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On the occurrence of rainfall over southwest sector of monsoon depression

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ABSTRACT. The generally observed feature that there is good rainfall activity in the southwest sector of the monsoon depression when it moves northwestwards/westnorthwestwards and in the northeast sector of the monsoon depression when, after recurvature, it moves northwards/northeastwards has been explained on the basis of ω—equation.

1. Introduction

Numerical computations of vertical velocity using simplified quasi-geostrophic adiabatic ω-equation in our earlier study (Rao and Rajamani 1970), showed upward motion in the southwest sector agreeing with the well known feature that there is maximum rainfall activity in the southwest sector of the monsoon depression (or low). It was explained in that paper on the basis of simplified ω-equation how the advection of vorticity by thermal wind causes upward motion in the western sector. In the present paper, considering ω-equation in a more detailed manner, it is explained why the rainfall is generally more widespread in the southwest sector in the case of the monsoon depression which moves with westward component and in the northeast sector in the case of the depression which moves with eastward component.

There have been a number of studies made earlier on the occurrence of rainfall in the southwest sector like those by Pisharoty and Asnani (1957), Bedekar and Banerjee (1969), Rao (1976) and others. Bedekar and Banerjee (1969) and Rao (1976) have explained this observed feature considering the synoptic aspects of the monsoon systems. In this study an attempt has been made to explain this observed feature by applying ω-equation to the typical wind field and temperature field of the monsoon season.

2. Equation and discussion

The complete ω-equation based on the balance equation is given below :

$$\nabla^2 \omega + \frac{f^2}{\sigma} \frac{\partial^2 \omega}{\partial p^2} = \frac{f}{\sigma} \frac{\partial}{\partial p} (\mathbf{V} \cdot \nabla \eta) + \frac{R}{\sigma p} \nabla^2 (\mathbf{V} \cdot \nabla T) - \frac{f}{\sigma} \frac{\partial}{\partial p} \left(\zeta \frac{\partial \omega}{\partial p} - \omega \frac{\partial \zeta}{\partial p} \right) - \frac{f}{\sigma} \frac{\partial}{\partial p} \left(\frac{\partial \omega}{\partial y} \frac{\partial u}{\partial p} - \frac{\partial \omega}{\partial x} \frac{\partial v}{\partial p} \right) - \frac{\omega}{g} \nabla^2 \ln \sigma - \frac{2}{g} \nabla \omega \cdot \nabla \ln \sigma - \frac{f}{\sigma} \frac{\partial^2}{\partial p^2} (\mathbf{k} \cdot \nabla \times \tau) - \frac{R}{c_p \, p \, \sigma} \nabla^2 \dot{Q} - \frac{f}{\sigma} \frac{\partial^2}{\partial p \, \partial t} \nabla^2 \left(\psi - \frac{g}{f} z \right) \quad (1)$$

According to Krishnamurti (1968), the first two terms on the right hand side are one order of magnitude more than all other terms. Also, in the earlier study (1975), the authors have computed and found that the inclusion of effect of release of latent heat of condensation in the computation of ω-field increases the magnitude, but does not change the pattern of ω-field. This

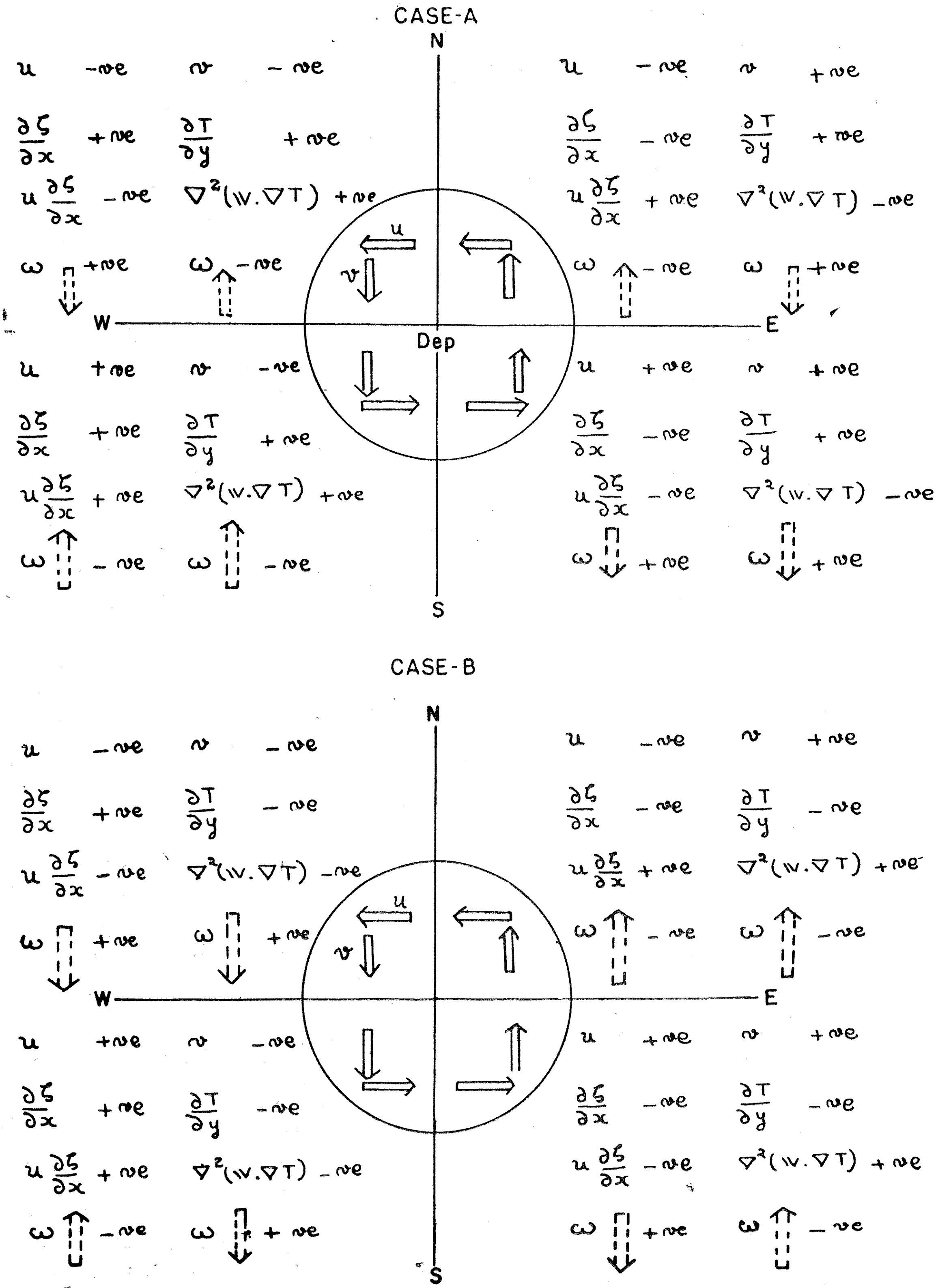

Fig. 1. Effects of the first two terms of ω-equation

would mean that our discussions can be restricted to the first two important terms for all practical purposes.

The L.H.S. of Eqn. 1, involves second order derivative in space and this can be shown to be proportional to "$-\omega$", (Holton 1972) assuming, the ω-field to be sinusoidal field (or even if it is a field that can be represented by a Fourier series, the following argument will hold good) :

Let,

$$\omega = W(p) \sin k x \sin ly$$

$$\nabla^2 \omega = -(k^2 + l^2)\, \omega$$

$$\frac{\partial^2 W}{\partial p^2} = -\left(\frac{\pi}{p_0}\right)^2 W$$

Therefore, we have

$$\nabla^2\omega + \frac{f^2}{\sigma}\frac{\partial^2\omega}{\partial p^2} \propto$$

$$-\left\{k^2 + l^2 + \frac{1}{\sigma}\left(\frac{f\pi}{p_0}\right)^2\right\}\omega$$

So, this equation states that there would be rising motion wherever there is increase of advection of positive vorticity with height and also where there is warm advection as explained very lucidly for an ideal situation by Holton in '*Dynamic Meteorology*' (1972). But, the case of monsoon depression is very different in the vertical structure, as regards the temperature patterns etc from the case discussed by Holton. Hence, applying ω-equation to the typical monsoon conditions, it is attempted to explain the observed feature of maximum rainfall activity in the southwest or northeast sector of the monsoon depression as the case may be.

First let us consider first term on right hand side of the ω-equation (Eqn. 1). It can be easily seen that $u\,(\partial\zeta/\partial x)$ is more dominant than $v\,(\partial\zeta/\partial y)$ as v is small compared to u, although $\partial\zeta/\partial x$ and $\partial\zeta/\partial y$ are comparable in magnitude. In the depression field $u\,(\partial\zeta/\partial x)$ is positive in the southwest sector where both u and $\partial\zeta/\partial x$ are positive and also in the northeast sector where both are negative. As the intensity of the system decreases with decrease of pressure, p, $\partial/\partial p\,(\mathbf{V}.\nabla\zeta)$ is positive or ω is negative in the southwest sector and northeast sector of the depression.

Next considering the second term on the right hand side of Eqn. 1, $\nabla^2\,(\mathbf{V}.\nabla T)$ is proportional to $-\mathbf{V}.\nabla T$ (as discussed in the case of ω). As can be seen from the temperature patterns of July (Rao 1976) temperature increases northward from Indian Ocean (5 deg. N), upto 25 deg. N or so and further north it decreases. As the isotherms are east-west oriented, $\partial T/\partial x$ is small compared to $\partial T/\partial y$. Generally the monsoon depression moves in the latitudinal belt of 18 deg. to 25 deg. N (*Tracks of Storms and Depressions in the Bay of Bengal and the Arabian Sea,* India Meteorological Department) during the months July and August. During the month September the depressions form at more southerly latitudes, around 15 deg. to 18 deg. N and move westwards or northwestwards and they recurve if they reach position north of 22 deg. N or so. Hence it is clear that the depression move with westward component south of 25 deg. N in July and August and south of 22 deg. N (approx.) in September and consequently the systems are in the field of temperature increasing northwards [case A-Fig. (1)]. It is assumed here that temperature variations across the depression is rather small so that $\partial T/\partial y$ is positive in the entire field of depression (studies on structure of depression, Daggupathy and Sikka 1977 and Krishnamurti *et al.* 1975, showed that the depression had a cold core 1-2 deg. C upto 600 mb and 1-2 deg. C warm core in upper troposphere. This shows the temperature variation is not only small but also around 600 mb level there would be much less variation of temperature as the cold core is changing to the warm core). Hence in western sector (where winds are northerly) $v\,(\partial T/\partial y)$ is negative making $\nabla^2\,(\mathbf{V}.\nabla T)$ positive and ω negative. In other words there is ascending motion due to this term in western sector. Similarly, it can be shown that due to this term in the eastern sector ω is positive or there is descending motion. As commonly known, this can be said as the warm advection in the western sector and cold advection in the eastern sector causing upward motion and downward motion respectively.

Considering the total effects of these two terms, their magnitudes are comparable (Krishnamurti 1968). In the northwest sector and northeast sector they are opposite in sign and in southwest sector and in southeast sector they have the same sign. However, in the southwest sector, ω is negative due to both terms and there is ascending motion. whereas in the southeast sector ω is positive due to both terms and there is descending motion. As there is descending motion due to both terms in southeast sector, we should expect that there would be clear sky conditions whereas in the northwest and northeast sectors there need not completely clear sky conditions. However, this vertical velocity is mainly due to large-scale motion. Hence, it does not preclude totally, the vertical velocity due to smaller scale motion. The effects of the two terms are represented pictorially (Fig. 1-Case A)

Generally in September the depression moves with westward component if it is south of 22 deg. N or so and if it is north of that latitude, it recurves and moves northwards or northeastwards (*Tracks of Storms and Depressions in the Bay of Bengal and the Arabian Sea,* India Met. Dep.). Then the depression would be near the foot hills of the Himalayas, north of 25 deg. N. In

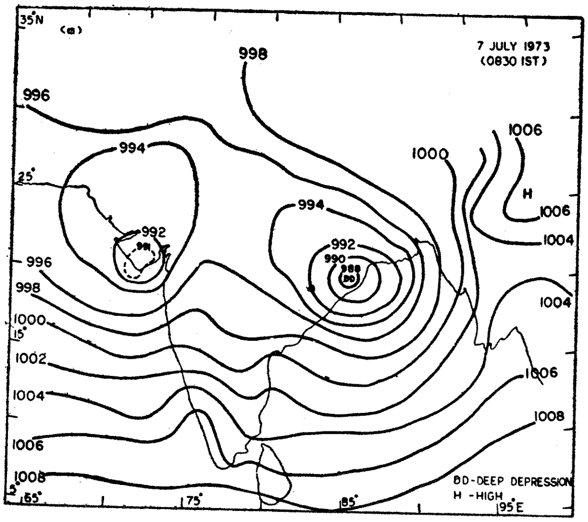

Fig. 2 (a). Position of the depression on 7 July 1973 (0830 IST)

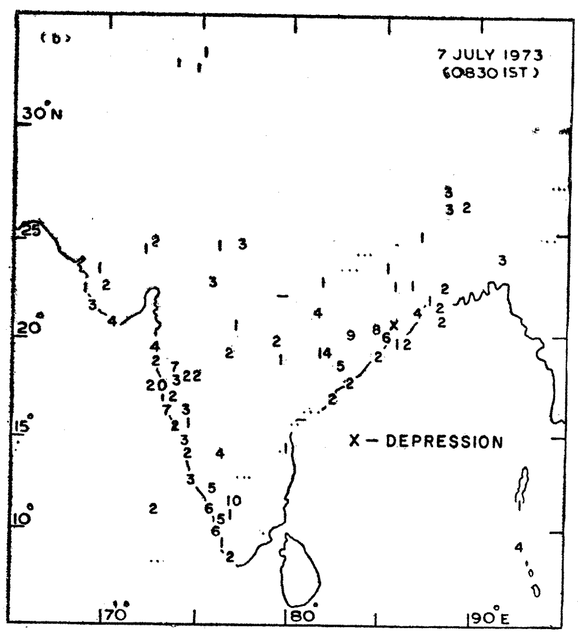

Fig. 2(b). 24-hour rainfall recorded at 0830 IST of 7 July 1973

September the latitude of maximum temperature shifts southward compared to July and August and therefore, in this region as can be seen from mean temperature pattern for the month September $\partial T/\partial y$ is negative, *i.e.*, temperature decreases northward (this is particularly so, in the northern sector of the depression). So $v\ (\partial T/\partial y)$ is negative in northeast sector and is positive in northwest sector. Consequently $\nabla^2\ (\mathbf{V}.\ \nabla\ T)$ is positive and ω negative in northeast sector Similarly it can be proved that due to this term, ω is positive in northwest sector and southwest sector and it is negative in southeast sector [Fig. 1-Case B]. As a result, due to both terms of ω-equation, there is upward motion only in northeast sector of the depression or low, thus explaining why there is more rainfall activity in the northeast sector of the depression or low. Fig. 1-Case B represents the effects of the two terms pictorially.

Although a number of studies have proved beyond doubt about the maximum rainfall activity in the preferred sector of the depression, two cases of synoptic situations, one moving with westward component and the other moving with eastward component with their respective rainfall patterns have been presented here in Figs. 2 and 3 as

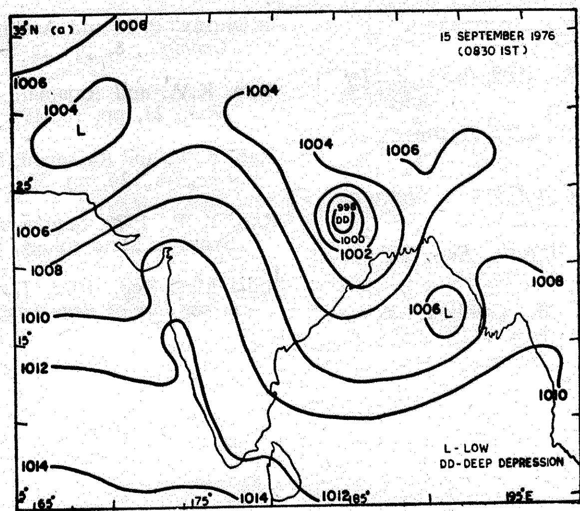

Fig. 3(a). Position of the depression on 15 September 1976 (0830 IST)

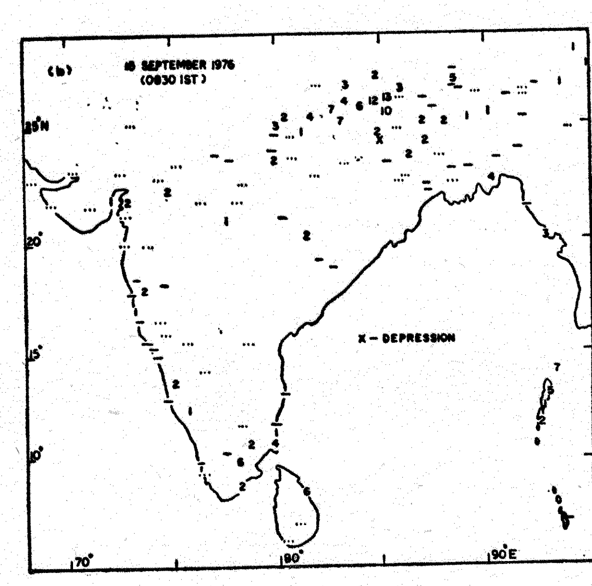

Fig. 3(b). 24-hour rainfall recorded at 0830 IST of 15 September 1976

illustrations. It may be noted that in Fig. 2(a) and Fig. 2 (b) rainfall amounts are reported to the south and even slightly to southeast of the centre of the depression. This is because those places have been in the southwest sector of the depression which had moved westward from East during the past 24 hours. Similarly the rainfall north of the centre of the depression [Fig. 3(a) and Fig. 3(b)] also can be explained. Also in the computational study made using quasi-geostrophic baroclinic model by Rao and Rajamani (1970), the regions of maximum upward motion at 850, 700 and 500 mb levels were found to be in the southwest sector (although the regions of upward motion extended a little to the northwest sector also) agreeing with the regions of rainfall activity.

3. Conclusion

The well known observed feature that the rainfall activity is maximum in the southwest sector in case of the westward or northwestward moving monsoon depression and in the northeast sector in the eastward moving monsoon depressions could be explained on the basis of ω-equation.

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