymmetric distribution of the wind field of downdrafts was obtained by the analysis of squall directions recorded during the project period and also those recorded in 1960 and 1961 in New Delhi region. The method of analyses adopted was to calculate the deviations of the directions of the squalls from the direction of movement of the thunderstorm for all the squalls recorded during the project period. On days when the actual movement of the clouds could not be obtained, a direct comparison with the mean wind direction in the layer 1·5 km a.s.l. to the top of the cloud, was made to obtain the deviations. The data are given in Table 2.

The results are also shown diagrammatically in Fig. 9. The figure is obtained by taking movement of the cloud along the X-axis, and showing the deviations given in Table 2 in the following three categories —

(1) Deviations within 60°

(2) Deviations between 60° and 120°

(3) Deviations above 120°

The high frequency of squalls with directions in the first category and the complete absence of squalls with directions in the last category are fully illustrated in the figure. A similar analysis was made for all the noteworthy squalls in northwest India reported in the New Delhi *Regional Daily Weather Reports* during the years 1960 and 1961. As radar pictures for computing the cloud movements were not available, the comparison was made between the squall direction and the direction of the mean wind in the layer between 1·5 and 12 km. The data are given in Table 3 and their diagrammatic representation in Fig. 10. As can be seen the results are similar to those for the project storms. The higher frequency in category (1) is naturally to be expected in the case of these relatively fast moving storms.

Some interesting interpretations of the diagrams shown in Figs. 9 and 10 can be given.

(1) Since the squall direction is usually the direction in which the thundercloud is situated with respect to the station, the diagrams give roughly the frequency of squalls in different sectors of a moving cloud.

(2) Since a squall is a gusty wind which satisfies certain defined criteria, the frequencies can also be interpreted as a measure of the relative wind velocities in the various sectors of a thunderstorm.

It may be mentioned in this connection that the squalls given in Table 2 are mostly from the three anemographs records. As the other project stations

TABLE 2

Direction of squalls and direction of movement of thunderstorms (Project period)

Date	Prevailing surface wind Dir./speed (kts)	Height of top of *Cb* (ft)	Mean wind between 5000 ft and top of *Cb*	Movement of *Cb* Dir. from/ speed (kt)	Squall data			Deviation in the direction of squall from the direction of movement of *Cb* (deg)	Remarks
					Dir./speed (kt)	Time (IST)	Stn†		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
11 Jun 61	ESE/15	45000	280°/14	NW/xx	WNW/26	1715	PLM	30	
14 Jun 61	NW/15	35000	276/15	W/15	NW/28	1600	RDG	40	
					W/27	1753	SFD	05	
					WSW/28	1825	PLM	30	
16 Jun 61	WNW/15	40000	307/19	WNW/15	NNE/28	1825	LDR	90	
					NNE/40	1835	SFD	90	
					N/30	1835	PLM	60	
17 Jun 61	WNW/15	40000	295/15	xx/xx	N/28	1558	SFD	65	
					N/28	1600	LDR	65	
					NNW/28	1608	PLM	45	
					NNE/41	1618	PLM	90	
					NW/28	1624	SFD	20	
					N/29	1630	LDR	65	
					N/25	1652	PLM	65	
					NNE/30	1724	PLM	100	
18 Jun 61	Var./Light	30000	310/13	WNW/08	WSW/33	1525	PLM	45	
					SW/25	1603	SFD	70	
					WNW/33	1710	PLM	0	
					W/26	1723	PLM	40	
					NW/46	1723	SFD	15	
					NW/42	1726	LDR	15	
					W/31	1753	SFD	40	
2 Jul 61	ESE/08	40000	150/08	ESE/xx	E/23	1616	SFD	25	
					SE/45	1624	PLM	25	
					E/25	1808	PLM	25	
					SE/25	1808	LDR	25	
					SE/25	1810	SFD	25	
3 Jul 61	SE/10	35000	120/11	E/10	E/28	1830	LDR	0	
					E/30	1844	SFD	0	
5 Jul 61	ESE/05	18000	060/12	NE/xx	NE/30	0810	LDR	0	Only large *Cu* in great number
					ENE/32	0812	SFD	25	
					NE/30	0824	PLM	0	
					NE/30	0905	PLM	0	
					NE/23	1006	PLM	0	
5 Jul 61	ESE/05	25000	107/11	xx/xx	SE/23	1806	SFD	30	
					SSE/31	1936	SFD	50	
					ENE/27	1946	PLM	40	
					ENE/31	2002	PLM	40	
7 Jul 61	Var./E Gusty/10	55000	272/05	WSW/xx	SW/28	1644	PLM	25	
					SW/32	1700	SFD	25	
					W/58	1716	PLM	25	
9 Jul 61	WNW/05	xxx	014/07*	xxx	NNE/28	0916	SFD	10	*Assumed height 40,000 ft. No. radar pictures available
					NNE/22	0920	PLM	10	
25 Jul 61	ESE/05	40000	105/07	SE/08	SE/24	1910	PLM	0	
4 Aug 61	W/10	45000	346/09	N/10	N/34	1412	SFD	0	
					NNE/23	1510	PLM	25	
20 Aug 61	NW/10	xxx	275/21*	xxx	NNE/43	1920	PLM	110*	*Assumed height 40,000 ft. as radar pictures are not available
					N/40	1955	SFD	85	
					NNE/42	2020	LDR	110	

Var. — Variable

†PLM — Palam (Station No. 2), RDG — Ridge Observatory (Station No. 4), SFD — Safdarjung (Station No. 1), LDR — Lodi Road Observatory (Station No. 7)

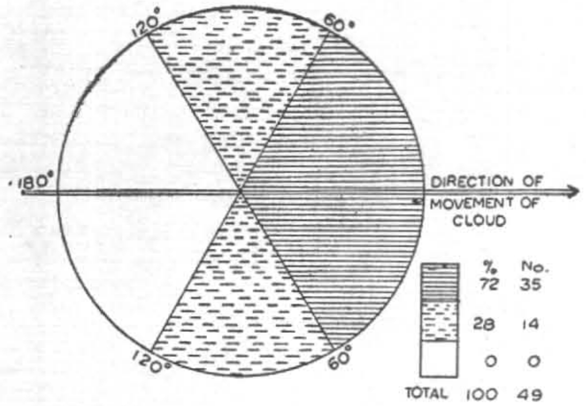


Fig. 9. Frequency of deviations of squall directions for squalls recorded during the project

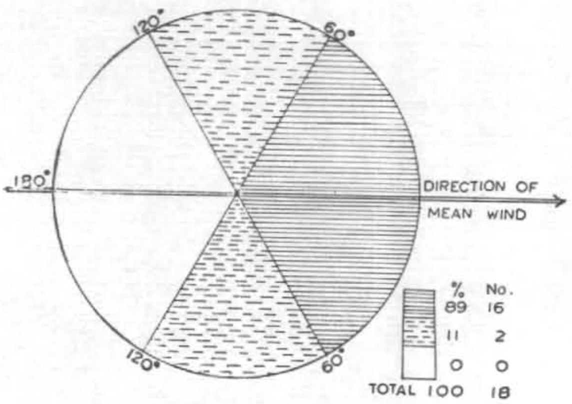


Fig. 10. Frequency of deviations of squall directions for all squalls in northwest India reported in New Delhi Regional Daily Weather Report — 1960 and 1961

TABLE 3

Direction of squalls and direction of movement of thunderstorms in northwest India during 1960 and 1961

Date	Time (IST)	Station	Squall	Mean wind in layer between 5000 to 40,000 ft Direction/speed (Deg)/(kts)	Deviation of squall direction from the mean wind direction (degrees)	Remarks
7 Mar 60	1752	Safdarjung	NW/90	277/23	40	
7 Mar 60	1745	Lodi Road	NW/63	277/23	40	
9 Mar 60	Evening	Safdarjung	SW/60	247/28	30	
15 Jun 60	0340	Do.	NE/48	305/23	120	
2 Jul 60	1325	Do.	SE/50	180/04	45	
14 Apr 61	1800	Do.	SW/50	240/24	15	
29 Apr 61	2000	Do.	SW/42	268/32	45	
11 May 61	1802	Do.	NW/52	295/23	30	
12 May 61	2130	Do.	NW/55	260/16	50	
13 May 61	0010	Do.	NW/42	252/37	60	
	0210	Do.	NW/39	252/37	60	
	0240	Do.	NW/50	252/37	60	
18 May 61	1937	Do.	W/40	270/48	0	
13 Apr 61	1935	Karnal	WSW/60	220/60*	25	*Mean wind upto 30,000 ft along the track of this storm (Please see text on pages 532-533)
21 May 61	0020	Jodhpur	NE/55	287/27	115	
	1735	Allahabad	SW/57	245/29	20	
25 May 61	1930	Do.	NNW/47	290/23	45	
	2030	Do.	NNW/40	290/23	45	

were not equipped with anemographs, it is quite possible that the milder squalls might have been missed by the observers. Also the limited watch hours at those stations accounts for the low figures of squall reports from them.

The results obtained above with the available data seem to indicate that the strongest winds from the downdraft can be expected slightly ahead of the cell centre and the direction of these winds will be nearly the direction of movement (from) of the cloud. The winds at the rear sector of the cell are weak and on many occasions calm conditions prevail there.

Apart from the asymmetric distribution of the wind field, another feature noted in the present study was the highly transient nature of the high winds associated with downdrafts. The rapid changes in winds both in space and time are brought out clearly in the sequence charts given in Fig. 13. It is seen in Fig. 13 that while Palam Airport recorded a maximum speed of about 58 knots, Safdarjung which lay more or less along the line of propagation of the storm recorded only a maximum speed of 32 knots and even this appears to have been partly caused by a cell downstream, as Safdarjung experienced rain earlier than Palam.*

The above aspect suggests a rapid fanning out of the downdraft air as it moves away from the central area in the forward sector.

Various workers have examined if any correlation exists between the squall velocities and the synoptic data of the station like the vertical distribution of the temperature, the maximum winds in the upper air and so on (Tripathi 1956, Bhalotra 1957, and Koteswaram and Srinivasan 1958). However, due to the transient and localised nature of the downdraft wind field, there is an inherent difficulty in trying to correlate the squall velocity recorded at a station as representative of the maximum velocity of the downdraft wind field, which alone is likely to have any correlation with the synoptic conditions.

The above discussion of the surface wind fields beneath a mature storm has been with reference to a single or isolated thunderstorm. On occasions when downdrafts from a number of storms are affecting the same area, modifications to the model of wind field given above are noticed. It is noticed that on many occasions the cold air left behind by an earlier cell seems to act as a 'block' or 'reflector' for later winds. The extreme values of deviations in Tables 2 and 3 may be due to such effects.

Another feature noticed in the study is that surface winds in the wake of a thunderstorm are affected by the spreading out of the dome of cold air left behind along the trail of the thunderstorm. Cold weak winds have been observed at comparatively long distances from the original downdrafts area. Also the winds at the lateral edges of the storm continue to be fairly strong for sometime after the storm has moved away (apparently due to the reinforcement of the original dynamical gusty winds by the winds caused by the spread of the cold dome).

(e) *Surface pressure changes*

The usual pressure changes associated with thunderstorms are —

(*i*) a small drop of pressure below growing cumulus,
(*ii*) a large rise of pressure as the downdraft of the major storm reaches a station and
(*iii*) a pressure dip associated with some severe storms.

These have been studied and discussed by various earlier workers. Such discussions have not been repeated here even though the above features have also been noticed from the present data.

From purely physical considerations, the equation for pressure changes caused by a thunderstorm can be written as

$$\frac{dP_s}{dt} = (-g)\int_0^{\propto} \frac{d\rho}{dt}\,\partial z + (-g)\int_0^{\propto} \frac{dL}{dt}\,\partial z - \int_0^{\propto} \rho\,\frac{d\dot{w}}{dt}\,\partial z + f\left(\frac{dw'}{dt}\right)_s \qquad (1)$$

where,

P_s = Surface pressure,
ρ = Mass of air in unit volume,
L = Mass of water (ice) content in unit volume,
$\dot{w}$ = Vertical component of acceleration,
$f\,(dw'/dt)_s$ = A term involving the impact effect of the downdraft at the surface.

The above equation can be very much simplified for changes of pressure caused by cold air from the thunderstorm area at stations in the vicinity to —

$$\triangle P_s = (-g)\int_0^{h} (\triangle\rho)\,\partial h \qquad (2)$$

where h is the height of the cold air.

As can be expected from equations 1 and 2, it was noticed that at stations lying directly in the path of the thunderstorm, the pressure rise often showed

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* A detailed explanation of Fig. 13 is given in the section on "Surface pressure changes"

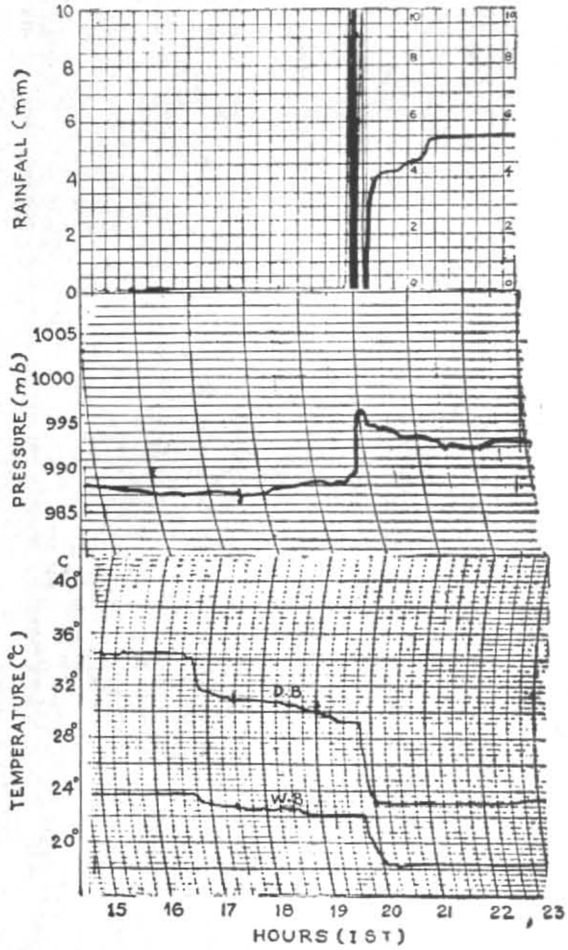

Fig. 11. Ridge Observatory (Station No. 4) — 20 August 1961

two phases. Usually the squall carrying the cold air reaches the station ahead of the storm itself. In such cases a rapid rise of pressure and a sharp fall of temperature occur at the station (eq. 2). A second rise (which may sometimes merge with the first and give the impression of a continued rise) is usually seen when the storm cloud and the precipitation reach the station (eq. 1).

The pressure falls rapidly by an amount equal to the second rise as soon as the storm crosses over the station. Thereafter it falls very slowly as the cold dome of air left behind by the storm gradually spreads out to adjacent areas and its height decreases. Figs. 11 and 12 give two typical examples of the two-phase pressure jumps recorded at stations (4) and (3) on 8 August and 17 July respectively. In the case of the August storm at station (4) — Fig. 11, the rise of pressure was very sharp being as much as 6 mb in 15 minutes. The two phases are not clearly separated during the pressure rise but the distinction is clear in the falling

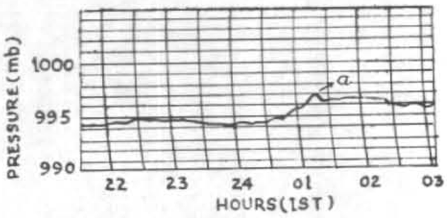

Fig. 12. Chart of N.P.L. (Station No. 3)
a=Nose

pressure period. It can also be seen that the pressure at the station continued to fall but very slowly after the overhead cloud had moved away (the precipitation had ceased) for the next two hours even though the temperature remained constant at the lower level.

Sequence charts for studying the mesoscale pressure systems of thunderstorms were prepared for all the thunderstorm days. However, it was found that the network was too small to study the changes in the pressure pattern caused by a thunderstorm during its entire life cycle. Only major changes associated with mature storms could be followed with some certainty. Two sets of sequence charts are given in Figs. 13 and 14.

These charts are prepared at 15-minute intervals commencing from a time just prior to the occurrence of the thunderstorm sequence. The elements presented are —

PPP — Standardised station level pressure in mb upto the first decimal place. (The figure 9 in hundreth place is omitted). (The pressures were standardised by fixing the station level pressure of Safdarjung just prior to the occurrence of the thunderstorm activity, as the station level pressure at all the stations)

P_cP_c — Change in pressure during the preceding 15 minutes

TT — Dry bulb temperature

RR — Rainfall in full millimetres over a period of 15 minutes centred on the time of chart (a measure of the intensity of rainfall occurring at the time of chart)

Surface winds are plotted when available.

Fig. 13 — This sequence of charts refers to a case when the ground weather at the stations in the network is chiefly dominated by a single thunderstorm. On 7 July 1961 a large thunderstorm moved from WSW to ENE across the middle of the network. Apparently the storm reached the mature stage just before it came over Palam and the

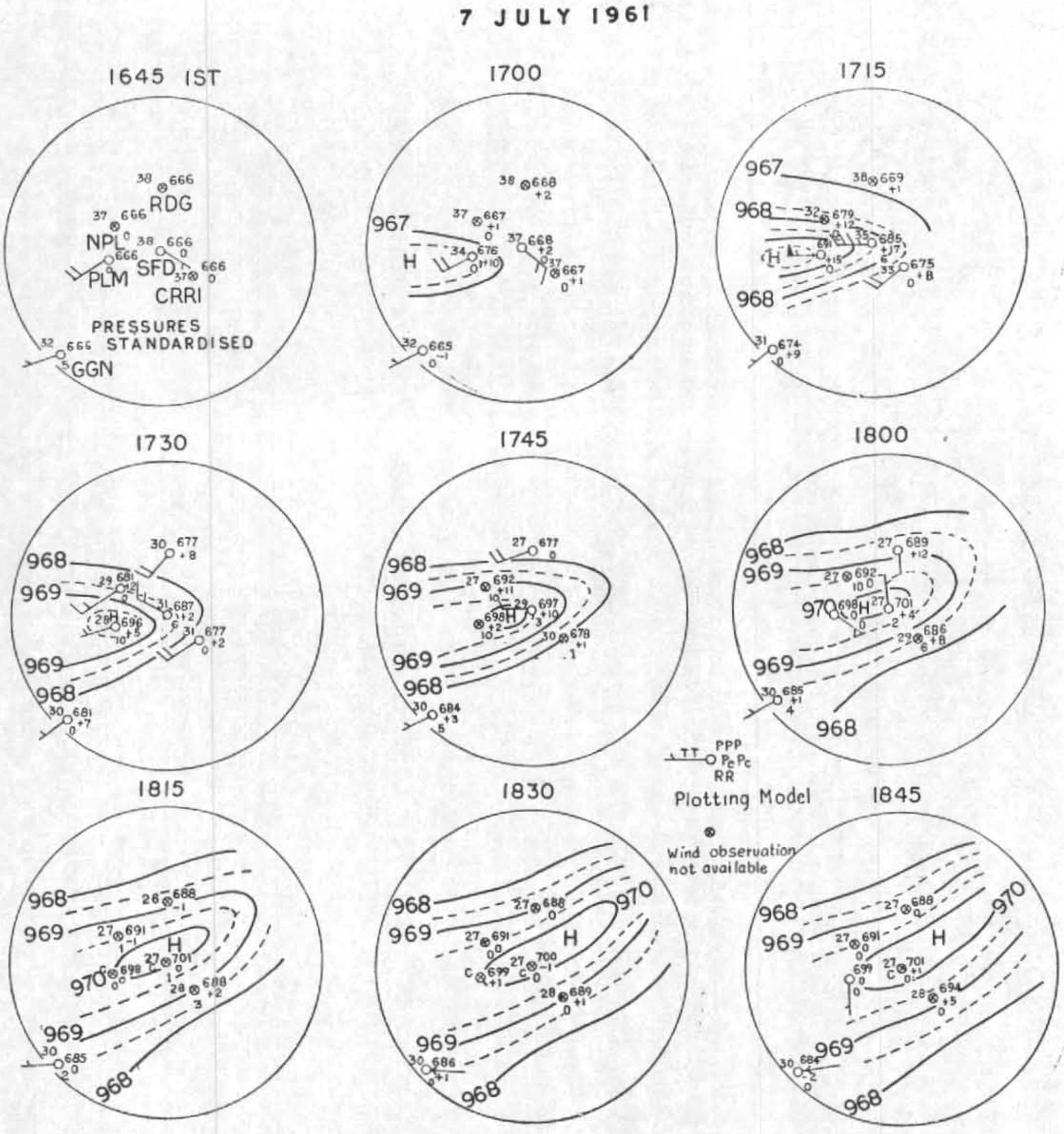

Fig. 13. Development of mesoscale pressure system in association with the passage of an isolated storm moving from WSW to ENE

RDG — Ridge Observatory
NPL — National Physical Laboratory
SFD — New Delhi MMO (Safdarjung)
PLM — Palam MMO
CRRI — Central Road Research Institute
GGN — Gurgaon Observatory

PPP — Station level pressure in tenths of a millibar (First 9 omitted)
P_cP_c — Pressure changes during the last 15 minutes
TT — Temperature in degrees Centigrade
RR — Rainfall amount in millimetres, in the last 15 minutes (t — trace only)
C — Wind Calm

associated cold air reached the stations in the network earlier than the storm. As can be seen from the chart, the squall occurred at Palam and Safdarjung much earlier than the precipitation. Apparently the downdraft considerably decreased in intensity even by the time the cloud was overhead Palam. The rapid rise of pressure in the area as the cold air from the downdraft spread out is brought out clearly by the sequence charts.

It is also to be noticed that even during the short period covered by the charts and the small area of the network a number of smaller cells affected the weather at some of the stations (rain at station 1 at 1715, at station 7 etc) apart from the main storm.

Fig. 14 — 20 August 1961 was a day of considerable convective activity and a large number of cells were present in the area. The sequence charts bring

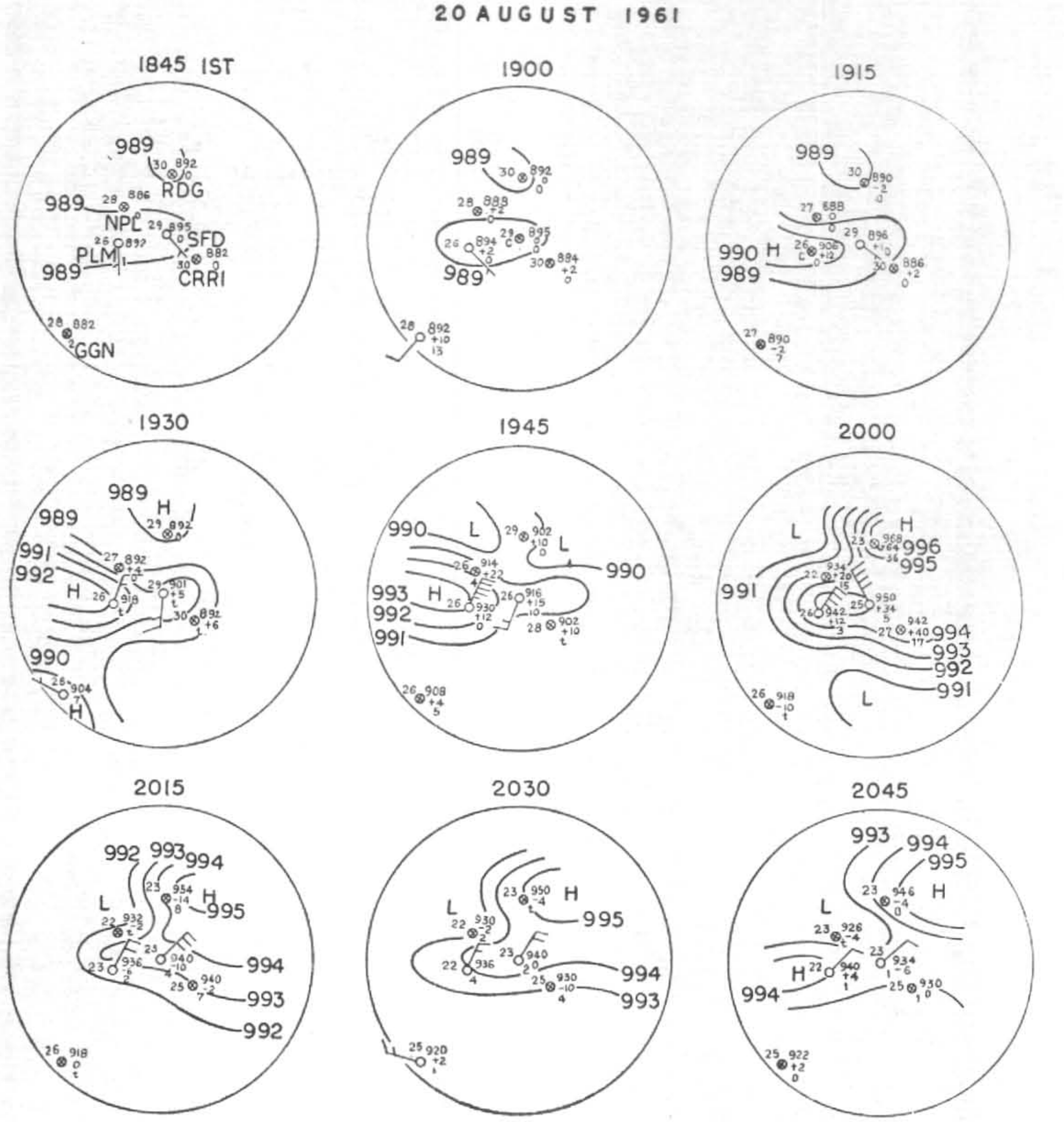

Fig. 14. Development of mesoscale pressure patterns in association with the passage of multistorm system across the network from W to E

(For plotting model and abbreviation used, please see Fig. 13)

out clearly the pressure systems associated with the different thunderstorms which affected the area. The steep pressure gradient associated with the cell which affected Ridge station (No. 4) was spectacular. As the greater part of the thunderstorm area was to the north of Safdarjung and Palam, the cumulative effect of the various downdrafts resulted in strong lateral outflow at these stations for considerably long periods. In both the cases shown in Figs. 13 and 14 the post-storm fall has been partly nullified by diurnal pressure rise. But it is generally noticed that the pressure in the area affected by thunderstorm downdrafts, never comes back to the original undisturbed value for considerably long periods (6–8 hours).

While the above cases deal with storms which caused noteworthy pressure changes, it may be mentioned that on a number of days in July and August, station pressures were unaffected or very slightly affected (less than 0·5 mb) by thunderstorm activity in the area. Such is mostly the case on days of general rainfall and heavy cloudiness, when the only noticeable effect of thunderstorms is to increase the amount of precipitation along their path.

(f) *Temperature and humidity changes*

Changes in the surface temperature and humidity occur only during the mature stages of the thunderstorm. The advent of the downdraft air is

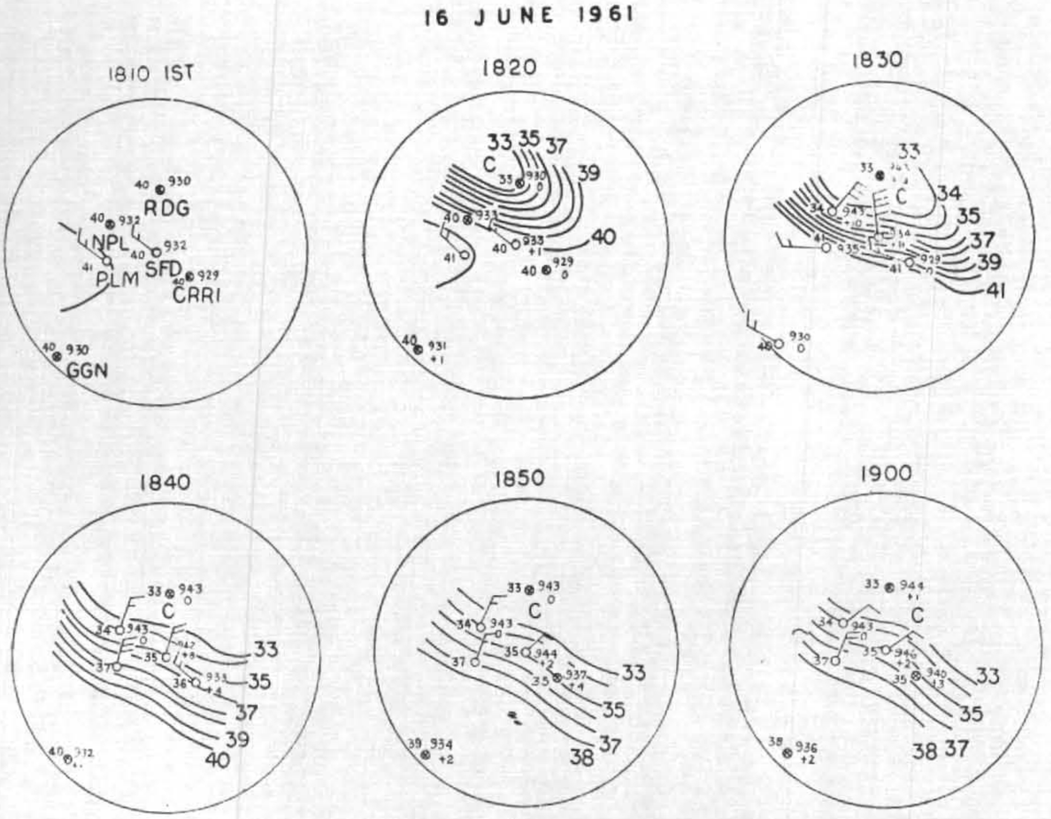

Fig. 15. Isotherms showing propagation of cold air
(Movement of storm — from WNW to ESE)

accompanied by a sharp fall in temperature and a sharp rise in humidity.

In the pre-monsoon season, the maximum temperature in Delhi area is normally around 40°C and the relative humidity during the afternoon period is about 20 per cent. The duststorms are usually accompanied by a temperature fall 3° to 6°C, and a humidity rise of 10–25 per cent. On days, when slight precipitation also occurs at the station, the changes are more pronounced. Temperature drops of 10°—12°C and rises in R.H. of 40–50 per cent are not uncommon on such occasions. But even in these cases the humidity seldom reaches saturation.

During the monsoon season, the maximum temperatures are around 35°C and the humidity is usually around 60 per cent during the afternoon hours on days of light clouding. On such days, the temperature fall is usually of the order 2° to 5°C and the humidity reaches saturation during the thundershowers. However, on days of general cloudiness and rainfall, the thundershowers usually do not cause any noticeable change of the surface temperature.

In Fig. 15, the propagation of cold air across the network is shown by sequence charts prepared at 10-minute intervals. The storm moved from WNW to ESE just touching the Ridge station. The downdraft apparently started first at that station. The storm gave light rain. Fig. 16 shows the advance of the pressure surge line, as the cold air flowed across the network as shown in Fig. 15. The diagram to the left shows the isochrones of the advance. The actual barograph traces are shown on the right, placed in the order of their distance from the storm.

7. Conclusions and results

The present study of the mesoscale features of summer thunderstorms around Delhi area has revealed the points given below—

(1) The summer thunderstorms of Delhi area are mesoscale phenomena whose linear dimensions are of the order of 10 km,

(2) They usually contain 3 or 4 primary convective cells,

(3) A radar patch may contain several major convective cells, each of which retains its own life cycle and dominates the ground weather in its vicinity,

(4) The winds at all levels from the sub-cloud layer to the top of the cloud contribute to its movement,

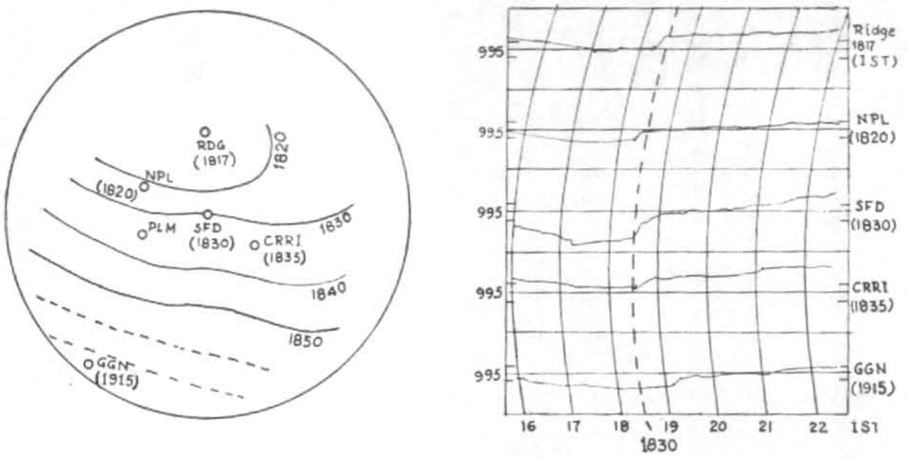

Fig. 16

Isochrones showing propagation of pressure jump line (16 June 1961)

Barographs showing the time of commencement of pressure jumps (16 June 1961)

(The number in brackets shows the time in IST)

RDG — Ridge Observatory, NPL — National Physical Laboratory
SFD — New Delhi MMO (Safdarjung), PLM — Palam MMO
CRRI — Central Road Research Institute, GGN — Gurgaon Observatory

(5) The chief feature of the downdraft wind field is its asymmetry, with the highest winds in the forward sector of the cloud,

(6) The directions of the recorded squalls are within 60° of the direction of movement (from) of the cloud on about 75 per cent of the occasions and between 60° and 120° on about 25 per cent of the occasions,

(7) The wind fields caused by convective clouds are very localised in space, highly variant in time and transient in duration,

(8) The areal dimensions of the mesoscale pressure systems caused by the thunderstorms are of the same size as the thundercloud in the initial stages of the mature thunderstorm. But the spreading of the downdraft cold air causes both an areal expansion of the pressure High and a decrease in its absolute pressure value,

(9) The pressure gradients caused by the thunderstorms reach on some occasions values which are two orders of magnitude greater than the normal synoptic gradients,

(10) Except for an increase in precipitation, thunderstorms do not have any discernible effect on the ground weather at stations over which they pass on days of general cloudiness and precipitation.

Due to the limitations of this pilot scheme, some of the conclusions arrived at may have to be treated as tentative.

8. Acknowledgements

This pilot project was formulated at the instance of Shri P. R. Krishna Rao, Director General of Observatories (retired), to whom the authors wish to express their grateful thanks for the opportunity given to them for this study. They wish to acknowledge the kind co-operation extended by Shri A. K. Roy, Officer-in-charge of the Cloud Physics Unit of the National Physical Laboratory, Delhi and the permission to use the radar observations of that unit. They are also thankful to Dr. P. Koteswaram for going through the manuscript and giving helpful suggestions.

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