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Distribution of equivalent potential temperature in the field of monsoon depressions

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सार — इस शोधपत्र में अवदाब की संरचना में स्थानिक विचरण, जो तुल्यांक स्थितिज तापमान से निरूपित है, का परीक्षण किया गया है। बढ़े हुए और दब हुए संवहन क्षेत्रों को ज्ञात किया गया है। वह ऊँचाई, जहां कपासीवर्षी मेघों के शिखर पहुँच सकते हैं, ज्ञात की गई और इसकी वास्तविक मानों से तुलना की गई है। उपरितन वायु के तापमान की भी गणना की गई है और मानसून वायुमण्डल के माध्य से इसकी तुलना की गई है। उच्च एवं निम्न आपेक्षिक आर्द्रता वाले क्षेत्रों को दर्शाया गया है और संवहनी क्षत्रों के साथ इनका सम्बन्ध स्थापित किया गया है और उस पर चर्चा की गई है।

ABSTRACT. Spatial variation in the structure of the depression as portrayed by equivalent potential temperature has been examined in this paper. Areas of enhanced and suppressed convection have been identified. Height to which the cumulonimbus tops could penetrate have been obtained and compared with those actually observed. Upper air temperatures have also been computed and compared with the mean monsoon atmosphere. Zones of high and low relative humidity have been demarcated and its relationship with convective areas, established and discussed.

1. Introduction

The equivalent potential temperature is the temperature a parcel of humid air attains when it is lifted dry adiabatically till it reaches the lifting condensation level, then pseudo-adiabatically till all the moisture is condensed out and thereafter is brought down adiabatically to 1000 mb level. Saunders (1957) has, however, shown that heat retained by condensed water and the latent heat of ice affect θ_e to a large extent. He has shown that the difference could be more than 3°C for a presssure drop of 700 mb from initial state at 900 mb. The equivalent potential temperature which takes into account both the moisture and the temperature is a more meaningful parameter for illustrating thermodynamic characteristics of the atmosphere than either temperature or moisture alone. It is a definite measure of heat stock of air. It also offers an easy method for identifying the degree of convective instability in the atmosphere.

Garstang *et al.* (1967) observed that the equivalent potential temperature portrays differences in the thermodynamic structure during period of suppressed and enhanced convection better than other observed meteorological variables. For the monsoon months in India from analysis of wet bulb potential and equivalent potential temperatures, Rao (1960) found that convective instability is a normal feature and extended to a 4-6 km from the surface. Srinivasan and Sadasivan (1975) brought out differences in the thermodynamic structure of the atmosphere over India between active and weak monsoon periods from an analysis of equivalent potential temperature. They found that the convective instability is slightly more during weak monsoon than in active monsoon situations.

The magnitude of convective instability depends largely on the synoptic scale disturbance. During the monsoon period the degree of convective instability is enhanced over the Indian region through which the depressions form and move. Srinivasan *et al.* (1975) studied the thermodynamic structure of monsoon depression (north-south section) of July and August 1970-71 by using this parameter and brought out the asymmetry between the south and north sectors of monsoon depressions. They found a region of neutral convective instability just south of depression centre.

In the present paper a mean vertical profile of equivalent potential temperature has been obtained for the monsoon depression. Distribution of convective instability has been depicted and discussed.

Based on the low level distribution of this parameter the heights to which the cumuli could penetrate have been obtained and compared with the heights actually observed during monsoon.

2. Method of analysis and data used

Several methods are available for evaluation of θ_e. Rao (1953) prepared tables from which θ_e could be obtained given the pressure, humidity and temperature. Betts and Dugan (1973), Betts and Miller (1975), Simpson (1978) etc have derived expression to compute θ_e. Recently Bolton (1980) has suggested a simplified procedure to compute θ_e which is also valid even in tropical environment.

Table 1 contains values of θ_e obtained from the conventional method (Berry *et al.* 1945) and those of Rao (1953), Simpson (1978) and Bolton (1980). The difference between θ_e values from the classical method and each of the methods mentioned above are on the positive side for methods of Simpson and Bolton whereas, the errors are generally negative in case of Rao's technique. The differences are due to new procedures involving empirical formulae introduced for the vapour pressure of water, the lifting condensation level temperature etc. These differences, by and large, appear small when we consider the limitations of the accuracy with which absolute values of humidity and temperature in clouds and near saturation environments can be measured. The mean root square difference between the conventional and other methods was found least when θ_e is calculated from Rao's technique.

In this study as such Rao's (1953) tables have been utilised to obtain the θ_e.

The study is based on 27 depressions which formed in July and August months during 1961-74 and moved in the westerly or westnorthwesterly direction across the country. In all 88 depression-days were considered in the analysis. A distance of 1000 km with respect to surface position of the depression at 0830 IST was chosen as the depression field. Upper air temperature and humidity data of the stations at 00 GMT were collected for all radiosonde stations within the depression field. These values at each level were plotted against the distance of the stations from the centre of depression drawn. Values were then picked up at 100, 200, 300, ..., 1000 km distances from the smoothened curves.

Since temperature and humidity form the two basic parameters on which the equivalent potential depend, it may be worthwhile to discuss first the distribution of dry bulb temperature and relative humidity.

3. Vertical profiles of dry bulb temperature and relative humidity

3.1. *Temperature distribution*

Distribution of dry bulb temperature both in the horizontal and vertical has been presented in the

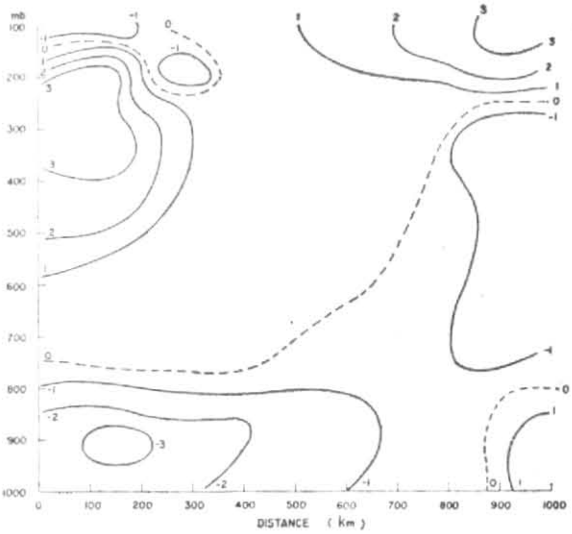

Fig. 1. Isolines depicting departure of dry bulb temperature (°C)

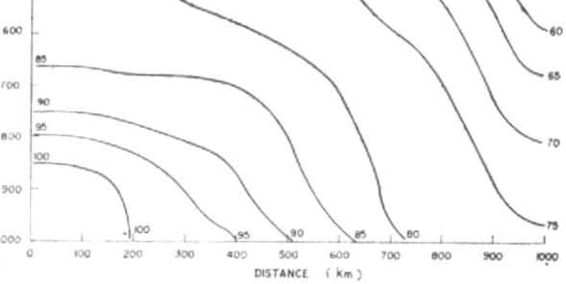

Fig. 2. Vertical cross-section of relative humidity (Per cent)

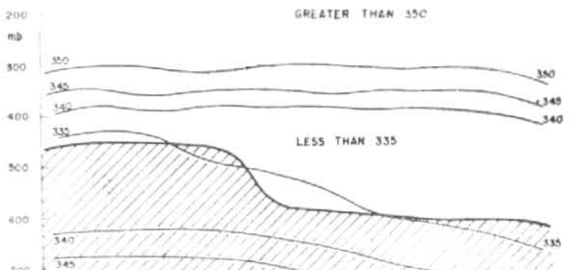

Fig. 3. Vertical cross-section of equivalent potential temperature (Regions of convective instability is shaded)

TABLE 1

Values of θ_e (°K) obtained from different methods

Initial pressure (mb)	Berry *et al.*	K.N. Rao	Simpson	Bolton
1000	360.3	362.5	364.8	361.9
1000	351.6	350.9	352.9	353.3
850	354.3	353.2	354.6	355.1
850	352.3	351.8	353.3	353.6
700	350.2	349.5	350.2	350.4
700	348.1	346.9	348.3	348.5
500	347.7	346.4	348.1	348.1
500	345.4	344.7	345.6	345.8

paper entitled "Mean upper air structure of monsoon depressions" by Chowdhury and Rao (1976). They found low temperatures in the lower troposphere, the cooling being a direct consequence of precipitation. In the present study, in place of dry bulb temperature, its departure at different levels have been worked out and the anomalies discussed. For this purpose the 00 GMT upper air temperature for July published by the India Met. Dep. (1979) based on data from 1968-75 were utilised. The stations chosen for this purpose where the ones which are normally affected by the west or westnorthwest moving depressions, *viz.*, Ahmadabad, Bhubaneshwar, Bombay, Calcutta, Delhi, Lucknow, Nagpur and Visakhapatnam. For each of the levels an arithmetic mean of the temperature for all the above stations was obtained for July. This was assumed to represent the "*monsoon atmosphere*". Departures were then computed of the temperature in the depression field from that of the "*monsoon atmosphere*". The results are depicted in Fig. 1. The lower troposphere (*i.e.*, below 800 mb) is characterised by negative anomalies. This is observed upto about 700 km from the depression centre. It implies that air is colder due to active rainfall taking place in this zone. In fact upto about 400 km, *i.e.*, the region of vigorous rainfall activity, the lowest anomaly is about —3°C. In the upper troposphere, the air is somewhat warmer with largest departures of about +3°C observed between 400 & 200 mb, upto about 200 km from the centre. The high temperature in the upper troposphere is perhaps due to the upward transfer of latent heat released in the middle troposphere by moisture condensation.

In the extremity of the depression field the anomaly pattern is rather different. The lower troposphere is slightly warmer as this region is free from intensive clouding and rains. On the other hand, in the middle troposphere negative anomalies are seen. The cooling may be due to radiative loss of energy from the top of the moist layer. Gray (1970), found that although the subsiding air warms the atmosphere, this warming is less than the radiative cooling. The upper troposphere is, however, warmer in the extreme end of the depression field where, perhaps, subsidence more than compensates the radiative loss.

3.2. *Humidity profile*

In the monsoon season, large influx of moisture occurs with the moist layer extending normally upto 3-4 km. However, in association with monsoon depressions, huge amount of moisture is pumped up in the atmosphere to great height, sometimes beyond 500 mb (or 6 km). From the humidity point of view, in this study the depression field could broadly be divided into two zones (Fig. 2). An extensive area around the depression centre upto about 700 km is the region of a very high humidity (greater than 80%). The high humidity zone more or less coincides with areas of active precipitation. This is also the location where in the lower levels, positive vorticity is advected. Beyond this zone, comparatively drier air prevails. This is particularly so in the layers above 850 mb where the humidity falls to a value below 70%. This drier environment is perhaps a product of small scale subsidence.

4. Distribution of equivalent potential temperature

The vertical cross-section of θ_e is shown in Fig. 3. The isopleths have been drawn at an interval of 5°. Regions of convective instability, *i.e.*, $\partial \theta_e/\partial z < 0$ have been marked in the diagram. The areas of convective instability extend upto about 450 mb to a distance of 400 km from the centre and descends down to about 650 mb beyond. The pronounced low values observed at large distance for the centre are associated with low values of the humidity (*cf.* Fig. 2), *i.e.*, it is the relatively dry air which contribute toward lower θ_e values.

Vertical profiles of θ_e for individual distance ranges have also been obtained. For a few selected distances, it is illustrated in Fig. 4. It may be mentioned that as log θ_e is proportional to the total entropy of the air, and also $\theta_e \sim (1/c_p)(Agz+c_p\,T+Lq)$ these profiles also represent the vertical distribution of energy. The figure brings out clearly the difference in the environment at different ranges. Away from the centre of the depression, in the lower troposphere, there is in general gradual decrease in the value of θ_e . The maximum difference occurs in the lower level close to the ground and is about 9°C between 100 km and 1000 km. Upto some 400 km minimum θ_e is observed at the normally expected height in the monsoon field, *i.e.*, 400-500 mb; beyond 400 km the minimum is located between 600 & 500 mb.

Also away from the centre of depression, the θ_e lines are more inclined, *i.e.*, the horizontal gradient of θ_e is larger than close to the centre. The degree of instability increases in the lower

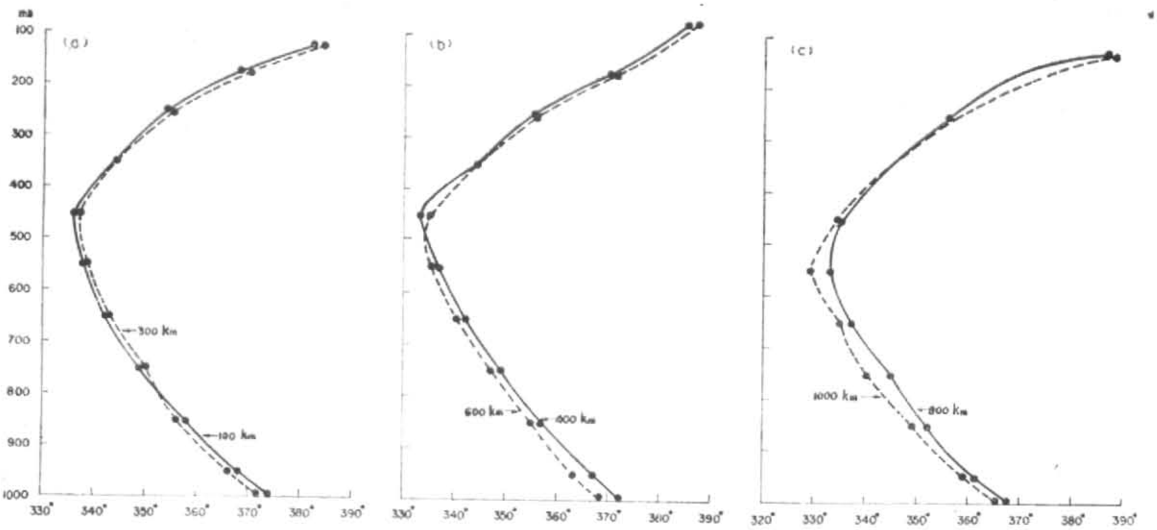

Fig. 4. Vertical distribution of equivalent potential temperature at selected distances from the depression centre

levels away from the centre, but absence of low level convergence mechanism, general dryness of the troposphere and slow subsidence together combine effectively to suppress cloud growth and erodes the cloud tops in spite of increased instability with the result that the weather there is subdued. Another partial explanation for general absence of *Cu* cloud clusters in this outer region of the depression field may be that the region is affected by downdrafts of the cumuli within the inner depression field. Zepser (1969) also observed that the spreading downdrafts strongly suppress buoyancy. Williams (1970) in his study on cloud clusters in trade wind region of westnorth Pacific observed that in clear areas there is a downward motion between surface and 300 mb. Another thermodynamic constraint to *Cu* development in the clear areas is the entrainment of dry air. As we have observed in an earlier section, the air in outer regions of depression particularly beyond 700 km is comparatively dry. An entrainment of the air-mass will cause rapid erosion of *Cu* towers. In the areas near the depression centre, no such constraint exists so that *Cu* development is easily achieved.

It, therefore, appears from the above that in region near the centre upto about 400 km the air is more buoyant and it is, therefore, a region of vigorous monsoon. In contrast the outer areas in the depression field are areas of decreased convection and are generally cluster-free. In other words, the central parts of a monsoon depression field where the rainfall is large corresponds to the thermal structure associated with the so-called "*active monsoon*" conditions while the peripheral regions of low rainfall correspond to the thermal structure associated with "*weak*" monsoon conditions (*cf.* Srinivasan and Sadasivan 1975). The analysis also suggests that the region of strong monsoon with ascending air near the centre and that of weak subsidence away from it appear to be components of the vertical circulation of the depression, as first postulated by Koteswaram and George (1960) and later confirmed by Srinivasan *et al.* (1975).

4.1. *Vertical cross-section*

In the method of composition adopted in the above analysis all sectors have been treated alike and naturally, therefore, has resulted in the loss of some important details. It is well known that the forward sector gets the greater part of rainfall associated with the monsoon depression. Hence, it was thought appropriate to prepare a west-east oriented vertical section of the θ_e field, 1000 km on either side of the depression centre (Fig. 5). It may be mentioned that in a pioneering study on this subject Srinivasan *et al.* (1975) prepared a NE-SW oriented vertical section from Lhasa to Madras and studied distribution of θ_e for two depressions when the depression centre was close to the West Bengal coast and also composited 8 cases across the centre of depression. They found (*a*) a pronounced minimum in θ_e between 800 and 600 mb 3-4° latitudes south of the depression centre, (*b*) θ_e to be nearly constant in the lower troposphere in the immediate vicinity of the centre in the north and over an area of 200 km to the south. In the present case examination of Fig. 5 leads to the following conclusions :

(*i*) In the region about 300 to 500 km the west, of the centre, strong moist convection results in θ_e which is nearly constant with elevation in the lower to middle troposphere. This constancy also suggests that the lapse rate tends to approach the saturated adiabatic lapse rate and the vertical ascent carries the moisture to greater heights.

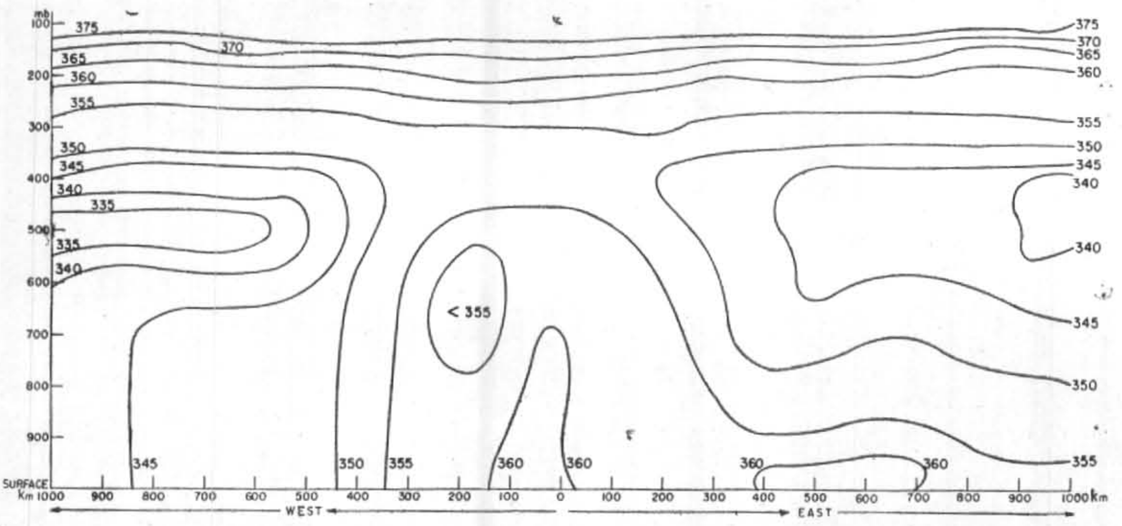

Fig. 5. Vertical profile of equivalent potential temperature along west-east of depression centre

The clouds in this zone of monsoon depression may be considered insulated cores or "*hot towers*" (Sikora 1976), capable of accomplishing the required vertical lifting of boundary layer air into the upper atmosphere conserving θ_e. This also explains the occurrence of a heavy rainfall belt 200-400 km of the depression centre.

(*ii*) Further west, about 800-900 km from the centre, θ_e is again constant with height but this constancy is restricted to the lower troposphere. Here again the lapse rate is moist adiabatic but the air does not rise to higher levels. In this connection it is worth pointing that Chowdhury and Gaikwad (1983) found a secondary high rainfall zone in the field of monsoon depression, about 800 km west of the centre.

(*iii*) Minima in θ_e, a characteristic feature of the monsoon field, is seen at the usually noticed levels between 500 & 400 mb. The first one, seen beyond 500 km west of the centre is very prominent while another one is located about 900 km east of it. This would imply that over these areas θ_e decreases more rapidly with height which should normally lead to more active convective instability. That the weather over these areas, in general, is rather subdued, is perhaps because initially the convective instability may be helpful in promoting convection, prolonged cumulus convection stabilises the environment and reduces the vertical gradient of equivalent potential temperature (Anthes 1982).

(*iv*) Another minimum, though less marked, is seen close to the centre between 550 & 700 mb, which may perhaps has resulted from compositing.

(*v*) Above 300 mb θ_e increases with height over the entire depression field.

5. Vertical penetration of undiluted cumuli towers

Assuming :

(*i*) lower tropospheric air rises saturated adiabatically,

(*ii*) θ_e is conservative during the ascent,

(*iii*) absence of dry air entrainment which causes rapid erosion of cumulus towers and

(*iv*) presence of boundary layer convergence which contributes to the initial lifting mechanism and thus allows the parcel to attain buoyancy, it is possible to determine areas where *Cu* cloud cluster development is easily achieved and hence to theoretically determine the height of *Cb* from θ_e values.

Near the surface the largest value of θ_e noticed at the centre and to the east of the depression field is $\approx$ 360°K (Fig. 5). This same value occurs aloft near 300 mb level close to the centre and near 200 mb level to the east. Penetrative convection without entrainment can transport saturated surface air up to 200-300 mb level which agrees with the observed tops of *Cb* clouds in the depression field.

6. Conclusions

The study reveals :

(*i*) Negative temperature anomalies, as compared to "*mean monsoon atmosphere*" are observed over the active rainfall belt and extends upto middle troposphere.

(*ii*) Comparatively drier air with relative humidity less than 80 per cent prevail beyond about 700 km of the depression centre.

(*iii*) The vertical gradient θ_e increases slightly with distance from the centre of depression.

(*iv*) In the region near the centre upto 400-500 km, convective instability is observed to great height and is, therefore, a region of pronounced convection while the outer areas of the circulation field, the convection is suppressed.

(*v*) Over the central parts of a monsoon depression field the thermal field correspond to the active monsoon conditions while the peripheral region of low rainfall correspond to the thermal structure associated with weak monsoon conditions.

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