STRUCTURE AND DYNAMICS OF MONSOON DEPRESSIONS: THE MONEX DEPRESSION (JULY 1979)[1]

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1. INTRODUCTION

It is generally believed that although the initiation of the onset of the Asiatic monsoon is related to the planetary scale heat sources and sinks (due to asymmetric continentality and different thermal properties of land and ocean), the maintenance and the short term variability of the monsoon is primarily determined by the release of the latent heat of condensation, a major portion of which occurs in association with synoptic and large scale disturbances. The monsoon disturbances therefore play a very important role in the dynamics of the planetary scale monsoon circulation. Preliminary studies based on the FGGE/MONEX data tend to support the conjecture that even if the large scale thermal and dynamical circulations are conducive for onset, the onset process requires a finite amplitude perturbation for northward propagation and establishment of the monsoon over India.

There are several classes of monsoon disturbances (depending upon their space-time scales), the most important of these being the east-west oriented monsoon troughs which move north and south, and the monsoon depressions which 'appear' over the Bay of Bengal and move northwest over India. In this paper we shall confine our discussion to the mechanisms responsible for the formation of monsoon depressions.

There have been many suggestions about the mechanisms for the formation of monsoon depressions. During the first quarter of the century, there were attempts to explain the dynamics of monsoon depressions based on extra-tropical frontal dynamics models which were subsequently abandoned when upper air soundings failed to show sufficient baroclinicity. Subsequent attempts to explain the dynamics of monsoon depressions were influenced by the quasi-geostrophic development theory. In recent years, empirical evidence has been presented to show the relationship between the formation of monsoon depressions, the presence of warm pools at 200 mb (Moula, 1968), and decreased vertical shear (Raman et al., 1978).

The possibility of monsoon depression formation being forced by dynamical instabilities of the mean monsoon flow was examined by Shukla (1977, 1978). Barotropic instability analysis was carried out for each level separately and it was found that both the lower and the upper levels were barotropically unstable. However, since the upper levels, due to the presence of the westerly and the easterly jet streams, had the largest available kinetic energy, the growth rates and the amplitudes were largest for the upper level jet. The most unstable mode for the joint barotropic-baroclinic instability was also found to be dominated by the upper level instability whose phase speed was larger

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than that of a typical monsoon depression. A joint CISK-barotropic-baroclinic instability analysis of the monsoon flow suggested that the latent heat of condensation is the most crucial source of energy for the growth and maintenance of the monsoon depressions. It is interesting to note that during the 1880's Eliott had suggested that the latent heat of condensation may be the primary energy source for initiation and maintenance of monsoon depressions; however, a quantitative treatment of interaction between latent heating and dynamics was not possible until recently when Charney and Eliassen (1964) and Ooyama (1964) developed the CISK theory. Based on CISK-barotropic-baroclinic instability studies it was concluded that the barotropically unstable lower layers are the primary triggers for the onset of the instability which is further amplified by the latent heat of condensation. In addition, it was conjectured that the role of the terrain is to force a large scale flow which is barotropically unstable at lower levels.

Recently, Mishra and Salvekar (1980) have shown that baroclinic instability alone can account for the growth of the monsoon depressions. This erroneous conclusion is the consequence of the choice of a highly unrealistic meridional temperature gradient at the ground and arbitrarily chosen vertical wind shear at the lower levels. In the classical baroclinic instability problem (Eady, 1949), the primary forcing comes from the meridional temperature gradient at the surface, and the choice of an unrealistic vertical shear at the lower levels is equivalent to specifying an unrealistic meridional temperature gradient at the ground. In the real atmosphere the observed vertical shear near the surface is largely determined by the frictional forces and the boundary layer dynamics. The internal jet instability (Charney and Stern, 1962) of the upper level flow calculated by Mishra and Salvekar is in agreement with the earlier calculations (Shukla, 1977; Goswami et al., (1980)); however, it does not provide the explanation for the monsoon depressions. Satyan et al. (1981) have calculated the barotropic-baroclinic instability of the monsoon flow which includes vertical shear of the meridional wind. As it was implicit in the work of Eady (1949), vertical shear of the meridional wind is always unstable because there is no stabilizing beta effect. The results of Satyan et al. therefore appear to be a mere artifact of the choice of large vertical shear in the meridional wind for which there is no observational evidence.

In most of the instability studies of the monsoon flow there has been too much emphasis on the concept of a 'preferred scale.' It is fairly clear by now that the latent heat of condensation is the most important energy source for the monsoon depressions. It is important to note that the concept of maximum growth rate as a criterion for the preferred scale, which is quite reasonable for shear instabilities, is not necessarily suitable for the condensation-driven instabilities. As was pointed out by Shukla (1978), a large growth rate does not necessarily imply that the wave will attain the maximum amplitude and dominate over the other waves. The fastest growing wave will equilibrate faster and therefore the most preferred wave will be determined by its ability to maximize the utilization of the available moisture. The potential for dominance is therefore calculated as the ratio of the imaginary and the real parts of the complex phase speed. These considerations indeed gave the most preferred scale to be about 3000 km, which is contrary to the statements by Keshavamurty et al. (1978) and Mishra and Salvekar (1980) that the earlier studies failed to get a preferred scale.

2. WHERE DO THE MONSOON DEPRESSIONS FORM?

It has been generally assumed that the monsoon depressions originate over the Bay of Bengal and, therefore, most of the instability studies have examined the flow over this region. A recent study by Saha et al. (1981) has shown that during the 10-year period, 1969-1978, more than 80% of the monsoon depressions appearing over the Bay of Bengal were associated with predecessor disturbances coming from the east. This suggests that the cyclogenesis over the Bay mainly involves the amplification of a pre-existing disturbance and one need not have to investigate the conditions for the growth of infinitesimal disturbances. Since the sea surface over the Bay is the warmest at that latitude and the low level flow is convergent due to the presence of the monsoon trough, the CISK mechanism appears to be the most appropriate to explain the growth of the monsoon depressions. It remains to be clarified as to why for some weak disturbances CISK mechanism leads to rapid growth and for others it does not.

It is interesting to note that the westward propagating disturbances in the tropics seem to be ubiquitous as they can be traced back to the Pacific, the Atlantic and the African land masses. The formation of the monsoon depressions, the intense easterly waves, and the cyclonic storms, etc., depends upon the existence of suitable large scale environment where these pre-existing weak disturbances can grow.

3. FORMATION OF THE MONEX DEPRESSION (JULY 1979)

The cyclonic circulation over the Bay of Bengal was first observed on July 5 at about 500 mb (there was no data above 500 mb) and it later descended to the lower tropospheric levels. This behavior was also noticed in the study of the past cases by Saha et al. (1981) and Raman et al. (1978). We know that the upper level easterly jet always satisfies the necessary conditions for barotropic instability and internal jet instability. Is it possible that the growth of the amplitude in the lower troposphere is caused, at least in part, by the downward radiation of wave energy? This possibility is being examined by Held and Desmukh (personal communication). However, since the upper level waves propagate westward with a large phase speed, it needs to be examined whether their stay over the Bay is long enough to build sufficient low level amplitude.

It has been shown by Saha and Shukla (1980) that there was some evidence of a westward propagating disturbance which may have amplified into a monsoon depression over the Bay of Bengal. It has also been shown by Nitta and Murakami (1980) that the lower level flow over the Bay was barotropically unstable during the growth of this depression.

It was noticed during the field phase that the extent and the organization of the clouds associated with the depression was not well defined and in spite of a well defined dynamical circulation, the cloudiness was poorly organized. It was also observed that the amplitude of the disturbance was prominent only in the lower and middle troposphere; the amplitude at 900 mb and below was rather weak. This leads to a speculation that rapid growth of the monsoon depression over the Bay of Bengal depends upon its ability to utilize the latent heat of condensation by drawing on the boundary layer moisture convergence. If the initial disturbance does not have sufficient amplitude in the lowest layers, where the mixing ratio is the highest, moisture convergence and associated latent heating may not be adequate to intensify the disturbance. We do not understand why some of the disturbances develop large amplitudes in the lowest layers and others do not. We also do not understand what determines the downward propagation of amplitude intensity. We hope that further theoretical studies may clarify the mechanism responsible for some of these observed features. It should be pointed out, however, that the phenomena of downward build up of the disturbance amplitude is also noticed for the growth stage of the tropical cyclones and, therefore, in some respects, the growth of a monsoon depression is not very different from the growth of a tropical cyclone. The monsoon depressions, however, move over land only after a few day's stay over the Bay and therefore do not intensify into tropical cyclones.

4. MOVEMENT OF MONSOON DEPRESSIONS

It is generally observed that the phase velocity of the monsoon depressions over the Bay is smaller than that over the adjoining land. Pre-depression disturbances coming from further east have different phase velocities depending upon the level at which their amplitude is most pronounced. The low level flow over the Bay is generally westerly and if the depression has large amplitude at the lower levels, the steering effect will produce eastward movement. The beta effect and the lower boundary slope effect will produce westward movement. The role of the quasi-geostrophic dynamics, by the combined effects of differential vorticity advection and thickness advection in determining the phase velocity, will depend upon the structure of the large scale and the embedded disturbance. Preliminary computations by Sanders (1981) indicated that the quasi-geostrophic dynamics was not very dominant in determining either the growth or the movement of the depression during the developing stage.

It is suggested that the rapid westward propagation is related to the vertical structure of the monsoon depressions. If the depression attains sufficient amplitude at the upper levels, the steering effect of the upper level easterlies contributes to the westward movement. The slow phase velocity of the depressions over the Bay permits a faster growth and development of a vertically coupled disturbance which can then be influenced by the upper level easterlies.

If the disturbance does not have sufficient vertical coupling, which may be either due to weak dynamical forcing and/or due to lack of organized moist convection, the vorticity maxima at different levels move with different phase velocity in different directions and the disturbance develops strong vertical tilt which is followed by the weakening and decay of the disturbance. This was the case for the MONEX depression on 7-8 July, 1979, which developed strong vertical tilt and the magnitude of the tilt was accounted for by the vorticity advection at different levels (see Sanders, 1981).

The foregoing survey of the mechanisms of formation and movement of monsoon depressions can be summarized as follows:

(1) Monsoon depressions over the Bay of Bengal are caused either by amplification of westward propagating weak disturbances or by downward propagation of the internal jet instability of the easterly jet.

(2) The barotropic instability of the low level flow over the Bay of Bengal is conducive to the growth of weak disturbances. The presence of the surrounding terrain contributes to the establishment of such a large scale flow (monsoon trough over the head bay) which is barotropically unstable.

(3) CISK is the primary driving mechanism for the rapid growth of a pre-existing weak perturbation. However, if the amplitude of the disturbance at the lower levels is not sufficient to draw on the low level moisture convergence, the disturbance does not grow to a deep depression.

(4) Once the disturbance has attained adequate amplitude in the lower levels (either by downward propogation of wave energy or by CISK), the low level moisture convergence and latent heat of condensation is utilized more efficiently for the development of a vertically coupled deep disturbance which along with upper level easterlies contribute to the westward propagation of the disturbance. Absence of strong vertical coupling leads to vertical tilt and decay of the disturbance.

(5) Our ability to forecast the formation of monsoon depressions over the Bay of Bengal should be greatly improved with the establishment of upper air stations over the Burmese coast and further east.

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