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Effects of off-shore vortices on rainfall along the west coast of India

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(*Received 16 May 1955*)

ABSTRACT. Formation and dissipation of small scale circulations and vortices take place incessantly along the west coast of India, during the monsoon season. Some of these vortices are found to develop into singificant shape and size and make noteworthy contributions towards rainfall along the west coast. The occurrence of rainfall relatively heavier over the coastal stations away from the ghats than over sections close to the ghats is not an uncommon feature. This peculiar distribution of rainfall is found to occur under the influence of off-shore vortices.

These vortices are of the order of 30 to 100 miles in horizontal extent. They generally move northwards parallel to the ghats. The variations of surface winds experienced at the stations provided with autographic records reveal that there are a few significant points connected with all well-developed vortices, and that the rain fall associated with a vortex is usually heaviest between the 'core' region and the 'confluent' region of the vortex.

1. Nature of off-shore vortices

It is well-known that formation and dissipation of circulations and vortices go on incessantly in the motion of actual fluids. Instances of such large-scale vortices in the atmosphere are found in extra-tropical cyclones, tropical revolving storms, etc which are responsible for large-scale weather phenomena. They are also found on a smaller scale in other whirls like dust-devils, circulations associated with convective clouds and other ordinary eddies produced by hillocks, large buildings, etc.

The vortices under examination in this paper are those whirls which are 30 to 100 miles in diameter in horizontal extent. These are distinctly smaller than the tropical cyclones but definitely larger than the cells associated with cumulonimbus and similar convective clouds. A small note on such vortices appearing over Colaba with the first burst of the monsoon has been published by Banerji (1928). He has accounted for the existence of vortices of 20 to 30 miles in diameter to the thermodynamic features, characteristic to a frontal region, prevailing along the monsoon front which is a surface of discontinuity between two air masses, one relatively warmer than the other. The present paper deals with similar vortices which are found to occur even well within the monsoon current more often in association with the periodic strengthening of monsoon along the west coast.

2. Mechanism behind the vortices

The dynamical process of the formation of these vortices can be understood if we consider the southwest monsoon current to be a non-uniform westerly stream in which there are narrow zones of relatively large horizontal velocity and of higher moisture content, with consequent difference in density from the general stream. It is generally accepted that even after the monsoon is fully established over the country, fresh surges strengthening the monsoon current along the west coast occur very often. The boundary of separation between the fresh stream and the already existing current becomes a region of discontinuity of wind velocity (or sharp wind shear), and also of slight discontinuity of air desnity, which are the two conditions favourable for the generation of waves. The isobars over the Arabian Sea, especially over the north and central portions, assume the typical non-parallel sinusoidal shape when strengthening of monsoon current takes place (Figs. 5—8). Such patterns of flow of currents also go to confirm that favourable conditions for formation of vortices exist in monsoon current. The field of motion at the boundary region of such streams is represented vectorially in Fig. 1. According to Bjerknes (1921), when the values of the sliding motion between the two streams at this surface of discontinuity exceed a certain limit, the wave motion transforms into vortex motion, resulting in the production of whirls. Some of these whirls which form in the current over the sea, reach the coast where, under favourable conditions, they develop further into vortices of significant shape and size.

Fig. 1. Shearing motion in the boundary region between two monsoon streams and formation of cyclonic eddies

(After V. Bjerknes)

In order to find out what these favourable conditions are, it is necessary to understand the airflow near the mountain barriers.

In discussing the air-motion over and around mountain barriers, with particular reference to the Western Ghats, Banerji (1930) has shown mathematically that close to the barrier, a portion of the current in the lower layers, should flow sideways as shown in Fig. 2. Such a flow is all the more feasible when we consider that the monsoon air mass consists of narrow streams of different velocities. For example, a strong stream of air striking a vertical wall perpendicularly will branch off horizontally so long as its vertical motions upwards or downwards are restricted and the currents on either sides are weaker. One portion would turn cyclonically and other anticyclonically.

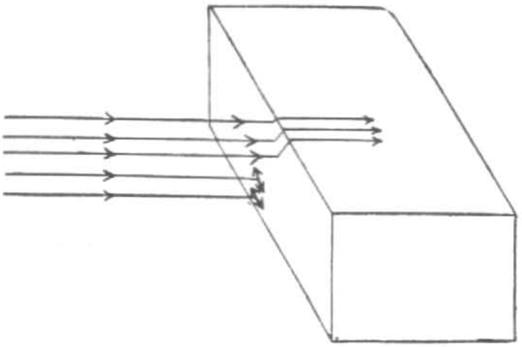


Fig. 2

The streamlines of flow, when two such adjacent streams exist, are shown in Fig. 3. A and B are two streams with horizontal velocity stronger than that of the prevailing currents C_1, C_2, C_3. The region R_1 is one of increasing cyclonic vorticity. The cyclonic eddies which form over the boundary region between the currents A and C_1 are bound to intensify further when they reach R_1. Similarly the region R_2, where the branch A_2 of current A, the current C_2 and the branch B_1 of the current B meet together, becomes an area of convergence producing conditions favourable for the accentuation of cyclonic vortices.

The height contours for 300, 600 and 900 metres of the Western Ghats adjacent to the coastal belt of Bombay (Fig. 15) show a concavity more or less to the east of Bassein. Such concavities in the Western Ghats exist elsewhere also. These concavities are found to be favourable spots for small-scale eddies to stagnate. Some of the eddies which get trapped in these concavities show, at times, signs of intensification before they finally dissipate.

A general picture of the streamlines of flow at the lowest layers of the atmosphere over and around the area of a fully-developed vortex is given in Fig. 4. Palmer (1952), in dealing with the transportation of waves in the easterlies in the equatorial atmosphere into vortex motions (vortices of large size), has shown with a series of such diagrams how the streamlines of flow get transformed gradually first in the lowest layers of the atmosphere and later on in the upper layers.

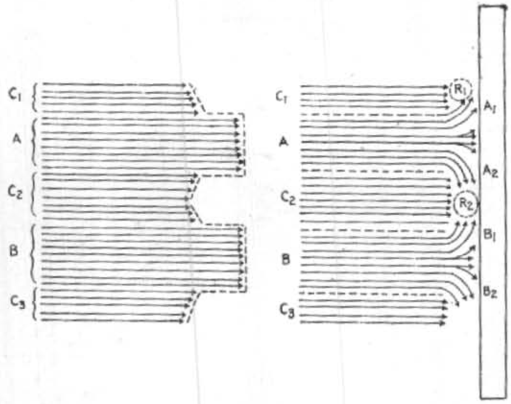


Fig. 3

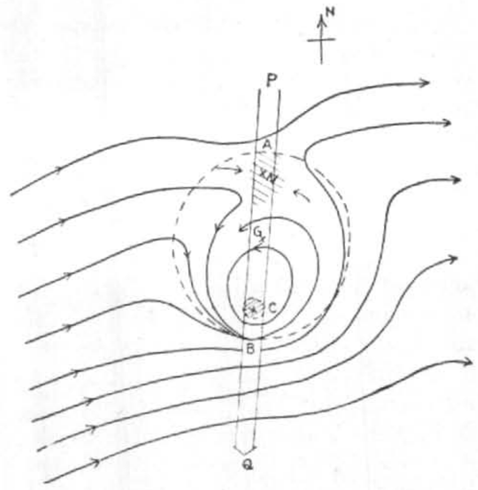


Fig. 4. Horizontal cross-section of hypothetical model of an off-shore vortex

3. A few typical off-shore vortices

A few typical synoptic situations, wherein well-developed off-shore vortices were seen to exist over the west coast, have been examined with relevant synoptic charts, available pilot balloon trajectories and the rainfall amounts recorded by all the rain-gauge stations over the coast and the Ghats. The vortices which passed over Bombay during the period under examination have been subjected to more detailed examination with the help of the autographic records of Colaba and Juhu (Santacruz). During the period under study, the anemograph was installed at Juhu and the self-recording raingauge at Santacruz (about 2 miles apart). A hypothetical model of one of those vortices has been prepared and its movements along the coast from Devgad to Bombay have been discussed. These are given in the following paragraphs.

3·1. *12 to 14 July 1951*—The synoptic charts (0830 and 1730 IST only) covering the west coast of India and the Arabian Sea during the period, 12th evening to 14th morning of July 1951, are reproduced (Figs. 5 to 8). The rainfall figures plotted on the 0830 IST charts are the amounts recorded during the preceding 24 hours while that on 1730 IST charts represent the rainfall since the previous 0830 IST observations. The corrected pressures in respect of ships' reports, whose times of observations were different from the times of the synoptic charts, are indicated within brackets by the side of the reported pressures. The isobars have been drawn at intervals of one millibar. The circles drawn in dotted lines indicate areas where the off-shore vortices were considered to be either developing or already existing.

Thus a series of vortices are shown to have existed, along and off the coast during the period. In the absence of any continuous record of observations at more frequent and closer intervals, it is difficult to follow their position, size, duration, continuity of movement from one synoptic chart to another. The rainfall charts (Fig. 9—a and b), in which the rainfall recorded by all rainfall reporting stations over the west coast and the Ghats on 13 and 14 July 1951 are marked, show clearly the effects of those vortices on the coastal rainfall. It could be seen that areas having concentrated heavy falls were those which were affected by one or more of the off-shore vortices during the preceding 24 hours.

The trajectories of pilot balloon ascents made at the coastal pilot balloon stations during the period are reproduced in Fig. 10. On account of the shallowness of these vortices, a balloon let off from a station which is being affected by a vortex is likely to pass out of the field of circulation of the vortex within a few minutes. However, the

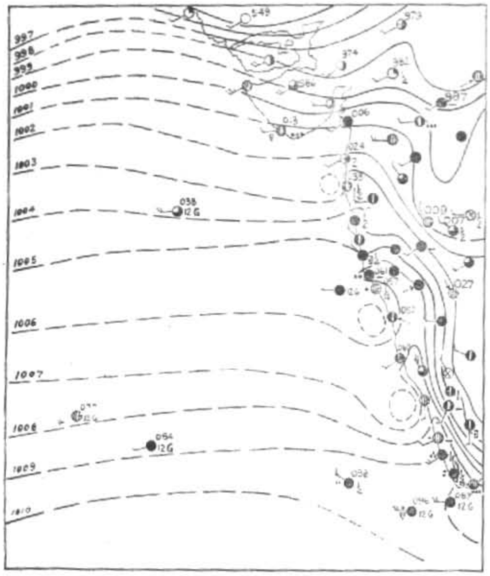


Fig. 5. 12 July 1951 (1730 IST)

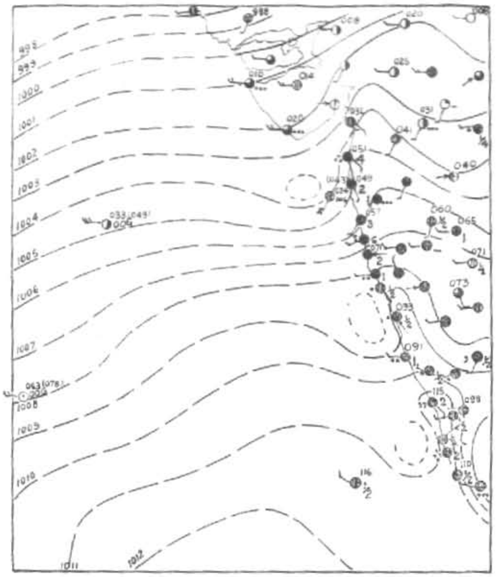


Fig. 6. 13 July 1951 (0830 IST)

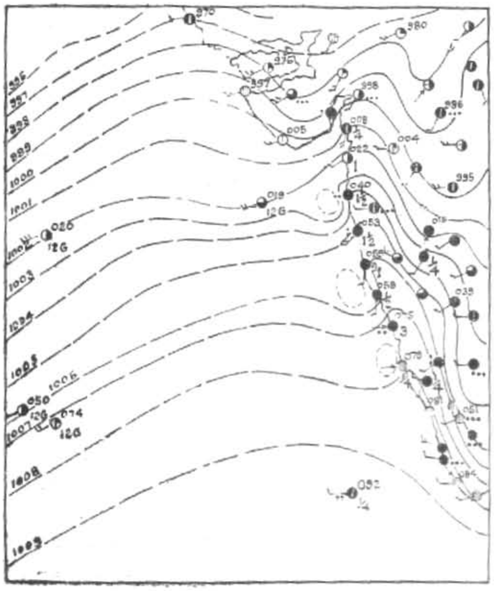


Fig. 7. 13 July 1951 (1730 IST)

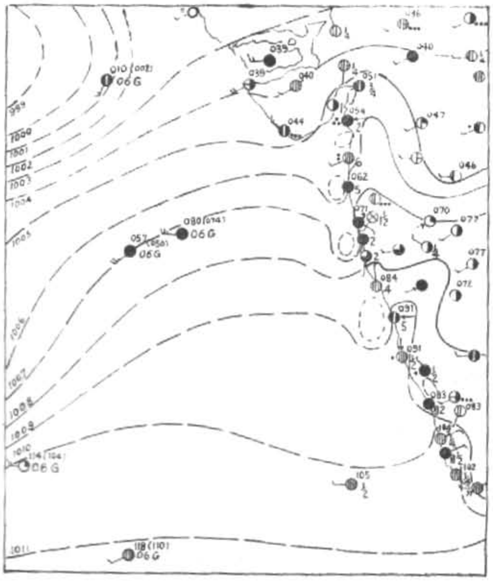


Fig. 8. 14 July 1951 (0830 IST)

trajectories indicate that within the strong westerly monsoon stream, winds having easterly components at the lower layers of the atmosphere existed over those localities which were affected by off-shore vortices.

The anemograms and hyetograms of Colaba and Juhu (Santacruz)—Figs. 11 and 12—provide detailed information on the vortices which passed over Bombay during the above period. Two well-developed vortices affected Bombay from 12th morning to 14th morning of July 1951. They are marked as A and B on the Colaba anemograms and as A′ and B′ on the Juhu anemograms.

3.2. *Vortex A*—It affected Bombay in the afternoon of 12 July 1951. Under its influence, the surface winds became weaker by 1200 IST at Colaba and by 1300 IST at Juhu. The direction started veering by 1230 IST at Colaba and 1330 IST at Juhu. The winds remained practically calm between 1300 and 1400 IST at Colaba and between 1400 and 1500 IST at Juhu, thereby indicating the passage of the neutral region of the vortex over both the stations. East to southeasterly surface winds prevailed till about 1745 IST at Colaba and 1845 IST at Juhu. Thereafter, westerly strong surface winds resumed over the stations, indicating the passage of the region 'B' of the vortex over both the stations.

The time-lag of about one hour noticed in the sequence of wind changes at Colaba and Juhu clearly indicates that the vortex moved from Colaba to Juhu at a speed of about 15 miles per hour. Assuming a uniform speed of 15 mph its diameter could be estimated to about 100 miles.

Rainfall is found to have occurred at both the stations just at the approach of the vortex. The absence of rainfall after the passage of the neutral region over the stations was mainly due to the fact that the stations were within the right-half portion of the vortex as could be seen from the sequence of wind changes. From the fact that strong surface winds set in over the stations when the region 'B' affected them, it may be inferred that there was lack of convergence and vertical lifting over the 'confluent' region. The absence of rainfall also supports this view.

3.3. *Vortex B*—This was a comparatively large-sized vortex which moved over to the stations from southwest, and remained affecting the area for an unusually long period of more than 24 hours.

The northeasterly movement of the vortex was maintained till about 0830 IST when the northeast quadrant of the vortex passed over the stations. Thereafter, the vortex apparently moved north to northwest when the stations came within the southeast quadrant. By about 1030 IST, Colaba was within the sector to the south of the core of the vortex, while Juhu remained on the northern side.

After about 1430 IST the vortex remained practically stationary during which period the 'core' region and the 'confluent' region remained over Bombay area with slight oscillations along the north-south axis. From the weak and variable nature of the winds, which prevailed over Colaba between 1430 and 1800 IST it may be inferred that the 'core' of the vortex was lingering over Colaba during this period, when a spell of continuous rain occurred over the station.

Although the 'core' shifted from Colaba soon after 1800 IST the north-south oscillation of the vortex brought it back again over Colaba between 2000 and 2400 IST when another spell of continuous and rather heavy rain occurred over the station. During these spells Kurla also recorded as much rain (5·5 in.) as Colaba, indicating that there was a belt of heavy rain atleast between Colaba and Kurla.

The surface winds at Juhu remained steady from southeasterly direction during the above mentioned periods, indicating that Juhu was all along within the quadrant to the northeast of the core. That is probably the reason for Santacruz, and also stations towards north of it, recording only comparatively small amounts of rain. The heavy fall

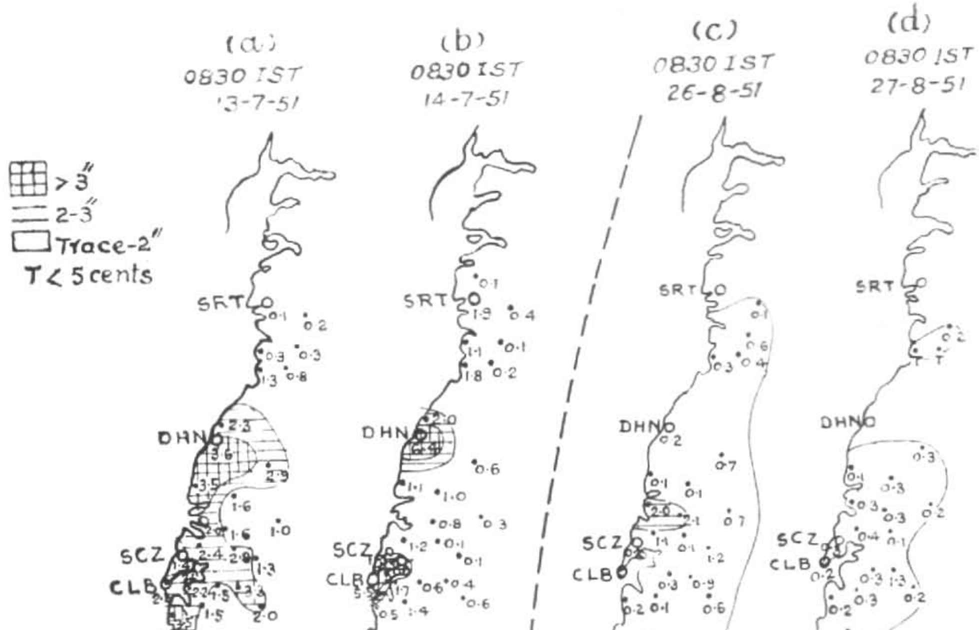
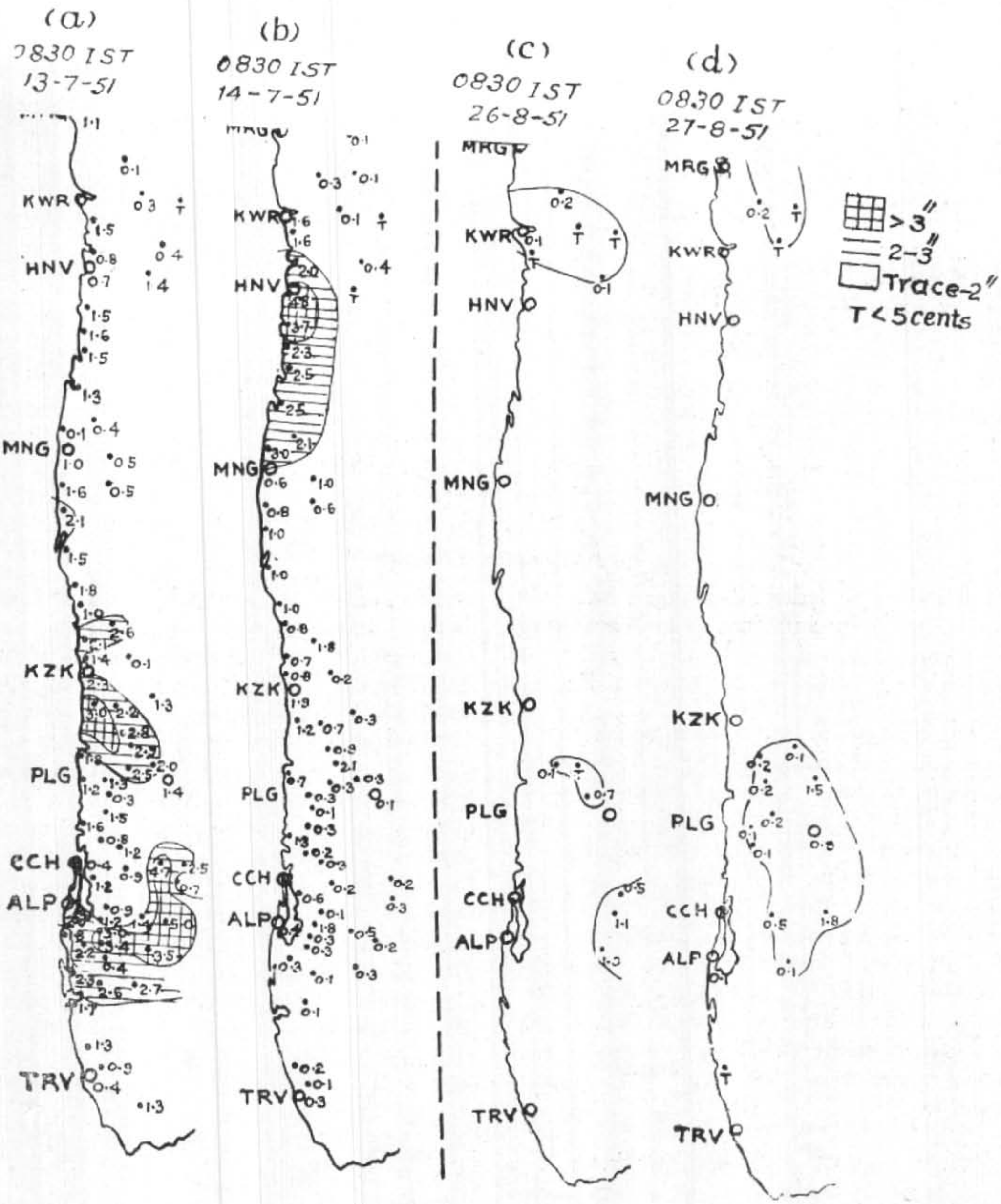


Fig. 9. Rainfall recorded during the preceding 24 hours by



the rainfall reporting stations over the west coast of India

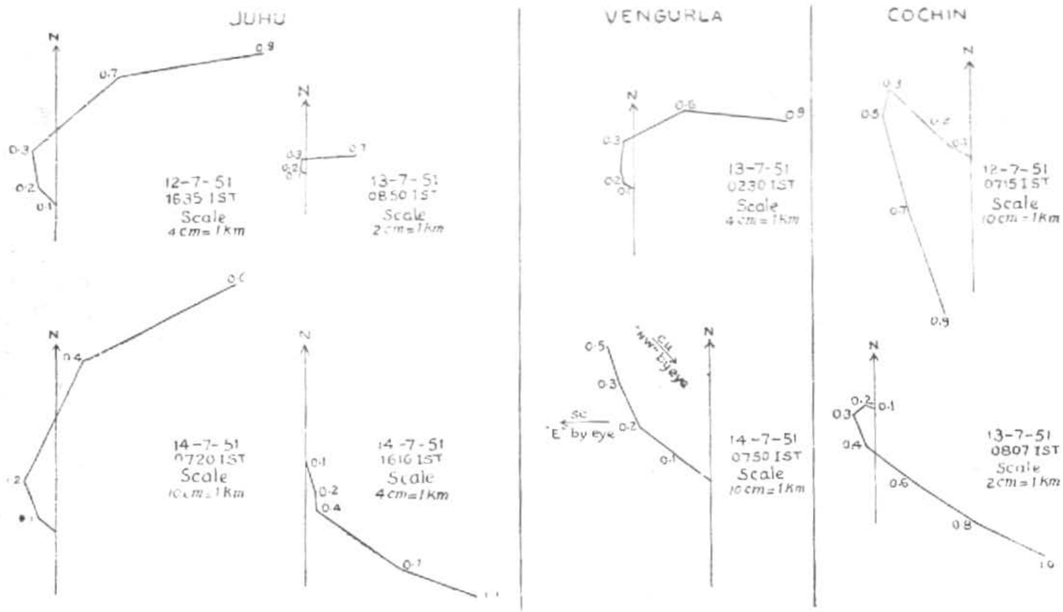


Fig. 10. Pilot balloon trajectories

of 6 inches recorded at Dahanu was definitely under the influence of a separate vortex which was existing between Surat and Dahanu at 0830 IST on 14 July 1951 (Fig. 8).

The portion of the vortex which moved over Colaba at about 0915 IST on 14 July 1951 appears to have affected Juhu by about 1145 IST (*i.e.*, $2\frac{1}{2}$ hrs later). From this, it may be inferred that the rate of movement of the vortex during that period was not more than 6 mph. Because of this non-uniform rate of movement of the vortex, its horizontal extent could not be estimated correctly. However, the synoptic charts (Figs. 6 and 7) also would show that it was a comparatively large-sized vortex, probably more than 100 miles in horizontal extent.

3.4. *16 to 18 July 1951*—Two other vortices, which reveal certain special characteristic features occurred during this period. The relevant synoptic charts for the period are reproduced in Fig. 13.

3.5. *Vortex C*—A reference to the anemograms of Colaba and Juhu (Fig. 14) would show that a vortex started affecting the surface winds at Colaba by 1700 IST and Juhu by 1800 IST of 16 July 1951. The 'neutral' region of the vortex affected Colaba during 1830 and 2130 IST and Juhu during 1930 and 2200 IST. The setting in of the westerly winds at both the stations soon after the passage of the neutral region would indicate that the portion of the vortex to the west of the neutral region was affecting the stations during that period. This was possible if the vortex had moved in a northeasterly direction till about midnight. The changes in surface winds at Colaba and Juhu soon after midnight show that the vortex moved thereafter in a northnorthwesterly direction. The core region appears to have reached the station after 0100 IST of 17 July 1951 and remained practically stationary between Colaba and Juhu with slight horizontal oscillation till about 1000 IST during which period the surface winds were light and variable.

A heavy fall of about 3 inches of rain fell over Santacruz between 0300 and 0500 IST. Continuous rain fell over Colaba between 0400 and 1000 IST when about 2·2 inches of rain were recorded. The rainfall amounts recorded by all the rainfall-reporting stations over and around Bombay coast are shown plotted on a map (Fig. 15). It is seen that Alibag which was apparently affected by the core region of the vortex, also recorded a heavy rain of 3·2 inches. It is significant to notice that the rainfalls during the same period at the other stations, especially those which are situated over the Ghats, were very scanty. One special feature of this vortex was that no rain fell over Santacruz and Colaba during the first eight to ten hours when the vortex affected the station. This was because the rainfall was confined to the region around the core of the vortex. This accounts for the fact that the area of heavy rainfall was limited to a very small portion of the coastal belt which was affected by the vortex.

3·6. *Vortex D*—This vortex was one whose course of movement could be traced over a long distance along the coast. Its existence to the southeast of Devgad, which is about 150 miles south of Bombay, on the morning of 17 July 1951 was noticeable on the 0830 IST synoptic chart of the day (Fig. 13—*a*). The 1730 IST synoptic chart of the day (Fig. 13—*b*) shows that the vortex developed further and lay in the evening between Harnai and Devgad. It gradually moved along the coast and passed over Bombay by the next morning.

Under its influence, the surface wind at Colaba started veering by 1730 IST and that at Juhu started backing by 2130 IST (Fig. 16). The veering of the winds at Colaba continued till 0300 IST of 18 July 1951. Similarly the backing of the winds at Juhu continued till about 0400 IST of 18 July 1951. In order to understand this peculiar change of winds at Colaba and Juhu in the opposite directions, the horizontal cross-section at the surface level of an hypothetical model of the vortex has been prepared (Fig. 17) on scale 1 inch = 16 miles, which is approximately the scale of the map in Fig. 18. The positions of the core of the vortex at the various hours have been fixed with reference to those points of the vortex which passed through Colaba and Juhu. The line joining the positions of the core which is taken as the track of the vortex is shown in Fig. 18. Similarly, the tracks traced on the horizontal cross-section of the vortex by the anemograph points (Juhu and Colaba) are suitably marked on the model (Fig. 17).

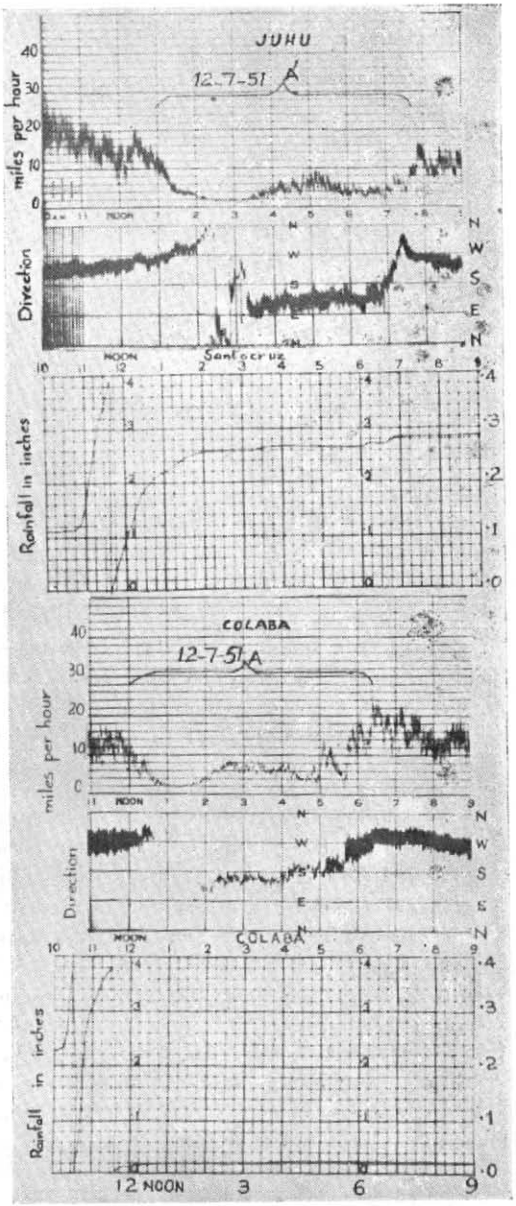


Fig. 11

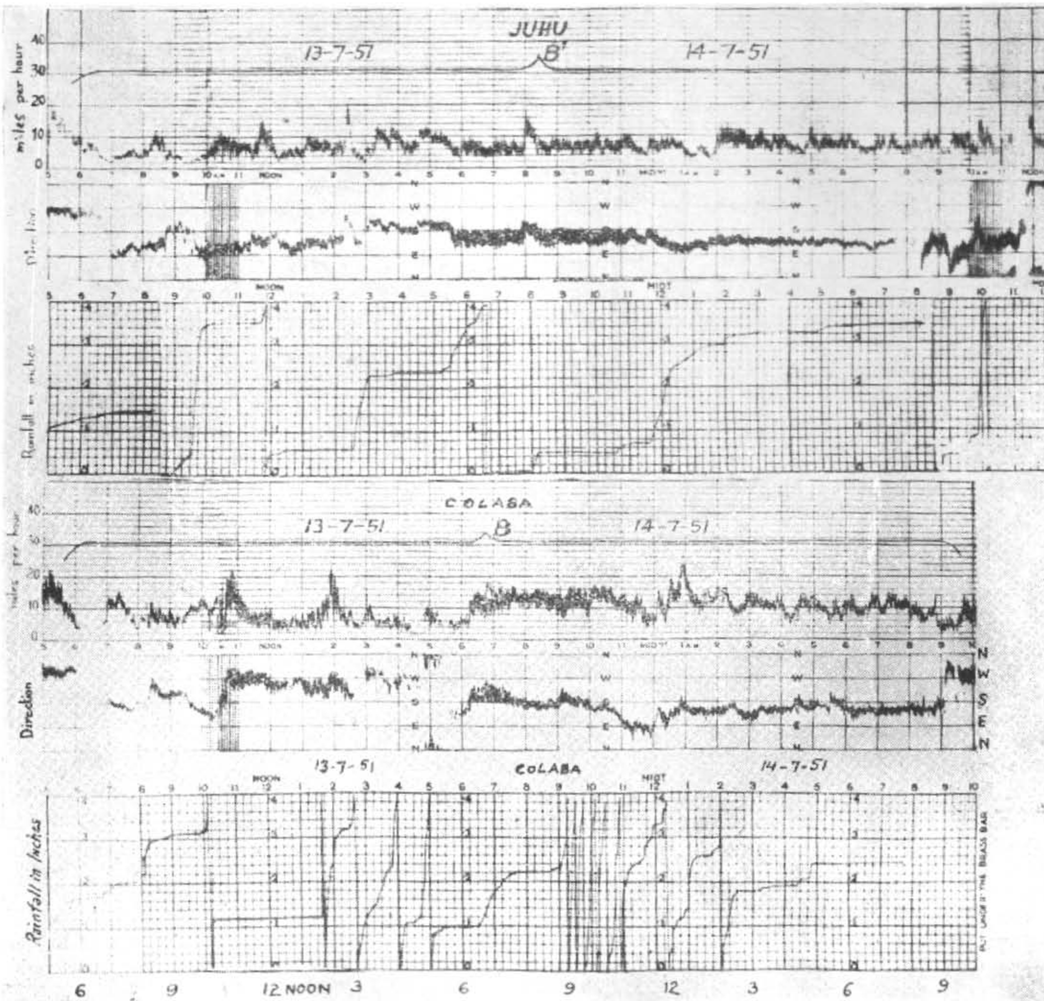
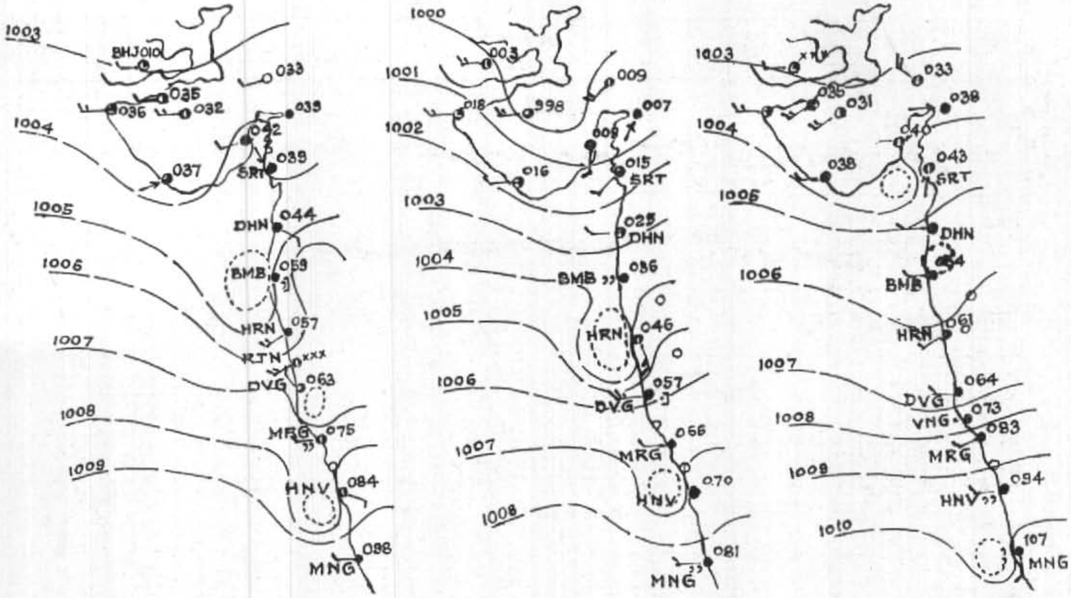


Fig. 12

The effective boundary of the vortex reached Colaba by about 2000 IST and Juhu by 2130 IST of 17 July 1951. The calm region associated with the 'Neutral' point passed over Colaba between 2100 to 2300 IST and over Juhu between 2200 to 2330 IST. The direction of movement of the vortex changed and became northwesterly after 2300 IST. It continued to move in the same direction till about 0200 IST. During this period the PQ axis also changed its orientation and it was more or less along northwest-southeast line. Thereafter, the orientation suddenly veered until it was along northeast-southwest line. This change was accompanied by the direction of movement of the vortex curving to northeasterly direction. It is found that the 'core' of the vortex bypassed Colaba, while it passed over Juhu between 0400 and 0500 IST. Although the northeasterly movement was maintained, the speed was considerably retarded after 0400 IST. Soon after 0500 IST, Colaba was outside the effective boundary of the vortex, but Juhu remained within the boundary till about 1400 IST of the day.

From the track of the core it may be inferred that the movement of the vortex



(a) 0830 IST 17-7-51 (b) 1730 IST 17-7-51 (C) 0830 IST 18-7-51

Fig. 13

was parallel to the contour line of the Ghats adjoining the coast. The retardation in the speed of movement occurred when the vortex reached the trough portion of the Ghats to the northeast of Bombay where it was apparently bottled up.

Rain fell over Colaba and Santacruz practically throughout the period they were under the influence of the vortex. Santacruz which was affected by the sector to the southwest of the core experienced continuous heavy rain (3·5 inches) between 0600 and 1400 IST. The amounts of rainfall recorded during the 24 hours preceding 0830 IST of 18 July 1951 at the relevant rainfall reporting stations are shown in Fig. 18. It shows that there was a distinct area of heavy rainfall over that region of the coast which was affected by certain portions of the vortex during the course of its movement along the coast.

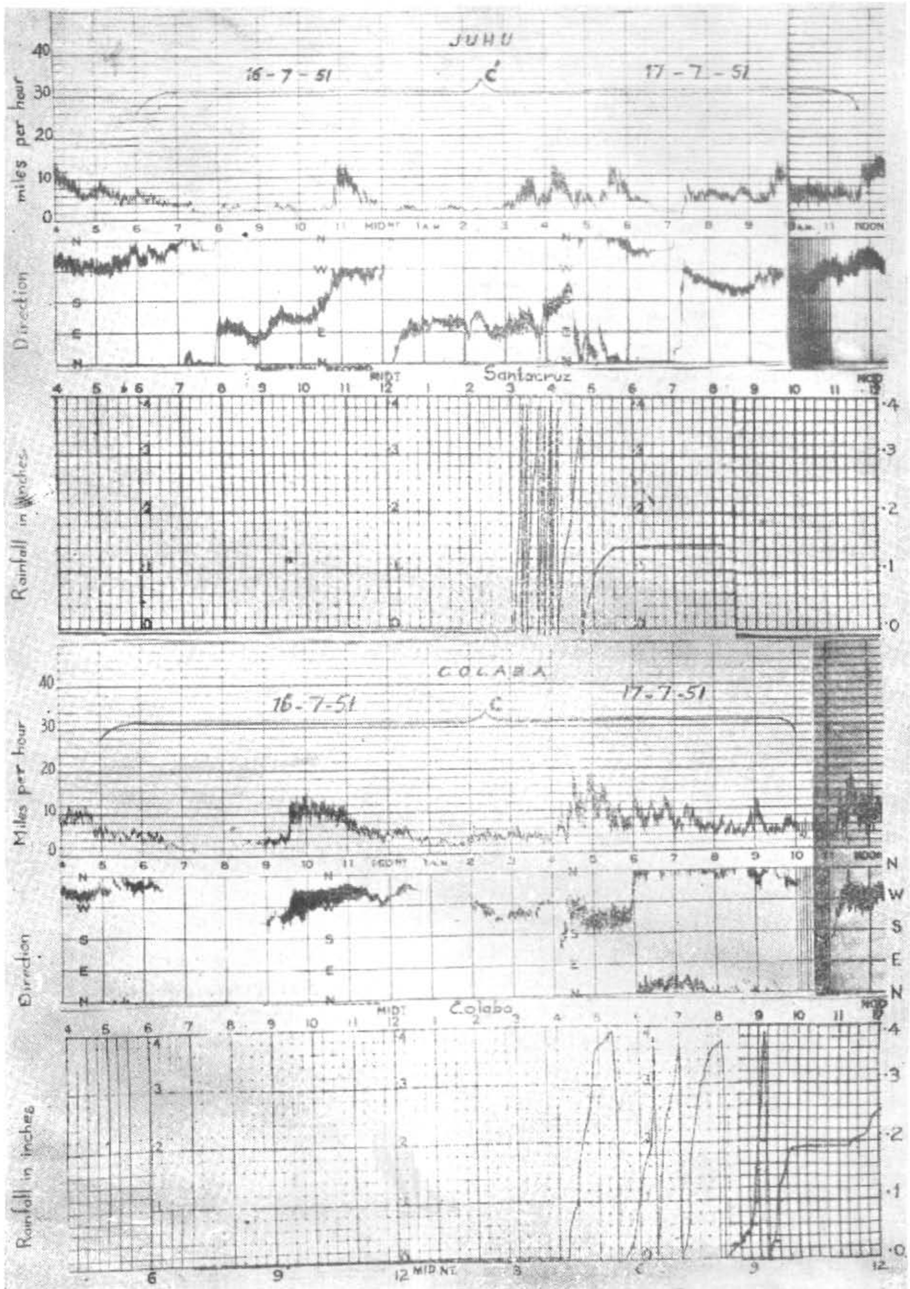
4. General characteristics of the vortices

From the typical situations presented in the previous sections and from many such cases which were noticeable on the day-to-day working charts the following would appear to be the general features of these off-shore vortices.

4·1. *Place of occurrence*—The vortices are found to occur all along the west coast. There are however a few favourite spots, as already pointed out, where more active ones are found to develop. One of those 'soft-spots' is near Bombay. It could be seen from the contour of the Ghats shown in Fig. 15, how far it is providing favourable orographical features.

Similar vortices have been found to exist along the east coast of India during the northeast monsoon season and also along the Burma coast during southwest monsoon season. The occurrence of similar vortices over inland regions has also been noticed occasionally.

4·2. *Size*—As already mentioned, these vortices are found to be generally of the order of 50 to 100 miles in horizontal extent. Some of them are so small as to be of even 20 to 30 miles in diameter, while there are some having diameters slightly exceeding 100 miles. The horizontal extent could be estimated by noting the time lag in the sequence of


JUHU
16-7-51
C
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Santacruz
Rainfall in inches
COLABA
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C
17-7-51
Miles per hour
Direction
Colaba
Rainfall in inches
MIDNT
NOON

Fig. 14

occurrence of weather phenomena associated with a particular vortex at two neighbouring stations and also by assuming a uniform rate of motion for the vortex.

The only data available for estimating the vertical extent of these vortices are the upper air winds. But unfortunately, on days when a station is being affected by a vortex, the heavy clouding denies us the pilot balloon data for heights more than about 1000 ft. Moreover, the pilot balloon observatories are too far apart to be affected simultaneously by the circulations associated with a single vortex. Despite these limitations from the trajectories of some of the pilot balloon ascents and also from the nature and quantity of precipitation associated with these vortices, it is inferred that some of the vortices extend upto 5000 ft or more, at least over narrow regions while some others are very shallow (below 1000 ft in height).

4·3. *Movement*—The movement of comparatively larger ones can be traced on consecutive synoptic charts. A study of such vortices reveal that they move along the coast from south to north, but it is difficult to say how far they move before they dissipate. The autographic records show that these vortices generally affect Colaba earlier than Juhu, thereby confirming the view that they generally move northwards over the coast. However, such movements are found to be not always along a straight path. Certain amount of oscillations on the east-west direction are noticed. When the vortex becomes stationary, slight oscillations occur along the north-south direction also.

The anemograms of both these stations reveal that there were time-lags in the sequence of significant wind changes recorded at Colaba and Juhu. The time-lag is generally about an hour in many cases thereby indicating that the normal speed of movement of these vortices is about 15 mph. Another important feature of the movement of these vortices is that either the movement is retarded or they even become stationary for some time under certain conditions. The

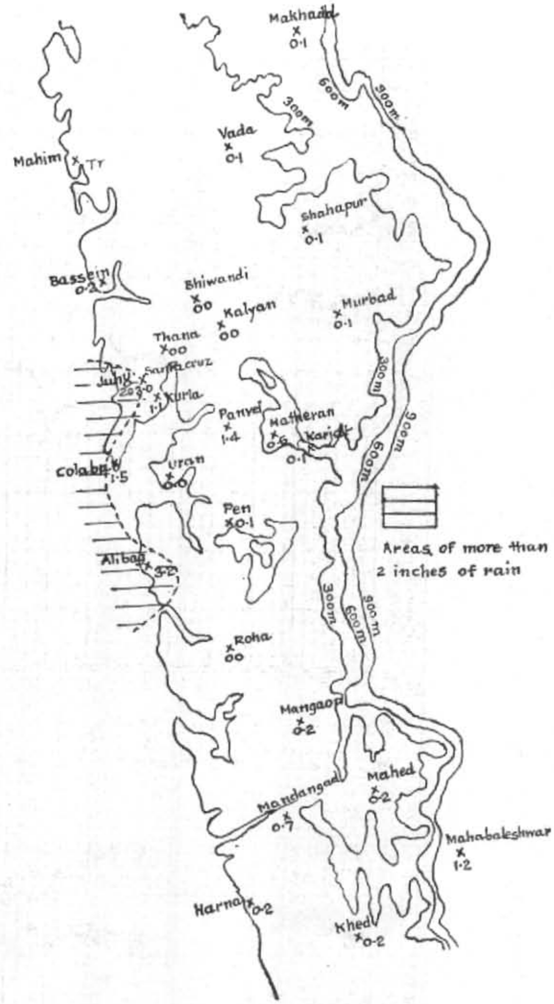

Fig. 15. Rainfall recorded within 24 hours preceding 0830 IST of 17 July 1951

retardation occurs mostly around those localities which are adjacent to the troughs in the contours of the Western Ghats. The retardations are generally found to be associated with accentuation of the vortices and consequent heavier precipitation. Such retardations generally occur during early morning hours. Incidentally, we may find in this phenomenon, at least a partial explanation for the precipitations being heavier and weather squally during the early morning hours at some of the coastal stations during

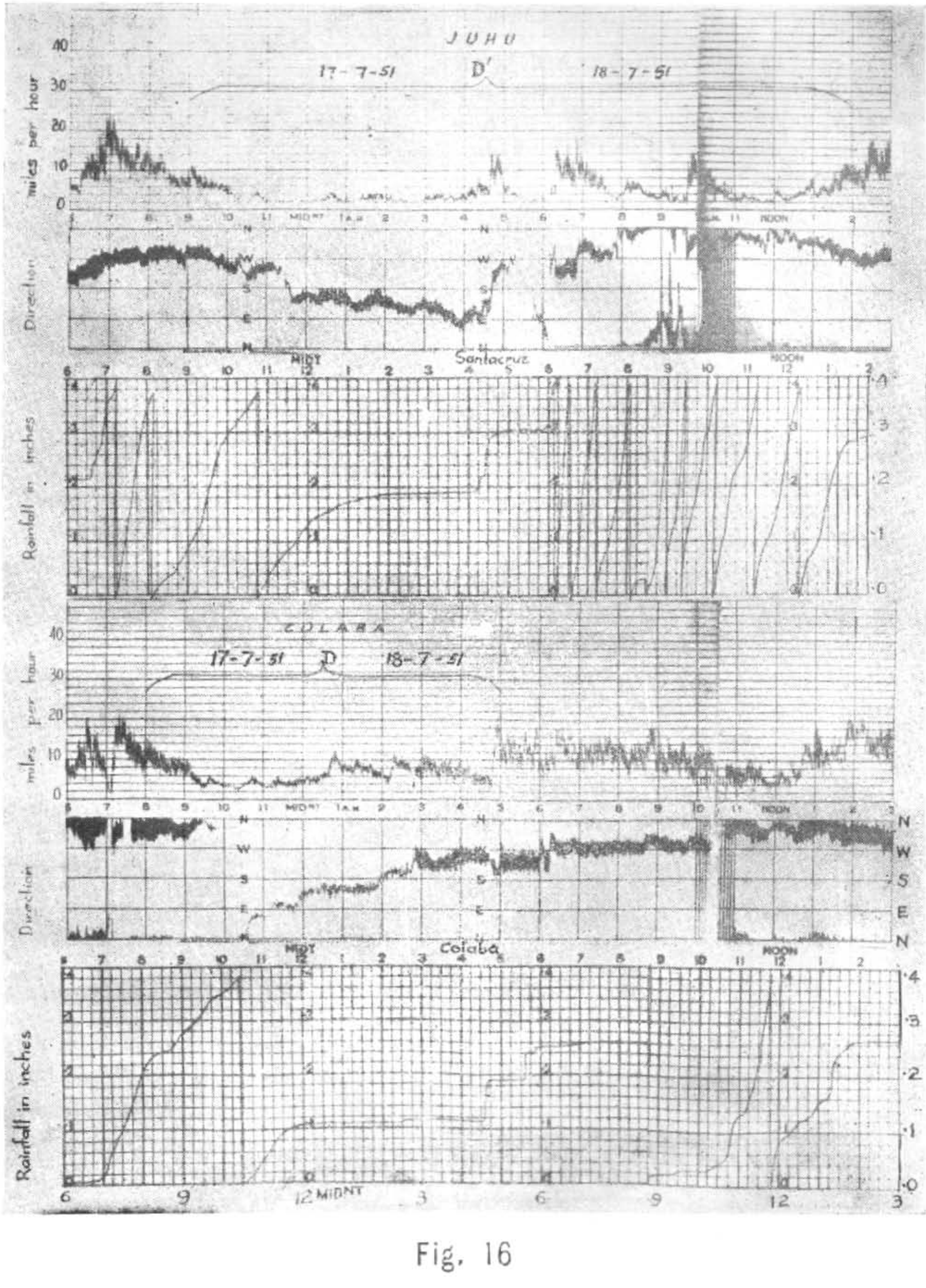
JUHU
17-7-51
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Fig. 16

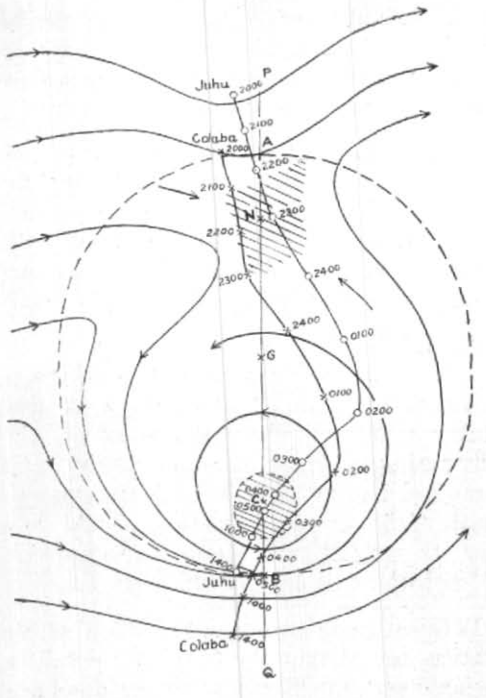

Fig. 17. Horizontal cross-section of the vortex 'D'

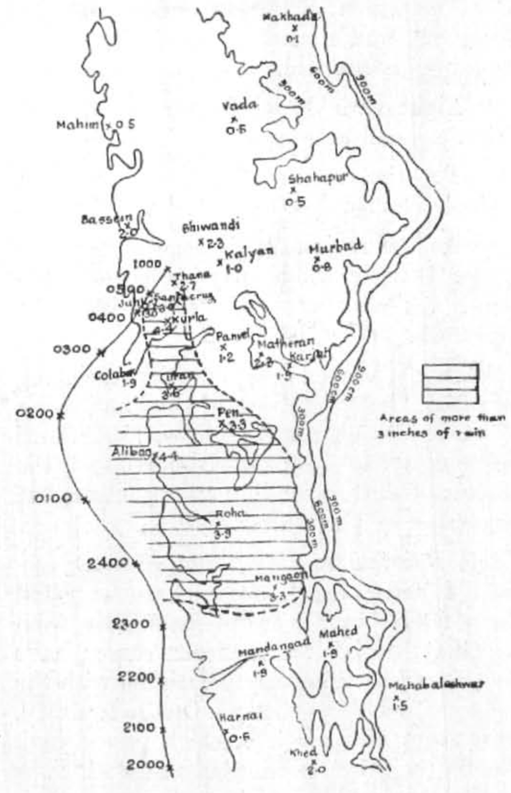

Fig. 18. Rainfall recorded within 24 hours preceding 0330 IST of 18 July 1951

the monsoon season. Mention has been made of such early morning heavy showers.

4·4. *Singular regions of the vortex*—The pattern of flow of air near the surface level associated with a Rankine vortex embedded in a uniform stream is shown schematically in Fig. 4. In such an idealised flow-pattern, the following four singular regions are noticeable—

(1) *Neutral region*—It is a region of mainly calm winds, where the irrotational circular motion is exactly opposed by the translatory motion of the uniform stream.

(2) *Central region*—It is a comparatively large area of steady and rather weak winds having a direction opposite to that of the general stream.

(3) *Core region*—It is an area of cyclonic circulation with a small central region of light variable winds.

(4) *Region of confluence*—It is a zone of steady winds in the direction of, and stronger than, the general stream.

The central points of the above regions are marked as N, G, C and B respectively. The boundary of the effective area associated with the vortex is indicated by a closed line. The 'Neutral' and the 'Core' regions are shown by shaded areas.

The resultant instantaneous directions of surface winds at various points within the effective area of the vortex are shown by the streamlines of flow indicated in the hypothetical model. The winds along a north-south traverse PQ, will have the following characteristic changes—

(1) Considerable weakening of the prevailing westerly winds will be experienced as the point 'A' is approached.

(2) The winds will be practically calm within the region around 'N'.

(3) The winds will change over suddenly to easterly and remain so until the region around 'C' is reached.

(4) Light variable winds are experienced within a small area around 'C'.

(5) To the south of 'C', the wind will suddenly change over to westerly.

(6) As the region 'B' is approached, the steady westerly winds may strengthen, becoming at times unusually strong within the region 'B'.

When the vortex moves northwards along the coast, the orientation of the line joining the areas of weak winds changes. The neutral region gets displaced towards northwest, the amount of shift depending upon the speed of movement of the vortex system.

4·5. *Rainfall associated with off-shore vortices*—Isolated small areas of concentrated heavy falls of rain over the coast away from the Ghats during the monsoon season have been found to be mostly associated with the passage of off-shore vortices. On the contrary, there were also vortices which passed over Bombay without causing any rainfall. Such vortices were found to be either very shallow, or the moisture content in the atmosphere over the area was relatively small.

Examination of the rainfall recorded at some of the coastal stations shows that there were instances when rainfall of the order of 1–2 inches which fell during break-monsoon period could be attributed solely to the influence of off-shore vortices (Fig. 9—c and d). It is therefore not unreasonable to expect heavy falls of the order of 3 inches or more under the influence of such vortices during strong monsoon period when the moisture in the atmosphere at the lower layers is very near the saturation stage.

On occasions when the presence of off-shore vortices at the surface level coincided with the existence of certain upper air conditions favourable for moderate to heavy rain it was found to have resulted in the occurrence of unusually heavy rain over the area.

Among the typical situations shown in Fig. 9, (a) and (b) represent days of strong monsoon conditions all along the west coast while (c) and (d) show the areas of rainfall during a break-monsoon period. A comparison of (a) and (b) with the synoptic charts of the period (Figs. 5 to 8) would show how the rainfall areas were closely associated with the existence of the vortices.

Detailed analyses made on a few of the vortices reveal that the heaviest rainfall associated with any vortex occurs over and near the Core region, particularly over the segment between 'C' and 'B'. Rainfall over the area to the left of the PQ axis is comparatively heavier than that over the other half of the vortex. The rainfall is found to be comparatively least over the quadrant to the right of AG.

5. Acknowledgements

I take the opportunity to acknowledge my grateful thanks to Dr. P. Koteswaram for suggesting the problem and to Dr. B. N. Desai and Dr. P. R. Pisharoty for their valuable guidance in making this study.

REFERENCES

Banerji, S. K.	1928	*Nature*, **122**, 3083.
	1930	The effect of the Indian Mountain Range on Air Motion (*Indian J. Phys.*, **5**, Pt. 7).
Bjerknes, V.	1921	*Geofysiske Publikationer*, **2**, 4.
George, P. A.	1952	*Mem. India met. Dep.*, **29**, Pt. 3.
Palmer, C. E.	1952	*Quart. J. R. met. Soc.*, **78**, 336.