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Some features of Squalls at Delhi

Y. P. R. BHALOTRA

Regional Meteorological Centre, New Delhi

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ABSTRACT. The paper contains a discussion on the local upper winds and the upper air temperatures and humidities on the days of squalls and the mechanism of squalls at Delhi. The direction of upper winds at various levels and in different months, which are favourable for the development of squalls have been stated. The correspondence between the direction of the upper winds at various levels and the direction of the following squall has also been given. An examination has been made of the relevant radiosonde data available from the routine ascents at New Delhi and the changes occurring in the upper air temperatures and humidities, prior to the passage of squalls, noted. Synoptic charts for the squally days have been studied in detail and the main factors responsible for the occurrence of squalls in different seasons, stated.

1. Introduction

The present paper is supplementary to the author's earlier paper (1954) and discusses the more interesting features relating to the development of squalls at Delhi. A detailed study has been made of the local upper winds and upper air temperatures and humidities on squally days and also the general synoptic conditions prevalent on such days, in order to determine the factors which are favourable for the occurrence of squalls at Delhi. The subject of squalls at Delhi assumes special importance in view of the fact that a large number of squalls, particularly during the hot months April–June when these are most frequent, are accompanied with duststorms which, in addition to the usual hazards associated with thunderstorms, offer another major hazard of bad visibility which reduces almost to zero in the severer types and the raised dust remains suspended in the air for hours together.

The statistics given in this paper are based on the data for the years 1944 to 1952, except when otherwise stated.

2. Direction of upper winds on days of squall

The percentage frequencies of the direction of upper winds over Delhi at 1·0, 1·5, 2·0, 3·0, 4·5 and 6·0 km, for different months, on the days of squalls and on normal days are given, separately for morning* and afternoon* winds, in Appendix 1. Morning winds have been taken for occasions when squalls occurred on the same day after the morning pilot balloon ascent, and afternoon winds when squalls occurred on the same day after the afternoon pibal balloon ascent. The percentage frequencies for normal days have been taken from the India Met. Dep. Normals (1943–50). The results of the comparison of upper winds on normal days and squally days are given below.

January-March—SE/E'ly winds upto 1·5 km, S/SW'ly at 2·0 km and SW/W'ly at 3·0 and 4·5 km, are predominant on squally days, both in the morning and afternoon. At 6·0 km, SW/W'ly winds in the morning and W'ly in the afternoon are more predominant. NW'ly winds are practically absent on squally days at all levels. The W'ly wind is most predominant at 3 km and above on normal days but on squally days there is a relative decrease in its frequency at 4·5 and 6·0 km in the morning and 3·0 and 4·5 km in the afternoon and a very large increase in the frequency of SW'ly wind. The SW'ly wind at these levels may, therefore, be considered as a greater guide for purposes of forecasting squalls.

*Morning winds refer to pilot balloon ascents made between 0100 to 0200 GMT and afternoon winds to ascents made between 0900 to 1000 GMT generally

April—E/SE'ly winds upto 1 km and SW'ly at 1·5 km in the morning and SE/S'ly upto 1·5 km in the afternoon are more favourable for the development of squalls. At 2·0 to 4·5 km, W/NW'lies remain predominant in the morning, as on normal days, but there is an increase in the frequency of SW'lies at 2·0 and 3·0 km; in the afternoon SW/W'lies are most predominant at these levels. There is a marked decrease in the frequency of NW'lies upto 1·5 km in the morning and upto 4·5 km in the afternoon and as such NW'lies at these levels may be considered as unfavourable for the development of squalls.

May—W'ly winds at 2 km and SW/W'ly winds at 3·0 to 6·0 km in the morning and W'ly at 2·0 and 3.0 km and SW/W'ly at 4·5 and 6·0 km in the afternoon, are more predominant.

June—W'ly wind upto 2·0 km in the morning and from 2·0 to 6·0 km in the afternoon, is most predominant on squally days.

July—W'ly wind at 1·5 km and NW'ly at 2·0 and 3·0 km in the morning and E'ly or W'ly winds upto 1·5 km and E'ly or NW'lies at 2·0 and 3·0 km in the afternoon, are more significant on squally days.

August—NW'ly wind at 1·0 and 1·5 km and N/NE'lies at 2·0 to 4·5 km in the morning and SE'ly or W'ly wind at 1·0 km and W/NW'lies at 1·5 and 2·0 km in the afternoon, are more favourable for the occurrence of squalls.

September—SE'ly or W'ly wind at 1·0 and 1·5 km, SE'ly at 2·0 km, and W/NW'lies at 3·0 and 4·5 km, in the morning and SW/W'lies or NE'lies at 1·0 and 1·5 km and W/NW'lies at 2·0 km in the afternoon, are more significant.

October—The number of observations available for this month is too small to give definite results. However, E/SE'lies at 1·0 km, SE/S'lies at 1·5 km and E/NE'lies at 2·0 and 3·0 km in the morning and E/SE' lies at 1·0 and 1·5 km and S/SW'lies at 2·0 km, in the afternoon, appear to be more predominant on squally days.

TABLE 1

	Height (km)				
	1·5	2·0	3·0	4·5	6·0
Morning winds	30 (113)	40 (105)	45 (80)	25 (41)	20 (35)
Afternoon winds	30 (106)	40 (100)	40 (91)	55 (63)	45 (47)

NOTE:—Figures within brackets indicate the total number of occasions

TABLE 2

Height (km)				
1·5	2·0	3·0	4·5	6·0
35 (90)	45 (88)	50 (67)	60 (39)	40 (17)

NOTE:—Figures within brackets indicate the total number of occasions

3. Correspondence between direction of upper winds and direction of squall

The percentage frequencies of the total number of occasions when the direction of the squall was nearly the same (within $22\frac{1}{2}°$) as the direction of the upper wind at a particular level, prior to the occurrence of squalls, are given in Table 1.

It would appear that the direction of the morning wind at 3 km and that of the afternoon wind at 4·5 km correspond more closely to the direction of the following squall than winds at other levels.

An examination of the pilot balloon ascents taken within 3 hours prior to the passage of squalls gives the results as in Table 2.

There is little correspondence between the direction of the squall and the direction of the resultant wind between 4·5 and 0·3 km prior to its occurrence. In only 25 per cent of the above cases the direction of the squall was similar to that of the resultant wind.

TABLE 3

Morning winds

		Height (km)									
		1·0		1·5		2·0		3·0		4·5	
		(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Mar	N	55	15·6	51	18·6	43	17·4	30	20·6	60	26·2
	Sq	61	13·1	61	14·9	58	13·5	71	16·9	80	25·8
Apr	N	52	15·4	45	16·0	45	18·0	34	19·2	90	27·8
	Sq	55	14·3	72	11·7	65	12·5	60	10·8	100	14·5
May	N	55	15·2	60	14·0	56	14·6	43	17·6	80	23·0
	Sq	60	13·9	75	11·5	78	11·7	65	13·0	90	19·6
Jun	N	46	18·4	53	15·2	55	14·2	58	13·8	80	15·8
	Sq	50	16·9	55	15·0	62	13·2	62	12·4	90	14·0
Jul	N	46	15·8	60	14·2	60	13·8	70	10·2	81*	12·0
	Sq	41	16·4	56	13·8	60	11·3	75	8·4	85	7·0
Aug	N	54	14·8	70	12·2	74	11·4	80	10·0	89*	9·3
	Sq	70	8·0	100	6·5	100	4·5	100	3·8	100	5·5

N—Normal days, Sq—Squally days, (a) Percentage frequency, (b) Average speed in knots

*These figures relate to speed of $\leqslant$ 14 knots

TABLE 4

Afternoon winds

		Height (km)									
		1·0		1·5		2·0		3·0		4·5	
		(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Mar	N	74	11·2	65	12·6	55	15·0	29	20·0	53	31·0
	Sq	75	9·6	70	11·0	70	10·7	46	15·8	70	24·4
Apr	N	64	12·4	65	12·4	63	13·4	38	17·8	76	25·2
	Sq	82	9·2	90	9·8	71	10·4	45	15·4	80	21·8
May	N	70	12·4	69	13·0	62	14·0	40	17·6	74	25·2
	Sq	76	11·0	76	11·8	62	13·4	40	17·6	60	25·4
Jun	N	70	12·0	70	12·0	68	12·8	45	16·5	85	20·6
	Sq	80	11·4	75	11·4	80	11·1	45	15·0	91	18·3
Jul	N	78	10·6	70	11·6	68	12·2	68	12·4	97	11·6
	Sq	85	8·4	80	9·6	70	11·8	70	12·0	100	9·0
Aug	N	80	10·2	78	11·4	72	11·8	75	11·4	96	10·3
	Sq	70	10·4	80	10·0	86	9·2	100	10·0	..	..

N—Normal days, Sq—Squally days, (a) Percentage frequency, (b) Average speed in knots

TABLE 5

	Height (km)				
	1·0	1·5	2·0	3.0	4·5
March	8·2	10·3	8·6	15·2	22·4
April	9·0	9·1	10·2	15·3	21·8
May	9·4	9·3	11·6	14·0	22·7
June	9·9	10·2	9·7	14·0	15·2

TABLE 6

	Height (km)				
	1·0	1·5	2·0	3·0	4·5
May	9·4	9·5	11·8	16·0	23·1

4. Speed of upper winds on squally days

Percentage frequencies of the total number of occasions when the speed of upper winds was ⩽14 knots at heights of 1·0 to 3·0 km and ⩽28 knots at 4·5 km and also the average speeds in knots (at 1·0 to 4·5 km) on normal and squally days are given in Tables 3 and 4 separately for morning and afternoon winds, for the months of March to August. The number of observations available for the months of January, February, September and October are too few to give reliable results. The values for the normal days have been taken from the India Met. Dep. Normals.

Average speed of afternoon upper winds on days during the period, March—June when squalls occurred within 3 hours following the afternoon pilot balloon ascent are given in Table 5.

The average speeds of afternoon upper winds on days when severe squalls (peak velocity ⩾50 mph) occurred within 3 hours following the pilot balloon ascent, during the month of May, are given in Table 6.

A comparison was also made of the speed of the resultant wind between 4·5 km and 0·3 km, on the above days of squall, with the normal resultant velocity in this layer, in the month of May. It is seen that in 80 per cent of the cases, the resultant velocity on squally days was less than the normal resultant velocity and in the remaining 20 per cent of the cases, it was almost equal to the normal resultant velocity.

It is seen that (*i*) The average speed of upper winds, both morning and afternoon, is on most of the squally days, almost equal to or less than the average speed of normal winds. The number of occasions on which upper winds on squally days are stronger than the normal winds is small, (*ii*) The upper winds have a tendency to become somewhat lighter shortly before occurrence of squalls, (*iii*) Lighter upper winds do not mean that the following squall will be severer, as the speed of upper winds prior to the passage of severe squalls is almost the same at all levels as the speed of winds prior to the occurrence of other squalls, (*iv*) There is no relation between the ground speed of the squall and the speed of upper winds prevailing prior to its passage as may be seen from Table 7.

That the speed of upper winds decreases before the occurrence of squalls may, perhaps, be due in a number of cases to the presence of a line of upper wind discontinuity near the station, which is one of the most important factors leading to the development of squalls at Delhi, as well be discussed under the mechanism of squalls in Section 8.

5. Upper air humidity on squally days

The percentage frequencies of the total number of occasions when the humidity mixing ratio at a particular level was above a certain value on normal days and on squally days are given in Table 8. The data from the latest available radiosonde ascent prior to the occurrence of squalls have been used in working out the figures for squally days. The percentage frequencies of mixing ratio for the normal days have been obtained from the India Met. Dep. Normals. The values of mixing ratio have been fixed so as to include most of the squally days. It will be seen that there is generally an increase in the upper air humidities, particularly

TABLE 7

Date	Time of squall (GMT)	Time of p.b. ascent (GMT)	Speed of squall (Knots)	Speed of upper winds (knots) at 0·3	0·6	1·0	1·5	2·0	3·0	4·5	6·0 km
20 May 1950	1130	0900	60	7	9	5	6	9	13	17	11
3 Jun 1952	1435	0900	38	23	26	29	28	20	31	27	37
2 Aug 1952	0715	0200	40	4	4	4	5	5	3	6	3
		0900		2	3	2	1	2	6	..	..

TABLE 8

		900 mb	850 mb	700 mb	600 mb
†Jan–Feb	Mixing ratio (in gm/kgm)>	6	5	4	*
	N	40	45	35	*
	Sq	90	70	75	*
March	N	55	60	45	*
	Sq	100	90	80	*
April	Mixing ratio>	5	5	4	
	N	50	40	40	22
	Sq	80	70	75	100
May	Mixing ratio>	7	7	6	4
	N	63	50	40	50
	Sq	80	70	70	70
June	Mixing ratio>	12	12	8	6
	N	50	35	45	30
	Sq	70	60	70	65
July	Mixing ratio>	18	18	10	7
	N	55	25	65	60
	Sq	80	70	80	60
August	Mixing ratio>	18	18	10	7
	N	50	15	60	55
	Sq	80	60	80	50
September	Mixing ratio>	16	14	10	7
	N	50	50	30	40
	Sq	70	70	60	60
October	Mixing ratio>	10	10	6	
	N	25	15	25	*
	Sq	70	60	100	*

N—Normal days, Sq—Squally days

*No. of observations at this level is too small to give reliable results

†These months have been grouped together as the number of squally days during this period is small and these belong to the same season with same temperatures at all levels

TABLE 9

Height (mb)	Jan-Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
900	40 (90)	40 (75)	20 (85)	20 (85)	40 (75)	70 (80)	 (80)	60 (70)	45 (80)
850	40 (85)	40 (75)	25 (75)	25 (80)	40 (75)	75 (75)	85 (80)	60 (85)	45 (70)
700	60 (85)	60 (75)	40 (75)	40 (80)	60 (70)	75 (85)	75 (85)	60 (85)	60 (75)

NOTE—(1) Figures without bracket denote relative humidity (%)
(2) Figures within the bracket denote percentage frequency of the total number of occasions to which the value of relative humidity relates

upto 700 mb prior to the occurrence of squalls, on the day of squall or the day before. As will be discussed under the mechanism of squalls (Section 8), the increase in the humidities is mainly due to the incursion of moisture associated with the passage of western disturbances or their secondaries or the approach of monsoon or post monsoon depressions. As the radiosonde data used in the above table relate to ascents made, sometimes several hours prior to the occurrence of squalls, the actual values of the humidities at the time of squall may in many cases be higher than those given in Table 8.

6. Relative humidity on squally days

It is seen that the mean monthly upper air temperatures at all the standard levels on squally days (derived from the latest available routine radiosonde ascents, prior to the passage of squalls) are almost the same as the normal temperatures at these levels, for all the months. The percentage frequencies of the total number of occasions when the relative humidity was above a certain value, at any level, on squally days and on normal days will, therefore, be practically in the same ratio as the figures given in Table 8. Table 9 gives the minimum values of relative humidities prevailing at 900, 850 and 700 mb on most of the squally days.

7. Upper air temperatures on squally days

A comparison was made of the latest available upper air temperatures prevailing at the standard levels of 700, 600, 500 and 400 mb prior to the occurrence of squalls, and the temperatures obtaining at these levels on the previous day, in order to find if any significant change in upper air temperatures took place, prior to the passage of squalls. Table 10 gives the percentage frequency of the total number of occasions when a change (rise or fall) of more than 5°F, occurred at one or more of the standard levels in the layer 700—400 mb (with little or no change at other levels in this layer) during different seasons of the year.

TABLE 10

Period	Fall of more than 5°F	Rise of more than 5°F	Insignificant change	Total number of occasions
Jan—Mar	32	16	52	23
Apr—Jun	30	14	56	63
Jul—Sep	26	13	61	24
Oct	50	16	33	6

The percentage frequencies corresponding to a significant fall of 9°F or more, are given in Table 11.

TABLE 11

Jan-Mar	Apr-Jun	Jul-Sep	Oct
20	15	13	33

An examination of upper air temperatures on occasions when squalls occurred within about 3 hours following the radiosonde ascent, gives the following results (Table 12).

TABLE 12

Fall of 9°F or more	Fall of 5°F	Rise of 5°F	Insignificant change	Total No. of occasions
18	32	18	50	22

It may be mentioned in this connection that the squalls prior to which significant fall of upper air temperatures occurred were generally not severer than other squalls.

8. Mechanism of squalls at Delhi

The mechanism of squalls at Delhi during different seasons is discussed below. The air mass terminology as used in this discussion is after Roy (1946).

(*a*) *Winter period* (*December–March*)

In this season the usual air mass over northwest India is the dry cold Polar Continental Transitional (NP_c) air flowing in more or less westerly or northwesterly streams. Occasionally, under influence of a western disturbance or a secondary western disturbance, moist and comparatively warmer $\overline{T_m T_c}$ air (its depth depending on the intensity and latitudinal position of the disturbance) invades northwest India or parts of this region, as a southerly stream, causing weather. In most of the cases the moisture is pulled up from the Arabian Sea, directly under the influence of a passing western disturbance (or an induced secondary) and rarely in association with a low pressure area over northeast Arabian Sea and neighbourhood. On a few occasions, moisture travels into the area of the western disturbance, from the Bay of Bengal also, actuated by a well marked high pressure cell over Vindhya Pradesh, east Madhya Pradesh or Orissa and neighbourhood.

The following appear to be the main causes responsible for the occurrence of squalls at Delhi, during the winter season, as revealed by a study of the synoptic situations in each individual case.

(*i*) Presence close to Delhi or passage across Delhi of a well-marked line of upper wind discontinuity associated with an active western disturbance or a secondary western disturbance.

(*ii*) Development of a marked discontinuity at Delhi between dry and cold N'lies (NP_c or P_c) in the rear of an active western disturbance moving eastwards across northern parts of the country, particularly eastern parts of the Punjabs, and moist and comparatively warmer S'lies.

(*iii*) *Insolation*—This factor was operative only in the later part of March. The squalls of this type are generally known as the air mass type, occurring in the afternoon, mainly owing to insolational trigger.

The percentage frequencies of the total number of occasions when the above causes were effective in giving rise to squalls, are given below—

Cause (*i*)	Cause (*ii*)	Cause (*iii*)	Total number of occasions
35	51	13	31

It may be mentioned in this connection that the following factors which help development of thunderstorm cell, were also present on some of the occasions—

(1) *Advection of cold air in the upper levels*—On 20 per cent of the occasions, significant advection of cold air took place in the upper levels prior to the occurrence of squalls, the main causes of development of squalls being (*i*) or (*ii*) above.

(2) *Under cutting of warm moist air by a shallow layer of cold air flowing out of a near thunderstorm cell*—In the absence of a radiosonde ascent very close to the time of occurrence of squall and prior to it, it is not possible to say with sufficient degree of confidence, on how

many of the occasions, this factor was operative in the development of squalls. However out of 7 ascents which happened to be within 3 hours prior to the passage of squalls, on 2 occasions this factor also appeared to be functioning. Both these occasions happen to fall under category (*iii*) above.

(*b*) *Hot* (*Pre-monsoon*) *period* (*April–June*)

During this season, the wind pattern at the higher levels continues to be similar to that of the winter period but a reversal of wind circulation takes place in the lower levels. A trough of low develops over northern India, in the lower layers, in April. With the advance of the season, this heat low gets accentuated and shifts more westwards and is fully established over northwest India and adjoining Western Pakistan by the middle of May. The usual air mass over northwest India is the hot dry Tropical Continental (T_c) air, with nearly dry adiabatic lapse rate upto a height of 3 to 4 km and with super-adiabatic lapse rate developing in the afternoons in the first half to one kilometre, owing to intense insolation. Marked turbulence in the afternoon scoops out large quantity of loose dust from the ground to considerable height, causing poor vertical visibility obscuring the sky. Occasionally, in association with a western disturbance on an induced secondary low or a westerly upper air trough of low or owing to accentuation of the seasonal heat low, a sufficiently deep influx of $\frac{T_m}{T_c}$ air takes place into northwest India from the Arabian Sea. Owing to humidification in the lower levels $\frac{T_m}{T_c}$ air mass acquires a higher wet bulb temperature which together with high lapse rate that prevails in the upper T_c air, causes atmosphere to develop marked latent instability and if a suitable trigger is present, the energy of latent instability is realised. Owing to very unstable structure of the atmosphere during this season the severest types of squalls (associated with duststorms and thunderstorms) occur during this period.

The principal factors leading to development of squalls during this period are as follows. Owing to large number of squalls occurring during this period, the month of May has been taken to be representative of this period and only the squalls occurring in this month during the period 1945-52, have been studied.

(*i*) Development of a discontinuity at Delhi. between dry N/NW'lies in the rear of an active western disturbance moving eastwards through the Punjabs particularly the Punjab hills, and moist S/SW'lies drawn under influence of an induced secondary low or a trough of low over Sind/Rajasthan or due to accentuation of the seasonal low over northwest India.

(*ii*) Presence close to Delhi or passage across Delhi of a well-marked upper wind discontinuity associated with a western disturbance or secondary western disturbance.

(*iii*) *Insolation*—The strong insolation during this season acts as an important trigger for the development of squalls.

The percentage frequencies of the total number of occasions when the above causes were operative, are shown below—

Cause (*i*)	Cause (*ii*)	Cause (*iii*)	Total number of occasions
50	17	31	70

It may be mentioned in this connection that on only 15 per cent occasions, significant advection of cold air took place at the upper levels prior to the occurrence of squalls. Evidence of undercutting by cold air is available only on one occasion.

(*c*) *Monsoon period* (*July–September*)

The normal isobaric situation in the southwest monsoon period is the seasonal heat low over northwest India and Western Pakistan with two, more or less stationary, closed low pressure cells, one over Baluchistan and the other over N.W.F.P. Associated with this heat low is the monsoon trough, over the Gangetic Valley extending from southwest Bengal to southeast Punjab(I). There are occasional variations in the intensity and position of the monsoon trough, mainly in association with depressions forming at the southeast end of this trough in the Bay of Bengal and sometimes in the northeast Arabian Sea, and these variations determine the type and the spatial distribution of the monsoon weather. Occasionally, with the seasonal low over Baluchistan becoming well-marked, mostly under influence of a westerly low pressure wave moving eastwards across extreme north of the country, fresh surges of monsoon air from the Arabian Sea, take place into northwest India.

Following are the *main* factors which cause squalls at Delhi, during the monsoon period.

(*i*) Development of a discontinuity close to Delhi between W/NW'ly T_c air extending S/SE wards during periods of weak monsoon over northwest India and the advancing E/SE'ly current moving W/NWwards under influence of a Bay depression, so that the axis of the monsoon trough is at or near Delhi.

(*ii*) Development of a discontinuity between NW/N'ly T_c air extending S/SE-wards in the rear of a secondary western disturbance, during periods of weak monsoon and the S'ly monsoon current from the Arabian Sea pulled up under influence of the seasonal low over Baluchistan and Sind, becoming well-marked.

(*iii*) Effect of insolation on the old Bay of Bengal or Arabian Sea monsoon air mass prevailing over Delhi.

(*iv*) Accentuation of the monsoon trough during the late night or early morning owing to nocturnal cooling of the submontane districts of Uttar Pradesh and the Punjab(I) causing a fresh surge of monsoon air from the Bay of Bengal over Delhi.

The percentage frequencies of the total number of occasions when each of the above factors was mainly responsible for the occurrence of squall, are given below—

Cause				Total number of occasions
(*i*)	(*ii*)	(*iii*)	(*iv*)	
40	10	40	10	38

On only 13 per cent of the above occasions significant advection of cold air took place at the upper levels, prior to the occurrence of squalls.

(d) Post monsoon period (October--November)

This is a transitional period during which the winter conditions are gradually established over northwest India. The usual air mass over northwest India is the T_c air with occasional incursions of NP_c air travelling southwards in the rear of an active western disturbance moving eastwards through extreme north of the country. Sometimes an influx may take place into northwest India of $E_m T$ air mass from the Bay of Bengal under influence of a depression moving inland in a northwesterly direction, or of $\underline{T_m} \ \overline{T_c}$ air mass from the Arabian Sea pulled up during the passage of a secondary western disturbance or an upper air trough of low or presence of a low pressure area in the northeast Arabian Sea. Under such conditions thunderstorms with squalls may occur over northwest India mainly by frontal interaction of $E_m T$ or $\overline{T_c} \ \underline{T_m}$ air-mass with T_c or NP_c air mass and partly as a result of instability which develops by the over running of the lower warm and moist air by the cold and dry tropical or extra-tropical continental air above.

Following are the main causes responsible for the development of squalls at Delhi, during the post monsoon period. No squalls occurred at Delhi in the month of November during the period in question, and the results of the study refer only to a few squalls which occurred during the month of October.

(*i*) Development of a discontinuity close to Delhi between NW/N'ly T_c or NP_c air and SW'ly $\underline{T_m \overline{T_c}}$ air from the Arabian Sea.

(*ii*) Development of a discontinuity close to Delhi between NW/N'ly T_c or NP_c air and S/SE'ly $E_m T$ air from the Bay.

(*iii*) Presence close to Delhi or passage across Delhi of a well marked upper wind discontinuity associated with a secondary western disturbance.

The percentage frequencies when the above causes were operative are given below—

Cause			Total number of squalls
(*i*)	(*ii*)	(*iii*)	
50	37	12	8

On 33 per cent of the above occasions significant advection of cold air took place at the upper levels, prior to the occurrence of squalls.

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APPENDIX 1

Percentage frequency of upper winds over New Delhi on normal days and squally days

(Morning winds)

Height (km)	Days	N	NE	E	SE	S	SW	W	NW	No. of observations
					JANUARY to MARCH					
1·0	N	7	3	2	6	7	7	12	51	—
	Sq	0	6	0	35	30	12	12	6	17
1·5	N	7	2	2	3	8	9	21	47	—
	Sq	0	0	0	12	53	12	17	6	17
2·0	N	4	1	1	2	5	12	29	43	—
	Sq	0	0	0	0	30	47	23	0	17
3·0	N	3	0	1	0	3	17	40	35	—
	Sq	0	0	6	0	19	31	44	0	16
4·5	N	1	0	0	1	2	14	64	16	—
	Sq	0	0	0	0	0	57	43	0	7
6·0	N	2	0	0	0	0	12	62	24	—
	Sq	0	0	0	0	0	50	50	0	6
					APRIL					
1·0	N	9	2	3	8	4	4	15	50	—
	Sq	0	0	23	28	5	9	14	22	22
1·5	N	4	0	3	2	5	3	20	60	—
	Sq	0	9	14	9	9	23	18	18	22
2·0	N	5	2	1	1	3	5	30	50	—
	Sq	5	0	0	5	9	14	32	36	22
3·0	N	5	2	1	0	3	11	36	43	—
	Sq	5	0	0	0	5	19	33	38	21
4·5	N	9	0	2	0	2	5	55	30	—
	Sq	0	0	0	0	0	0	50	50	6
6·0	N	5	0	0	0	0	5	64	22	—
	Sq	0	33	0	0	0	0	67	0	3
					MAY					
1·0	N	11	2	3	7	6	9	25	32	—
	Sq	9	4	0	15	15	7	24	26	46
1·5	N	8	3	1	4	4	9	26	40	—
	Sq	9	2	2	2	13	13	35	22	46
2·0	N	9	2	0	0	2	6	27	49	—
	Sq	5	0	0	2	12	9	50	21	42
3·0	N	9	0	1	1	1	6	32	48	—
	Sq	3	3	0	0	0	20	51	23	35
4·5	N	13	2	0	0	0	6	34	44	—
	Sq	0	0	0	0	10	20	55	25	20
6·0	N	16	0	4	0	0	4	50	27	—
	Sq	0	0	0	0	10	30	50	10	10
					JUNE					
1·0	N	7	2	2	13	6	5	26	36	—
	Sq	5	3	3	3	3	13	51	21	39
1·5	N	10	1	2	4	3	6	26	47	—
	Sq	6	0	0	0	0	9	49	37	35
2·0	N	12	4	4	3	3	4	21	49	—
	Sq	7	0	3	0	0	3	65	23	31
3·0	N	17	4	8	5	2	7	19	37	—
	Sq	17	0	4	0	4	4	35	35	23
4·5	N	24	5	0	3	3	23	16	29	—
	Sq	36	9	0	0	0	9	27	18	11
6·0	N	8	9	4	0	0	39	30	8	—
	Sq	0	0	0	0	0	25	38	37	8

N—Normal days, Sq—Squally days

APPENDIX 1 *(contd)*

(Morning winds)

Height (km)	Days	N	NE	E	SE	S	SW	W	NW	No. of observations
					JULY					
1·0	N	2	2	9	23	4	7	28	20	—
	Sq	0	0	8	15	8	8	42	19	26
1·5	N	5	6	10	18	7	3	21	31	—
	Sq	4	0	4	13	8	4	13	54	24
2·0	N	16	6	19	11	4	2	7	30	—
	Sq	9	5	14	9	5	5	0	52	21
3·0	N	26	11	14	12	6	2	6	18	—
	Sq	22	11	11	22	0	0	22	11	9
4·5	N	7	11	30	15	7	4	11	7	—
	Sq	17	0	33	17	0	17	17	0	6
6·0	N	10	20	0	40	20	0	10	0	—
	Sq	0	0	0	25	75	0	0	0	4
					AUGUST					
1·0	N	4	3	13	24	6	4	16	26	—
	Sq	18	0	9	0	0	0	18	55	11
1·5	N	7	4	22	14	1	2	12	33	—
	Sq	22	0	11	0	11	0	0	55	9
2·0	N	20	9	21	13	3	0	4	21	—
	Sq	50	25	13	0	0	0	0	13	8
3·0	N	20	8	21	13	3	2	5	15	—
	Sq	33	17	17	0	0	0	17	17	6
4·5	N	15	16	12	16	5	3	13	15	—
	Sq	25	25	0	25	0	0	0	25	4
6·0	N	6	11	6	39	6	11	6	6	—
	Sq	0	0	33	33	0	0	0	33	3
					SEPTEMBER					
1·0	N	13	3	9	11	5	3	17	35	—
	Sq	11	0	11	33	0	0	22	22	9
1·5	N	15	11	11	8	3	4	3	44	—
	Sq	11	0	0	33	0	0	22	33	9
2·0	N	26	9	6	6	4	3	6	40	—
	Sq	22	0	0	33	0	0	11	33	9
3·0	N	27	15	10	6	2	1	4	33	—
	Sq	13	25	0	13	0	0	13	37	8
4·5	N	19	6	17	17	4	5	8	11	—
	Sq	0	0	0	0	20	0	20	60	5
6·0	N	6	2	6	5	7	8	22	6	—
	Sq	0	0	0	25	0	0	50	25	4
					OCTOBER					
1·0	N	13	4	6	14	9	5	14	32	—
	Sq	0	0	33	33	0	17	0	17	6
1·5	N	18	7	4	3	3	5	12	47	—
	Sq	17	17	0	17	17	17	0	17	6
2·0	N	15	5	7	3	2	4	14	46	—
	Sq	0	17	17	0	17	0	17	33	6
3·0	N	17	9	5	3	3	4	14	40	—
	Sq	0	17	33	0	0	0	17	33	6
4·5	N	34	3	7	2	1	6	11	38	—
	Sq	0	0	25	25	0	0	50	0	4
6·0	N	12	6	4	3	2	9	42	17	—
	Sq	0	0	0	0	0	33	67	0	3

N—Normal days, Sq—Squally days

APPENDIX 1 *(contd)*

(Afternoon winds)

Height (km)	Days	N	NE	E	SE	S	SW	W	NW	No. of observa-tions
					JANUARY to MARCH					
1·0	N	5	2	4	8	6	6	15	50	—
	Sq	0	5	9	36	23	9	9	9	22
1·5	N	4	1	1	4	8	9	27	44	—
	Sq	0	0	5	24	33	14	19	5	21
2·0	N	3	1	1	2	8	14	32	38	—
	Sq	5	0	0	10	40	35	10	0	20
3·0	N	2	0	0	1	4	18	43	30	—
	Sq	0	0	0	5	17	55	22	0	18
4·5	N	1	1	0	0	1	13	58	26	—
	Sq	0	0	0	0	7	38	46	7	13
6·0	N	0	0	0	0	0	11	68	22	—
	Sq	0	0	0	0	0	17	83	0	6
					APRIL					
1·0	N	6	2	3	6	6	8	25	42	—
	Sq	9	5	9	14	18	9	18	18	22
1·5	N	1	0	0	2	4	12	30	51	—
	Sq	5	0	0	9	32	9	22	23	22
2·0	N	2	1	1	2	7	15	30	40	—
	Sq	0	0	0	9	14	24	38	14	21
3·0	N	2	0	0	1	3	11	46	37	—
	Sq	0	0	0	5	9	19	62	5	21
4·5	N	2	2	1	0	2	8	49	39	—
	Sq	0	0	0	0	0	19	69	13	16
6·0	N	9	1	1	0	0	9	49	34	—
	Sq	0	0	0	0	0	0	75	25	8
					MAY					
1·0	N	8	2	3	9	5	3	28	40	—
	Sq	13	0	9	19	9	9	22	19	32
1·5	N	6	1	2	5	7	7	29	43	—
	Sq	13	0	3	0	23	3	40	17	30
2·0	N	1	1	1	2	6	8	35	46	—
	Sq	7	0	0	3	13	7	47	23	30
3·0	N	2	0	0	1	2	8	42	44	—
	Sq	0	4	0	0	8	11	46	31	26
4·5	N	4	2	0	0	0	4	41	49	—
	Sq	0	0	0	0	0	26	42	32	19
6·0	N	8	0	0	0	0	2	44	46	—
	Sq	0	0	0	0	0	17	67	17	12
					JUNE					
1·0	N	9	3	11	7	3	4	21	36	—
	Sq	9	0	18	5	0	7	18	43	44
1·5	N	9	2	3	3	1	7	28	42	—
	Sq	7	5	13	3	0	3	27	43	40
2·0	N	7	3	6	3	1	6	26	47	—
	Sq	6	0	6	9	3	3	41	32	34
3·0	N	11	3	6	1	3	3	29	43	—
	Sq	10	0	0	0	3	3	48	35	29
4·5	N	15	4	4	0	3	5	22	48	—
	Sq	10	0	0	0	0	0	45	45	20
6·0	N	6	2	1	1	0	19	31	39	—
	Sq	0	0	6	0	0	13	50	31	16

N—Normal days, Sq—Squally days

APPENDIX 1 *(contd)*

(Afternoon winds)

Height (km)	Days	N	NE	E	SE	S	SW	W	NW	No. of observa-tions
					JULY					
1·0	N	7	7	22	17	6	3	16	16	—
	Sq	8	0	37	4	0	4	33	13	24
1·5	N	7	4	15	17	7	7	16	23	—
	Sq	0	0	36	9	0	9	23	23	22
2·0	N	10	7	14	19	3	4	16	25	—
	Sq	6	6	25	6	0	6	13	37	16
3·0	N	11	7	20	11	3	4	10	29	—
	Sq	0	0	33	0	0	8	17	42	12
4·5	N	19	8	19	12	4	5	8	21	—
	Sq	0	0	25	0	0	25	0	50	4
6·0	N	6	9	29	17	3	17	3	9	—
	Sq	50	0	0	50	0	0	0	0	2
					AUGUST					
1·0	N	6	5	21	13	4	3	22	21	—
	Sq	0	0	13	25	0	0	50	13	8
1·5	N	9	3	20	13	2	7	22	16	—
	Sq	0	14	14	4	0	0	29	29	7
2·0	N	8	4	15	18	3	6	18	22	—
	Sq	14	14	0	14	0	0	43	14	7
3·0	N	10	7	16	14	4	2	16	28	—
	Sq	0	0	33	0	0	0	33	33	3
4·5	N	16	10	21	9	3	5	9	25	—
	Sq	0	0	0	0	0	0	100	0	1
6·0	N	10	10	10	8	13	8	21	13	—
	Sq	0	0	0	0	0	0	100	0	1
					SEPTEMBER					
1·0	N	10	7	10	7	2	2	18	42	—
	Sq	0	25	0	0	0	25	50	0	4
1·5	N	10	9	9	7	4	2	12	43	—
	Sq	0	25	0	0	0	0	75	0	4
2·0	N	12	5	7	5	2	3	19	45	—
	Sq	0	0	25	0	0	0	25	50	4
3·0	N	15	5	7	3	2	5	16	43	—
	Sq	0	0	33	0	0	33	0	33	3
4·5	N	12	6	6	3	6	9	21	36	—
	Sq	0	0	0	0	0	50	0	50	2
6·0	N	10	3	2	2	4	15	47	15	—
	Sq	0	0	0	0	0	0	100	0	2
					OCTOBER					
1·0	N	12	5	8	7	3	3	11	44	—
	Sq	0	0	50	25	0	0	0	25	4
1·5	N	3	2	5	3	3	2	21	54	—
	Sq	0	0	33	33	0	33	0	0	3
2·0	N	9	3	4	3	2	6	19	51	—
	Sq	0	0	0	0	33	33	33	0	3
3·0	N	12	5	4	3	2	7	21	46	—
	Sq	0	0	0	0	33	0	33	33	3
4·5	N	10	4	4	3	1	8	29	41	—
	Sq	0	0	0	0	0	50	50	0	1
6·0	N	9	4	2	1	3	10	44	30	—
	Sq	0	0	0	0	0	50	50	0	2

N—Normal days, Sq—Squally days