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Thunderstorms over Poona and the possible use of a Squall Index

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ABSTRACT. Thunderstorms which occurred over Poona during the period 1946-51 have been separated into two classes, those associated with surface squalls equal to and above 30 mph and those thunderstorms with surface wind speeds less than 30 mph. Their relative frequencies in different seasons have been worked out. Various criteria that may be of importance in causing surface squalls in association with thunderstorms have been examined. A parameter, representing the difference of temperature between the dry bulb at 800 mb and the temperature of a saturated parcel of air in equilibrium with environment at 600 mb (the approximate freezing level) when brought down moist-adiabatically to the 800-mb level, which may be conveniently called a 'Squall Index' has been found to be significant in determining whether the thunderstorm of a particular day is likely to be associated with a strong squall or not.

1. Introduction

The present study was undertaken with a view to examine the various factors which may contribute to the occurrence of squalls at Poona, and to find out whether there is any reliable criterion which may be of use in anticipating the occurrence of a surface squall associated with the thunderstorm expected to occur on various synoptic and other considerations. The results have been encouraging. It appears that we may be able to use a 'Squall Index'— the difference between the dry bulb temperature at 800 mb and the wet bulb temperature of a saturated parcel of air in equilibrium with the environment at the 600-mb level when it descends moist-adiabatically to the 800-mb level— to estimate maximum gust speed in a particular thunderstorm.

Thunderstorms and squalls have been the subject of study by Sohoni (1928), Desai (1931), Venkiteshwaran (1932), Krishna Rao (1938), Mull and Rao (1950) and Ramaswamy and Mazumdar (1950).

A statistical study of squalls at Poona irrespective of their association with other atmospheric phenomena has been published by Ramakrishnan (1953). In the present paper, the question of thunderstorms, as such, has not been looked into, but only the question of discriminating between thunderstorms associated with surface squalls of 30 mph and above from those associated with surface wind gusts below 30 mph.

2. Data

For the above study, the dates and times when thunderstorms passed over Poona during the period 1946-51 were found out from the *Monthly Meteorological Registers.* The relevant anemograms, thermograms and tephigrams were also examined. The criterion for reckoning a thunderstorm was that thunder was heard at the observatory and some of the other characteristics of thunderstorms as shown by anemograms and thermograms were also present. Thunderstorms and squalls associated with tropical cyclones were excluded. The maximum speed in gust during each thunderstorm period was noted.

The number of thunderstorms in each month and year are given in Table 1. The month of June is divided into two periods, one previous to the onset of the monsoon and the other subsequent to the onset of the monsoon. The distribution of the thunderstorms according to gust speed is given

TABLE 1

Occurrence of thunderstorm

Year	Jan	Feb	Mar	Apr	May	Jun		Jul	Aug	Sep	Oct	Nov	Dec	Total
						(a)	(b)							
1946	0	1	0	6	4	0	0	0	0	7	4	1	1	24
1947	1	0	2	4	4	0	0	0	5	0	0	2	1	19
1948	0	2	2	0	1	5	2	0	0	0	10	11	0	33
1949	0	0	2	1	13	0	1	0	4	1	6	0	0	28
1950	0	0	2	4	5	3	0	0	2	7	5	0	0	28
1951	0	0	0	3	8	3	2	2	0	5	6	3	0	32
Total	1	3	8	18	35	11	5	2	11	20	31	17	2	164

TABLE 2

Distribution of thunderstorms according to maximum gust speed

Speed (mph)	Jan	Feb	Mar	Apr	May	Jun		Jul	Aug	Sep	Oct	Nov	Dec
						(a)	(b)						
0— 9	0	1	0	0	0	0	0	0	0	0	0	0	0
10—19	0	0	0	0	0	0	1	0	1	3	5	4	1
20—29	1	1	4	3	13	4	2	2	5	13	11	9	1
30—39	0	1	3	10	14	6	2	0	5	3	13	4	0
40—49	0	0	1	2	6	1	0	0	0	0	2	0	0
50—59	0	0	0	3	0	0	0	0	0	1	0	0	0
60—69	0	0	0	0	2	0	0	0	0	0	0	0	0
0—29	1	2	4	3	13	4	3	2	6	16	16	13	2
30 and above	0	1	4	15	22	7	2	0	5	4	15	4	0

(a) Till the onset of monsoon (b) After the onset of monsoon

TABLE 3

Distribution of thunderstorms according to number and maximum gust speed for each of the four seasons during 1946-51

Season	Total No. of thunderstorms	No. of thunderstorms with maximum gust speed of 30 mph and above	No. of thunderstorms with maximum gust speed of less than 30 mph
Pre-monsoon (Mar–onset of monsoon)	72	48 (67)	24 (33)
Monsoon (Onset of monsoon–Aug)	18	7 (39)	11 (61)
Post monsoon (Sep–Nov)	68	23 (34)	45 (66)
Winter (Dec–Feb)	6	1 (17)	5 (83)

NOTE—Figures in brackets indicate the percentage of total No. of thunderstorms

in Table 2. Table 3 gives their distribution according to number and gust speed, for each of the 4 seasons. It will be seen from Table 3 that the total number of thunderstorms in the pre-monsoon and the post monsoon periods are nearly the same, but only 34 per cent of the thunderstorms of the post monsoon period have gust speeds equal to or greater than 30 mph whereas for the pre-monsoon period, this percentage is 67. Ramakrishnan (1953) has also found that out of the 101 squally days (maximum gust speed 40 mph or above) which occurred in Poona in the period 1930-49, 66 occurred in the hot months of April, May and June and only 20 occurred in the months of September, October and November.

While the average values of the dry bulb temperatures at different levels for each month for Poona are readily available, the corresponding values of the monthly mean wet bulb temperatures had to be computed for this study. Wet bulb temperature data for the 500-mb level and aloft were rather scanty for the period studied. The computed values are given in Table 4.

Mean of daily maximum temperatures of Poona (based on observations from 1881—1940) from Climatological tables and normal of afternoon upper winds at 3, 4, 5 and 6 km over Poona based on observations from April 1937 to December 1950 for each month are given in Table 5. Two temperature differences called the 'Stability Index' and the 'Squall Index', explained hereafter, are also given in the same table. Table 6 gives the same elements for each season.

3. Analysis of data

As thunderstorms are instability phenomena, it was considered that greater surface heating and larger 'positive area' in a tephigram may give rise to thunderstorms with greater gust speed. Following a routine procedure adopted in U. S. A. (Showalter 1953), a 'Stability Index' was computed from the normal tephigram. This stability index is computed as the difference between the dry bulb temperature at 500 mb and that of a parcel of air at 800-mb level lifted along the appropriate adiabat up to the 500-mb level. If the difference was positive, the lifted parcel would be cooler than the environment and the situation stable. The basic assumption under the computation of this index is that due to the possible entrainment and mixing in the lower levels, an air parcel at 800 mb is representative of the ascending air. The values of this 'rough and ready' stability index for the normal tephigrams are given in column 4 of Tables 5 and 6.

It will be seen from Table 6 that the maximum temperature is greater by 12·1°F in the pre-monsoon when compared with the post monsoon months. As judged by the 'Stability Index' the normal tephigrams do not show instability in any month but it can be seen that the atmosphere is considerably more stable in the post monsoon than in the pre-monsoon. This is also seen from the study of isothermal and inversion layers above Poona-Hyderabad made by Roy and Mahalingam (1942). The inversion or isothermal layers were found to be most frequent between 2 and 3 gkm during the

TABLE 4

Average values of dry bulb and wet bulb temperatures at different levels over Poona at 1500 GMT (1946-51)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Surface (1834 ft above m.s.1)	D.B.	296·4	96·8	302·1	02·3	02·0	299·0	97·3	96·9	97·2	98·3	96·2	94·7
	W.B.	288·9	89·0	91·6	94·0	94·8	95·0	94·7	94·7	94·8	93·8	91·0	88·7
900 mb	D.B.	296·0	97·7	99·7	99·8	98·5	95·9	94·8	94·1	94·6	96·8	96·7	95·3
	W.B.	286·4	86·2	88·9	91·4	92·3	92·7	92·6	92·3	92·5	91·2	88·8	86·9
850 mb	D.B.	291·9	94·0	95·2	96·9	96·4	92·8	92·2	91·9	92·0	93·9	93·0	91·9
	W.B.	284·6	83·9	85·8	88·0	88·9	90·1	90·1	90·2	88·7	88·2	86·2	84·3
800 mb	D.B.	288·0	90·0	92·2	91·5	94·0	90·1	89·5	89·3	89·6	90·6	88·7	87·8
	W.B.	281·1	80·8	83·1	84·7	85·7	86·9	87·5	87·9	87·0	85·1	83·5	79·0
700 mb	D.B.	280·5	81·8	83·1	84·8	85·9	85·7	85·1	84·8	83·8	81·8	82·2	81·2
	W.B.	273·7	72·8	76·6	76·6	79·5	80·0	81·0	81·0	81·4	78·3	80·0	73·9
600 mb	D.B.	274·2	74·7	73·7	75·4	76·2	77·3	78·3	77·5	77·3	75·6	75·9	75·0
	W.B.	266·9	67·6	66·7	69·7	72·2	73·7	74·8	74·1	73·6	71·4	70·3	68·1
500 mb	D.B.	264·7	65·4	65·4	66·9	67·2	69·4	70·2	70·0	69·4	68·3	67·4	65·8
	W.B.	261·0 (1)	..	..	63·7 (2)	66·7 (10)	67·3	68·6	67·4	67·3	68·3 (7)	64·7 (7)	..
400 mb	D.B.	253·5	53·7	53·7	55·9	56·9	59·9	60·6	60·6	59·2	57·6	56·3	54·2
	W.B.	..	..	..	..	..	..	..	..	..	..	..	..
300 mb	D.B.	238·8	39·3	38·8	40·9	42·8	46·1	47·4	47·0	45·7	43·0	42·0	40·3
	W.B.	..	..	..	..	..	..	..	..	..	..	..	..
200 mb	D.B.	217·9	19·5	20·3	21·0	21·9	25·9	26·0	27·3	24·3	23·5	22·9	21·0
	W.B.	..	..	..	..	..	..	..	..	..	..	..	..

NOTE—1. Figures within brackets indicate the number of observations available for the computation of the average values

2. In the columns under Feb to Dec, the hundred digits 2 or 3 as the case may be, have been omitted

TABLE 5

Month (1)	Mean of daily maximum temperature (°F) (2)	Normals of afternoon upper winds (3)								Stability Index (°C) (4)	Squall Index (°C) (5)
		3 km		4 km		5 km		6 km			
		V	*D*	*V*	*D*	*V*	*D*	*V*	*D*		
Jan	86·5	5·6	251	8·2	273	10·7	273	13·5	275	4·2	2·0
Feb	90·5	6·6	245	8·5	265	11·1	277	14·0	277	5·5	4·0
Mar	96·9	5·5	238	6·2	274	9·1	284	11·6	284	2·2	6·5
Apr	100·9	4·6	221	5·5	229	6·6	309	8·4	303	1·6	5·2
May	98·8	5·2	284	5·4	152	5·5	040	6·4	354	0·7	6·8
Jun	89·4	5·2	230	4·8	192	4·2	245	5·1	243	1·2	2·0
Jul	82·5	11·6	263	5·6	042	8·7	084	6·5	050	1·2	0·5
Aug	81·7	5·8	260	4·6	219	4·3	127	5·3	122	0·7	1·0
Sep	84·6	4·8	313	4·8	317	5·1	298	4·9	034	1·0	1·3
Oct	89·4	4·9	065	4·8	068	5·2	017	6·1	330	2·3	3·6
Nov	86·5	4·6	084	5·1	064	5·9	332	7·2	319	3·8	1·7
Dec	84·9	5·1	297	6·3	273	7·9	267	10·4	265	8·0	1·4

V=Velocity in metre/sec, *D*=Direction in degrees

TABLE 6

Season (1)	Seasonal mean of daily maximum temperature (°F) (2)	Seasonal normal speeds of afternoon upper winds in metres per second (3)				Stability Index (°C) (4)	Squall Index (°C) (5)
		3 km	4 km	5 km	6 km		
Pre-monsoon (March–May)	98·9	5·1	5·7	7·1	8·8	1·5	6·2
Monsoon (June–August)	84·5	7·5	5·0	5·7	5·6	1·0	1·2
Post monsoon (September–November)	86·8	4·8	4·9	5·4	6·1	2·4	2·2
Winter (December–February)	87·3	5·8	7·7	9·9	12·6	5·9	2·5

months November to January. The level of maximum frequency was at a height of 5 to 6 gkm during February to April, but lowered gradually to 4-5 gkm during May to July and 3-4 gkm in August. In September, the frequency of occurrence was the same at all heights between 2 and 6 gkm. The stabilising layers were found to be quite frequent in October between 2 and 4 gkm.

Table 6 also shows that upper winds are stronger at all levels in the pre-monsoon than in the post monsoon, but the difference in values is not large enough to account for the greater frequency of stronger thundersqualls in the pre-monsoon months.

After examining the monthly and seasonal mean tephigrams, the actual conditions on the individual days of occurrence of the thunderstorms were examined. 'Scatter-diagrams' were prepared showing the relationship between maximum gust speeds and (1) maximum temperature of the day, (2) the negative stability index as a measure of the 'positive area', (3) a modified stability index after assuming suitable rates of entrainment and mixing at levels above 800-mb level and (4) speeds of the upper winds. The points on each of the above diagrams were greatly scattered and the maximum gust speeds do not seem to have a significant relationship with any of the parameters considered above.

A Squall Index defined as the difference between the dry bulb temperature at the 800-mb level and the wet-bulb temperature of a saturated parcel of air in equilibrium with the environment at the 600-mb level when it descends moist-adiabatically to the 800-mb level, was then considered. Its seasonal mean value, as is seen from the last column of Table 6, for the post monsoon period is 2·2°C, whereas for the pre-monsoon period when stronger squalls are more frequent, it is 6·2°C. No doubt its value for winter is slightly more than that for the post monsoon but the stability index for winter is very great, suggesting the preclusion of thunderstorms. Any way, these preliminary considerations were promising in favour of the squall index, and this line of thought was pursued.

4. Some theoretical considerations

The gusty surface wind accompanying a thunderstorm is associated with the downdraft in the thunderstorm. The vertical motion of the moving air of the downdraft, when it approaches the surface of the earth, is transformed into horizontal motion which causes local accelerations in the surface wind. Such horizontal accelerations of the wind near the ground also strengthen the gusts which result from the vertical shear in the horizontal outflow. Thus one may expect the speed of the maximum gust in a thundersquall to be directly related to the speed of the downdraft.

The processes initiating the downdraft of a thunderstorm are certainly very complicated. The generally-accepted thermodynamical process leading to a downdraft, as given by Byers and collaboraters (1949) in their "Thunderstorm Project", is outlined below.

As a consequence of the entrainment of the environmental air in a thunderstorm updraft, the lapse rate within the updraft becomes approximately that of the environment. (Apparently this is the reason why we did not find any significant correlation between the negative stability index—a measure of the positive area—and the magnitude of the horizontal squall). Any air dragged downwards by the falling rain warms at the moist adiabatic rate and soon becomes more dense than the air of the environment, even if the descending motion started at a level where the cloud temperature was higher than that of the environment. Due to the higher density of the descending air and the drag exerted on it by the falling drops, this air continues to descend. With sufficient water available to keep it saturated, it is subjected to an ever-increasing downward acceleration even when no air is entrained on its downward path.

Mull and Rao (1950) have suggested that the trigger for the downdraft is provided by cooling of the environment by melting of ice-crystals brought down to levels, with temperature higher than 0°C by the turbulence due to instability within the cloud as a result of the sudden congelation of the super-cooled layer. This would suggest that the downdraft usually commences from the freezing level.

Whatever the initial trigger for downdraft may be, there is generally a sharp drop in the wet bulb temperature with the onset of a thundersquall at the surface. This suggests that the squall is associated with air that descended along a saturated adiabat from a higher level, where the potential wet bulb temperature is lower than the corresponding value at the surface, although the entrainment of the environmental air and the rather vigorous mixing in the lowest couple of thousands of feet of the atmosphere may so modify the surface wet bulb temperature at the onset of the squall, as to considerably mask the lowering of the surface wet bulb temperature.

As the lapse rate of the environmental air on a thunderstorm day is greater than that of a saturated adiabat, the descending air will be colder than the environment. The greater this difference of temperature the more will be the speed of the downdraft. Byers and collaborators (1949) found the co-efficient of correlation between draft velocities and the observed deviations from the environment temperatures at individual levels to be 0·744.

In the present study, the maximum gust speeds were plotted against the actual fall in surface wet bulb temperatures and the scatter diagram (Fig. 1) obtained showed a significant relationship between the two. The correlation co-efficient for this grouping is 0·634 (n : 161).

5. The Squall Index and its use

Byers and collaborators (1949) found 'that downdrafts of a magnitude great enough to be detected by the aircraft first occur near 15,000 ft.' This is near about the freezing level which is also expected in the process envisaged by Mull and Rao (1950). This level over Poona, as found from upper air data and radar observations of bright bands, may be taken to be at 600 mb for purposes of a 'rough and ready' technique. Assuming that the saturated air of the downdraft descends moist-adiabatically from this level, the difference of its temperature T_1 from that of the environment T at an intermediate 800-mb level (approximately the middle level between 600 mb and surface level for Poona) may be taken to be directly related to the speed of the downdraft and hence to the associated maximum surface gust speed. For convenience, this quantity $T-T_1$ has been called the Squall Index, in this paper.

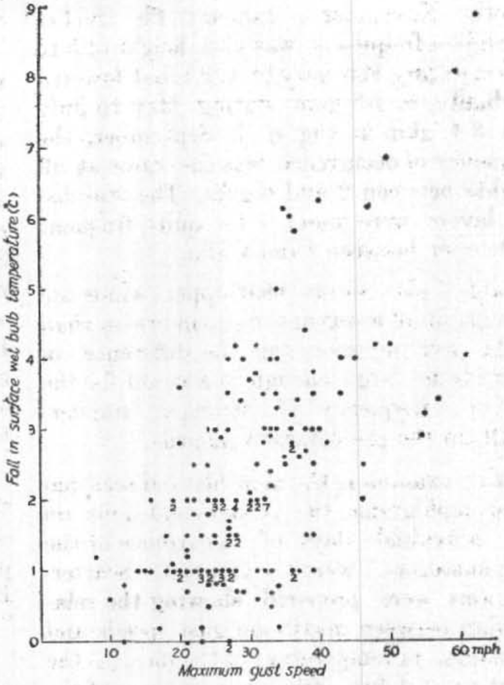

Fig. 1

(The numbers below the points give their coincident values)

The squall indices on the different days of occurrence of thunderstorms over Poona were found out from the immediately preceding radiosonde ascents and plotted against the maximum observed gust speeds. The diagram was encouraging but still there was an appreciable scatter of the points. It was considered that if the effect of the entrainment of the environment air by the downdraft is also

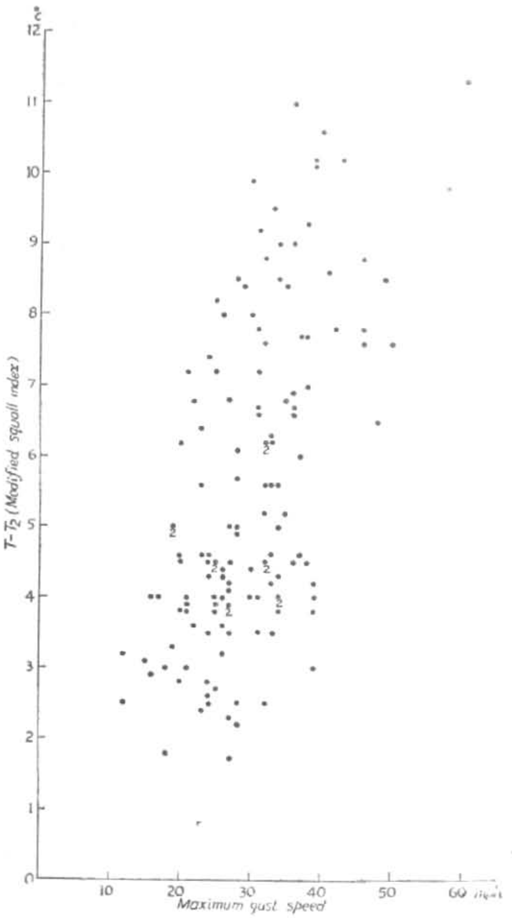

Fig. 2

(The numbers below the points give their coincident values)

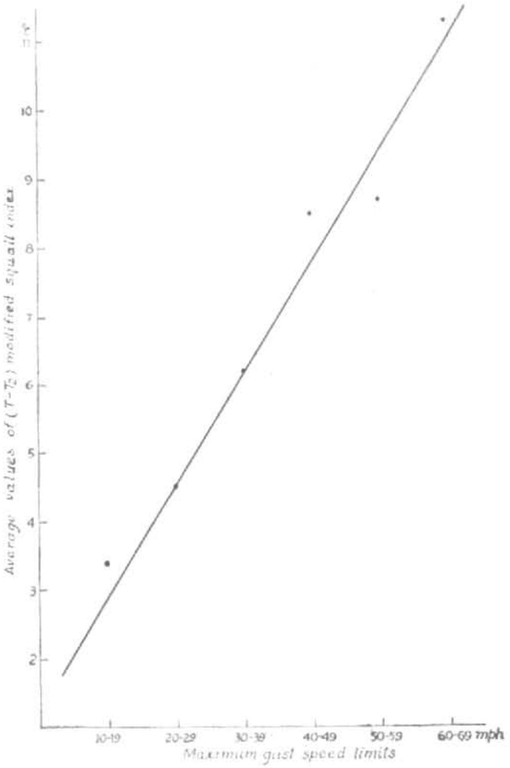

Fig. 3

taken into account, the 'Scatter' may be decreased. As the factors like the rate of entrainment, the exact level from which the downdraft descended, the availability of liquid water were all not accurately known, the following rough method was adopted to take the effect of mixing with the environment.

The descending parcel of air was assumed to mix with an equal mass of the environmental air at 700 mb and then descend to the 800-mb level as a saturated parcel. The temperature of such a saturated parcel at 800 mb was taken as T_2. Denoting the temperature of the environment at 800 mb by T, the difference $T—T_2$ was considered as the Modified Squall Index. These modified squall indices of the individual days were computed and plotted against maximum gust speeds and the resulting scatter diagram is shown in Fig. 2. The correlation co-efficient for this distribution was found to be 0·591 which is significant at 1 per cent 'level of significance' (n : 137).

The average values of $T—T_2$ for different maximum gust speeds which lie within certain limits are given in Table 7. The table speaks for itself. Fig. 3 represents the groupwise data graphically. The linear relation is striking, when one remembers the numerous

TABLE 7

Maximum gust speed limits (mph)	Average values of $T-T_2$ (Modified Squall Index) (°C)
10—19	3·4
20—29	4·5
30—39	6·2
40—49	8·5
50—59	8·7
60—69	11·3

'rough and ready' approximations used in deriving the modified squall index and the large time difference, often 24 hours, between the radiosonde ascents and the actual occurrence of thunderstorms.

6. Some instances of discrepancy in the observed gust speed and the Modified Squall Index

Byers and collaborators (1949) have observed that the thunderclouds more or less, move with the winds at 10,000 ft a.s.l. When the cold downdraft reaches the surface layers it spreads out in all directions. But as the relatively high horizontal momentum of the upper layers is transported downward, surface outflow-wind speeds in the direction of the thunderstorm movement are reinforced while those in the opposite direction are retarded.

Though the mean direction of surface wind during the maximum gust speed is greatly influenced by the terrain, it was seen in the present study, that in most cases, it is nearly the same as that of the wind at 10,000 ft, *i.e.*, the direction of the movement of thunderstorm. In a few cases where it was seen opposite to the wind at 10,000 ft the maximum gust speed was less than that expected from the $(T-T_2)$ value of the tephigram. Table 8 shows a few such cases. Apparently in these cases, the thunderstorms developed such that Poona was to the rear of these thunderstorms, and therefore, the maximum gust speed recorded at the observatory was less than the maximum gust speed of the particular thunderstorm.

7. Acknowledgements

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TABLE 8

No.	Date	Maximum gust speed			Direction of 0900 GMT upper wind at 10,000 ft	Modified Squall Index $(T-T_2)$ from preceding tephigram (°C)	Maximum speed expected from $(T-T_2)$ value (mph)
		Time (IST)	Dir.	Speed (mph)			
1	1-4-1947	1846	WNW	33	ESE	9·5	55
2	7-5-1949	2255	SW	21	ENE	6·7	40
3	14-4-1951	1727	NW	30	SE	8·0	45

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