INDIAN TROPICAL STORMS AND ZONES OF HEAVY RAINFALL

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(Received for publication, March 22, 1949)

ABSTRACT. The accepted explanation for the heavy rainfall in southwest monsoon depressions in India on the basis of frontal structure is not supported by radio-sonde data. An alternative explanation on the basis of convergence derived from the isobaric patterns is offered. It has also been applied to satisfactorily explain the distribution of heavy rain in the post-monsoon depressions.

It is well known that in the southwest monsoon depressions, widespread and heavy rain is confined to the southwest sector. This was explained by Ramanathan and Ramakrishnan (1944) as due to the ascent of old monsoon air over the fresh monsoon air as illustrated in Fig. 1. According to them the fresh monsoon air behaves as a cold airmass relative to the old monsoon air. A front therefore develops in the Western sector between the two air masses and it slopes up towards the south. Consequently the rainfall due to the upglide of the old monsoon air occurs in the southwest sector of the depression.

Examination of radio-sonde ascents in the southwest sector, however, showed that the existence of the front was doubtful as no marked temperature discontinuities were noticed. A depression devoloped in the NE Bay of Bengal on 1. 7. 45 and intensified into cyclonic storm by 0230 hrs. G.M.T. of 2. 7. 45. Widespread and heavy rain occurred in the southwest quadrant of the storm as will be seen from Fig. 2, which shows the isobaric distribution

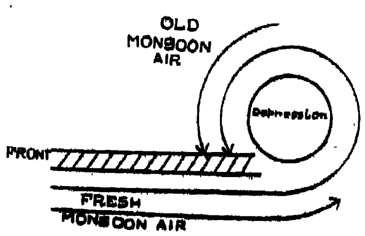

FIG. 1

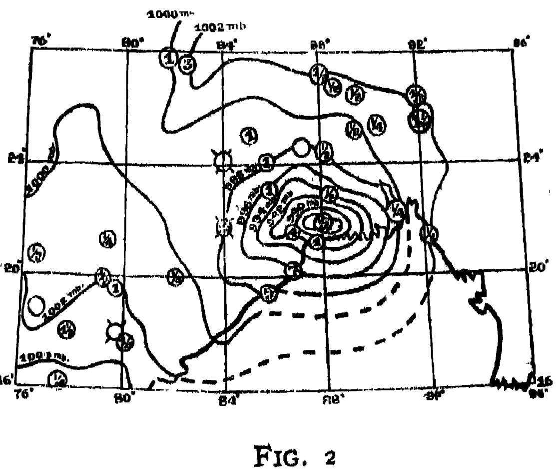

FIG. 2
Rainfall shown in circles.

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at 0200 hrs. G.M.T. of 2. 7. 45 and the rainfall amount in the preceding twentyfour hours. Cuttack situated in the southwest section, recorded seven inches of rain during the period. In Fig. 3 is given the radio-sonde ascent of 1300 hrs. G.M.T. of 1. 7. 1945. It will be seen that the ascent curve does not show the existence of two airmasses and hence the above explanation does not seem to be satisfactory. An alternative explanation for the rainfall in the southwest sector of monsoon depressions is given below :—

The equation for gradient wind is :

$$V = \frac{1}{\rho\lambda}\frac{\partial p}{\partial n} + \frac{1}{\lambda}\frac{V^2}{r} \quad \ldots \quad (1)$$

where V is the gradient wind and the other terms have their usual significance. r is positive for anticyclonic flow and negative for cyclonic. We proceed to find the horizontal divergence in the area $ABCD$ (Fig. 4) where AB and CD are two successive isobars of values p_0 and $p_0+\Delta p$ and AC and BD are respectively the wedge and trough lines. Due to the gradient flow which is along the isobars, the horizontal divergence, termed as longitudinal divergence by Bjerknes and Holmboe (1944) is :

$$V_2BD - V_1AC = \left[\frac{1}{\rho_2\lambda_2}\left(\frac{\partial p}{\partial n}\right)_2 BD - \frac{1}{\rho_1\lambda_1}\left(\frac{\partial p}{\partial n}\right)_1 AC\right] + \left[\frac{1}{\lambda_2}\frac{V_2^2}{r_2}BD - \frac{1}{\lambda_1}\frac{V_1^2}{r_1}.AC\right]$$

$$= \Delta p\left[\frac{1}{\rho_2\lambda_2} - \frac{1}{\rho_1\lambda_1}\right] + \left[\frac{1}{\lambda_2}\frac{V_2^2}{r_2}BD - \frac{1}{\lambda_1}\frac{V_1^2}{r_1}AC\right] \quad \ldots \quad (2)$$

Subscript 1 and 2 refer respectively to the values at AC and BD. As AC is to the north of BD, $\lambda_1 > \lambda_2$, while r_2 which refers to cyclonic flow is negative. The first term is therefore divergent while the second term is convergent. We have neglected variations in density which are generally small, particularly in barotropic conditions as in tropics. It can be shown that the net flow is longitudinally convergent when

r_1 is the critical radius of curvature for anticyclonic flow

r_2 =900 kms

$\frac{dp}{dn}$ $\frac{1}{150}$ mb/km

$AC = BD =$ 300 kms

and λ_1 and λ_2 correspond respectively to 25°N and 15°N.

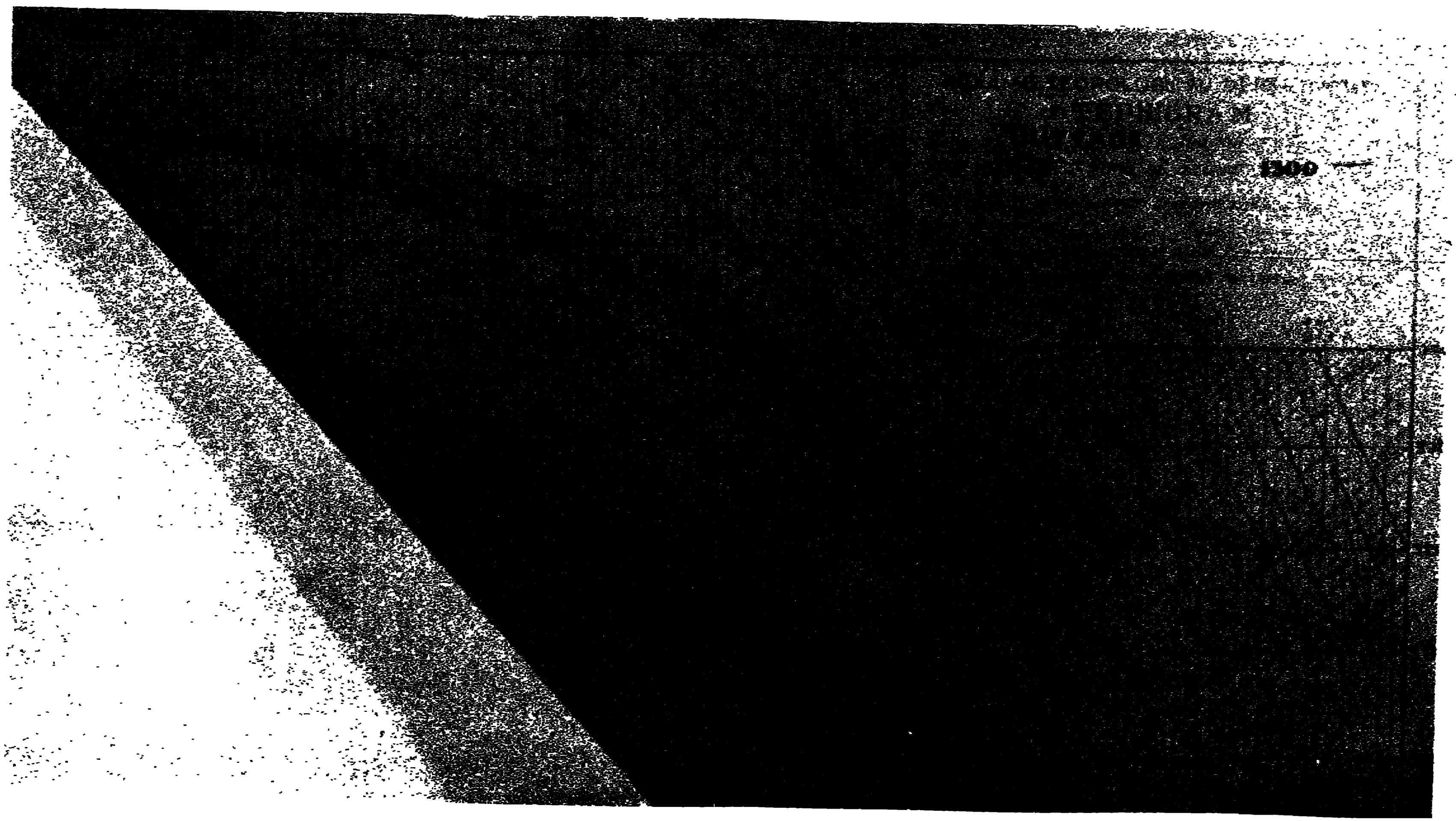

Fig. 3.

The above values of variables have been so chosen as to approximate to the conditions in the SW monsoon depressions in India. Thus under such conditions the airflow is longitudinally convergent from a high to low and by similar reasoning longitudinally divergent from a low to high.

Let us now briefly consider the case when the air flow is from east to west. As before, the divergence is:

$$V_2.BD - V_1AC = \left[\frac{1}{\rho_2\lambda_2}\left(\frac{\partial p}{\partial n}\right)_2 BD - \frac{1}{\rho_1\lambda_1}\left(\frac{\partial p}{\partial n}\right)_1 AC\right] + \left[\frac{1}{\lambda_2}\frac{V_2^2}{r_2}BD - \frac{1}{\lambda_1}\frac{V_1^2}{r_1}AC\right]$$

$$= \Delta p\left[\frac{1}{\rho_2\lambda_2} - \frac{1}{\rho_1\lambda_1}\right] + \left[\frac{1}{\lambda_2}\frac{V_2^2}{r_2}BD - \frac{1}{\lambda_1}\frac{V_1^2}{r_1}AC\right] \quad \text{... (2)}$$

In the present case λ_1 corresponds to a more southerly latitude than λ_2 and hence $\lambda_1 < \lambda_2$. r_2 is negative as it corresponds to cyclonic circulation. Thus for easterly flow from a high to a low both the terms are negative and there is longitudinal convergence. Similarly in an easterly current the air flow is divergent from a low to a high. The above points are illustrated in Fig. 6.

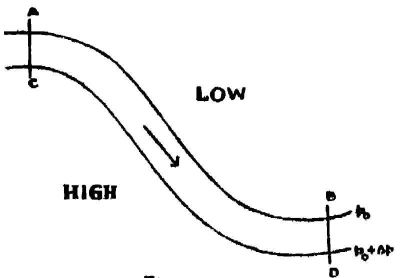

Fig. 4.

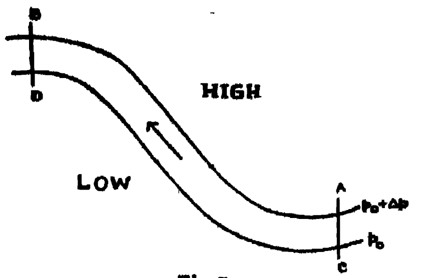

Fig.5.

FIG.

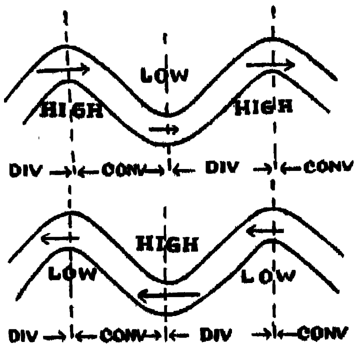

FIG. 6

Bjerknes and Holmboe (1944) have termed the divergence due to the cross-isobar wind component which arises owing to tangential acceleration as Transverse Divergence. V_t, the cross isobar component, is given by

$$V_t = \frac{1}{\lambda} v \frac{\partial v}{\partial s}$$

where s is measured along the isobar. The flow across the isobar is thus :

$$\int_{v_1}^{v_2} v_t . ds = \int_{v_1}^{v_2} \frac{1}{\lambda} v \, dv = \tfrac{1}{2}\left[\frac{v_2^2}{\lambda_2} - \frac{v_1^2}{\lambda_1} \right] \quad \ldots \quad (3)$$

This is the transverse flow at an isobar. The transverse divergence in the area $ABCD$ will be given by the difference between the flow at two successive isobars. This will be zero when the successive isobars are parallel. We may compare the quantity

$$\tfrac{1}{2}\left[\frac{v_2^2}{\lambda_2} - \frac{v_1^2}{\lambda_1} \right]$$

with the second term

$$\left[\frac{v_2^2}{\lambda_2} \frac{BD}{r_2} - \frac{v_1^2}{\lambda_1} . \frac{AC}{r_1} \right]$$

in equation (2). BD or AC and r_2 or r_1 are generally comparable quantities. Hence BD/r_2 and AC/r_1 will not be too small. For instance, in the numerical example given previously $-(BD/r_2) = \frac{1}{3}$. As r_2 has opposite sign to r_1 in the flow from a trough to a ridge or viceversa, the term for cross-isobar flow and the cyclostrophic component of longitudinal convergence (*i.e.* second term of equation (2) will respectively represent the sum and difference of nearly equal terms. Hence the transverse divergence (which is given by the difference between the cross-isobar flow at two successive isobars) may be neglected as compared with the longitudinal divergence (to which the main contribution is due to the cyclostrophic component). If the gradient is less in the ridges and more at the troughs, the difference between v_2^2 and v_1^2 will be negligible and hence in such cases transverse divergence can be neglected. As in tropical cyclones, the isobars open out at the ridges and come closer at the troughs, we are justified in taking account of the longitudinal divergence only.

We now consider the longitudinal divergence in a system of closed isobars moving west. $ABCD$ is a line dividing the low into eastern and western halves, (Fig. 7). The net divergence in the eastern half is :

$$v_1 AB - v_2 CD = \Delta p \left[\frac{1}{\rho_1 \lambda_1} - \frac{1}{\rho_2 \lambda_2} \right] + \left[\frac{v_1^2}{\lambda_1} \frac{AB}{r_1} - \frac{v_2^2}{\lambda_2} . \frac{CD}{r_2} \right] \quad \ldots \quad (4)$$

Here subscripts 1 and 2 refer respectively to AB and CD and $\lambda_1 > \lambda_2$. If the consecutive isobars are concentric, both the terms are negative and there is convergence in the eastern half and divergence in the western half. But in a depression moving to west $r_1 > r_2$ and this can cause V_1 to be sufficiently greater than V_2 for the second term to become positive. In such cases, the longitudinal divergence is probably small enough to be neglected. Where this difference in the radii of curvature r_1 and r_2 is not sufficient to make the second term compensate the first, in equation (4), it is necessary, as shown by Bjerknes and Holmboe (1944), that the circular isobars should be closer to the south than to the north for the resulting flow to be non-divergent.

The isobaric pattern with a southwest monsoon depression is shown in Fig. 3. The airflow between the two isobars P_1 and P_2 is from anticyclonic

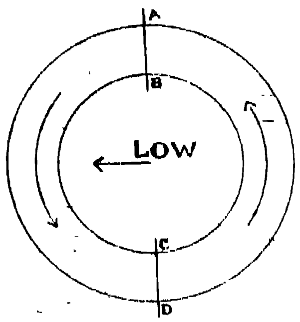

FIG. 7

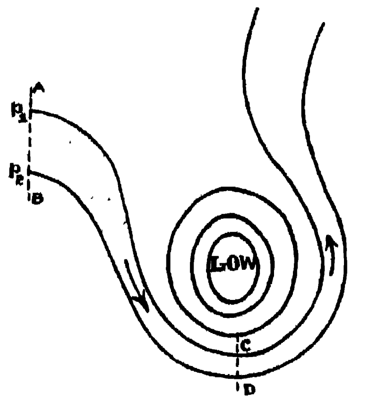

FIG. 8

curvature at AB to cyclonic curvature at CD and hence convergent, as shown before. It is apparent that the airflow between the isobars P_1 and P_2 is not appreciably convergent in any other portion. The values of the various variables, used for discussion in the earlier para, correspond to the conditions met in this case. But owing to the movement of the whole pattern to the west along with the motion of the depression, the curvature of the airpath is, however, greater than that indicated by the isobars. Correspondingly the contribution of the second term in equation (2) is greater and hence the longitudinal convergence is also greater. For reasons explained in the discussions of longitudinal divergence in closed isobars, the flow in the portion of the closed isobars seems non-divergent. Probably this is partly obtained by the slight crowding of isobars to the south in the closed system. As we recede away to the south from the centre of the depression, the perturbation, due to the depression on the normal west to east isobars, decreases and hence the convergence also diminishes. It will thus be seen that the area of maximum convergence is in the southwest sector of the depression but somewhat away from the centre. As convergence leads to rainfall, the occurrence of widespread and heavy rain in the southwest sector of southwest monsoon depressions is explained. As an illustration we give in Fig. 9 the isobaric map of 0230 hrs. G.M.T. on 30. 6. 1930, the rainfall distribution during the

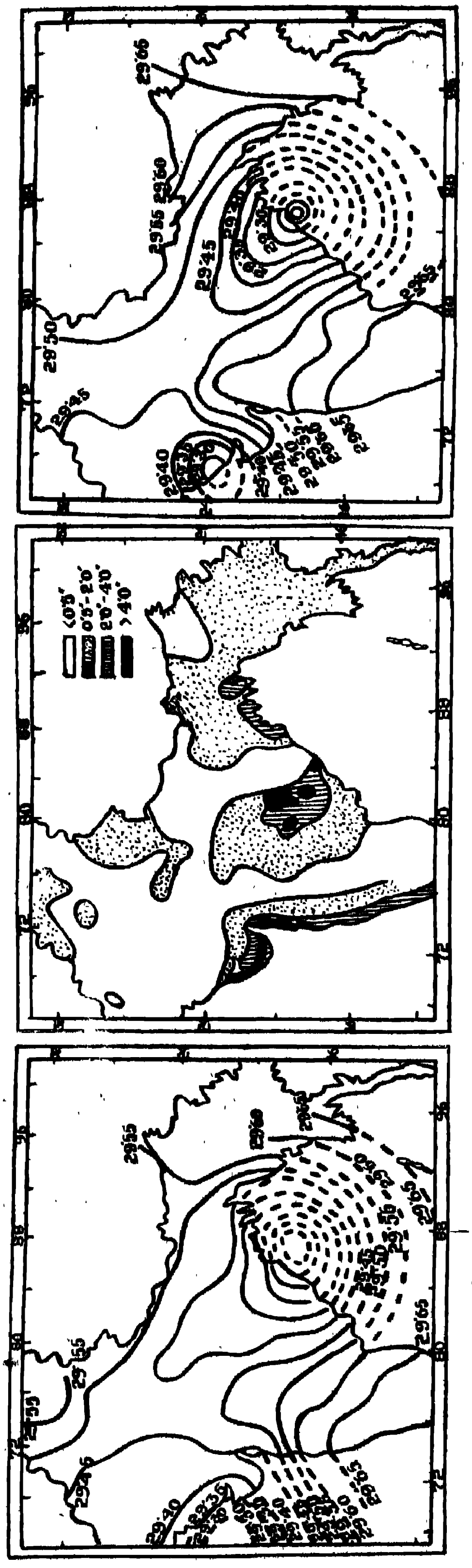

FIG. 9

(a) Isobars at 0800 Hrs. I.S.T. of 30.6.1930.
(b) Rainfall from 0800 Hrs. I.S.T. of 30.6.1930 to 1.7.1930.
(c) Isobars at 0800 Hrs. I.S.T. of 1.7.1930.

following twentyfour hours, and the isobaric map of 0230 hrs. G.M.T. on 1. 7. 1930.

In the post-monsoon depressions, the northeast sector gets the heavy rain. The distribution of isobars with such a depression is shown in Fig. 10. By reasoning similar to the preceding case, it can be seen that the area of convergence is only in the northeast sector, and hence heavy rain is confined to that area.

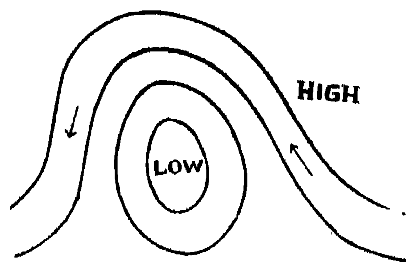

FIG. 10

The above discussion brings out how the rainfall distribution in tropical depressions affecting India can be explained from the zones of convergence derived from the isobaric patterns.

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