On the Vertical Tilt of Monsoon Disturbances

R. N. KESHAVAMURTY

Indian Institute of Tropical Meteorology, Poona

25 August 1971

1. Introduction

It is known that disturbances in the extratropics grow by the process of baroclinic instability (Charney, 1947; and others). They transport sensible heat down the gradient of temperature and thus produce eddy available potential energy (EAPE) at the expense of zonal available potential energy (ZAPE). They convert eddy available potential energy into eddy kinetic energy (EKE) by x-p overturnings. In the tropics, on the other hand, baroclinic instability appears to be a less important process for the growth of disturbances, and evidence is growing in favor of conditional instability of the second kind (Charney and Eliassen, 1964) as the mechanism for growth.

In the Indian summer monsoon, zonal mean temperature increases from south to north. Therefore, in order to convert from ZAPE to EAPE, monsoon disturbances have to transport sensible heat from north to south. The sensible heat transport by a wave is related to its vertical tilt in the x-p plane. A trough tilting eastward with height transports sensible heat southward. Thus, to transport sensible heat from north to south, monsoon disturbances must tilt eastward with height. Power- and cross-spectrum analysis has recently been employed for evaluating the vertical tilt of disturbances (Yanai *et al.*, 1968). The author has studied the power spectra of the v component of the wind over the Indian region during the monsoon season of 1967, which was a normal monsoon year (Keshavamurty, 1972). The vertical tilts of the different types of monsoon disturbances and their bearing on the energetics of these disturbances are indicated in this note.

2. Power spectra of large-scale disturbances of the Indian summer monsoon

The following three dominant peaks have been found in the v component of wind:

(a) In the lower troposphere
  (i) 15–20 days
  (ii) 5–6 days
(b) In the middle and upper troposphere
  (iii) 7–8 days

The vertical extent, horizontal wavelength and phase velocity of the disturbances corresponding to these periods are summarized in Table 1. From synoptic knowledge of the character of monsoon disturbances, these peaks have been identified with known disturbances. Thus, the 15–20 day peak has been associated with monsoon depressions, the 5–6 day peak with monsoon lows, and the 7–8 day peaks in the middle and upper troposphere with troughs or low pressure systems at these levels.

TABLE 1. Characteristics of Indian summer monsoon disturbances.

Period (days)	Level at which most marked (mb)	Vertical extent	Wave-length (degrees longi-tude)	Phase velocity east to west (degrees longitude per day)
15–20	850	Sea level to 400 mb	34	1.7
5–6	850	Sea level to 400 mb	20	3.6
7–8	500–400	700 mb to 200 mb	35	4.7

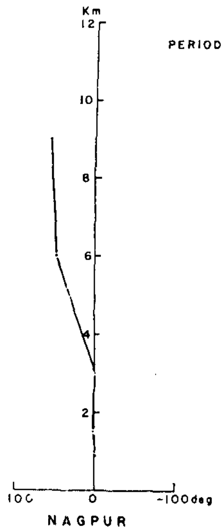

Fig. 1.

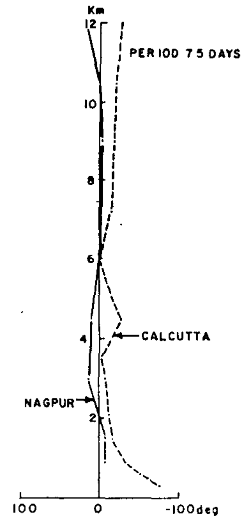

Fig. 2.

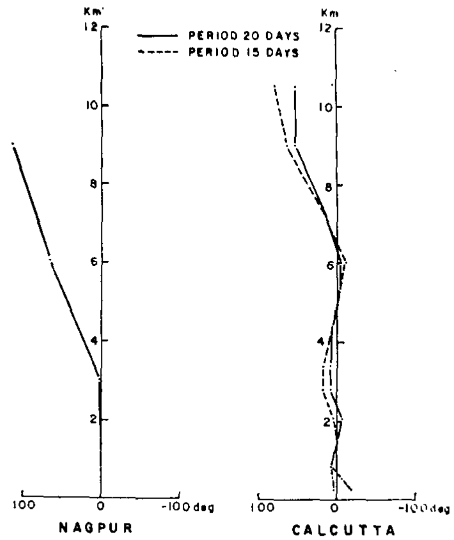

Fig. 3.

Vertical tilt (in the x-p plane) of monsoon disturbances.

3. Vertical tilt of monsoon disturbances

The vertical tilts of these disturbances were found, following Yanai *et al* (1968), by computing the phase difference of the disturbance at different levels with respect to a reference level. Figs. 1–3 show the vertical tilts of the disturbances for the three dominant periods at Calcutta and Nagpur which lie close to the tracks of monsoon disturbances.

It is seen that *monsoon lows* (of 5–6 day period) are nearly vertical in the lower troposphere and tilt westward with height in the middle troposphere (Fig. 1). Thus, they do not have the eastward tilt with height necessary for conversion from ZAPE into EAPE, and they therefore cannot grow by baroclinic instability.

The *middle and upper tropospheric disturbances* of 7–8 day period are also nearly vertical (Fig. 2) and thus are also not capable of growth by the above mechanism.

Coming to the *monsoon depressions* with 15–20 day periods, it is seen that they are either nearly vertical or have a small westward tilt up to about 7 km at Calcutta, which is close to the region of their formation (Fig. 3). These depressions extend up to about this height. At Nagpur they are vertical up to about 3 km and tilt westward with height above this level. However, the depressions are already in their weakening phase by the time they move into these parts. Therefore, we shall concentrate on the tilt at Calcutta. We are primarily interested in the initial development. That they are nearly vertical at Calcutta means that in the initial stages monsoon depressions are also not capable of growth by baroclinic instability. This is in conformity with the findings of Koteswaram and George (1960) who found that in their initial stages monsoon depressions do not have any significant thermal advection associated with them. Only in the later stages do they advect warm air to the west and cold air to the east, and can be sustained by baroclinic conversions. Rao and Rajamani (1968) also found conversion from EAPE to ZAPE in a monsoon depression. They, however, found conversion from EAPE to EKE.

4. Discussion

The nearly vertical or small westward tilt found in the case of monsoon lows and in the initial stages of monsoon depressions is possibly due to the following effect. When a cyclonic vortex is placed in a north–south temperature gradient (temperature increasing from south to north), it advects warm air to the west and cold air to the east. The warm air advected in the west rises and cools; but in the case of baroclinic growth the warming due to advection more than compensates for the adiabatic cooling. However, there is an additional effect which is generally not taken into account—the cooling of air in the lower troposphere by the evaporation of rain. Riehl (1969) has recently drawn attention to this effect. Rain areas in the tropics are generally cooler than non-rain areas at lower levels. Weak tropical disturbances have been described as cold-cored and hence as possible indirect systems (Riehl, 1954). In a disturbance in the Bay of Bengal, Ramage (1964) found that soundings inside the cloud region are colder than those outside for levels below 600 mb and warmer above. Miller and Keshavamurty (1968) found a similar temperature distribution in a mid-tropospheric cyclonic system over the northeastern Arabian Sea. The higher temperatures above 600 mb in the cloud and in the rain region as compared to those in the surroundings may be due to the release of latent heat and the consequent difference in lapse rates, that inside the cloud region being nearer to the saturation adiabatic and that outside being nearer to the dry adiabatic. The lower temperature below 600 mb in the cloud and rain region must be due to evaporation from rain.

Monsoon lows and depressions have overcast skies and heavy rainfall in the western sector and are relatively clear to the east. The wet-bulb cooling in the rain area to the west possibly compensates or overcompensates the advective warming in the initial stages leading to nearly vertical slopes or a westward tilt. Later on, however, when the advection of sensible heat has counteracted this effect, the monsoon depression can be maintained by baroclinic conversion.

It appears likely that the eastward tilt of easterly waves over the tropical Pacific found by Yanai *et al.* (1968) is due to wet-bulb cooling in the cloud and rain areas to the east of the wave axis.

This raises an important issue in the tropics. It is not sufficient to parameterize the release of latent heat. It is also necessary to parameterize the wet-bulb cooling in order to determine the correct temperature structure of tropical disturbances.

Acknowledgments. The author wishes to thank Dr. R. Ananthakrishnan and Dr. G. C. Asnani for their interest and discussion, and Mrs. Leela George and Mr. M. B. Gajare for assistance.

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