

Study of the structure of upper tropospheric easterlies over Peninsular India during the southwest monsoon season based on ESE data

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ABSTRACT. Exercise Storm Exchange (ESE) is the name given to the project in which a Canberra aircraft equipped with scientific instruments, loaned by the Royal Aircraft Establishment, Farnborough, U.K. flew in India for a period of 3 months from 21 June 1972 on studies of atmospheric conditions. One of the studies was to investigate the detailed structure of temperature and wind fields at different levels in the fast upper tropospheric easterly flow which prevails over Peninsular India, during the southwest monsoon season. The aircraft flew between Trivandrum and Bangalore at selected levels between 500 and 100 mb on 25 July 1972.

The study of the data thus collected, showed that small scale variations of significant amplitude are present in the thermal fields at all levels with the result that the thermal wind equation completely breaks down when it is sought to be verified for short distances. In some cases the actual shears differ from the thermal wind by one order of magnitude.

1. Introduction

The vertical structure of the monsoon circulation over south Asia is qualitatively well established in keeping with the thermal fields at different levels as far as the mean data are concerned. However, the day to day synoptic charts of the area show that this upper tropospheric easterly flow is more variable than the westerly flow of the middle latitudes.

Even the easterly jet sometimes appears as a narrow core of fast winds and at other times as a broad stream covering most of Peninsular India. It is highly streaky in nature. The easterlies are remarkably constant in direction but highly variable in speed (Mokashi 1971).

The conventional synoptic data also show that on many occasions the vertical wind shears do not fit in with observed distribution of temperatures in the concerned levels. It becomes difficult in such cases to judge whether the thermal wind equation has broken down due to dominance of ageostrophic wind components or the apparent disagreement is due to errors in observational data. To resolve such difficulties,

continuous observations of temperature and wind profiles at different levels are required. The use of instrumented aircraft for obtaining the same is an ideal method.

An opportunity to take such observations came when a Canberra equipped with scientific instruments was loaned by the Royal Aeronautical Establishment (United Kingdom) to the Government of India for a period of three months from 21 June 1972 to undertake studies on atmospheric conditions. The aircraft was flown from different places for different types of studies and the entire project was called Exercise Storm Exchange (ESE). The details of this project have been given in an article which is under publication elsewhere.

2. Data

The RAE Canberra is equipped with a Doppler Navigation system. With its help wind data of sufficient accuracy are obtained at frequent intervals. The navigators were requested to record winds as frequently as possible preferably every three minutes, which is about the maximum frequency that was possible.

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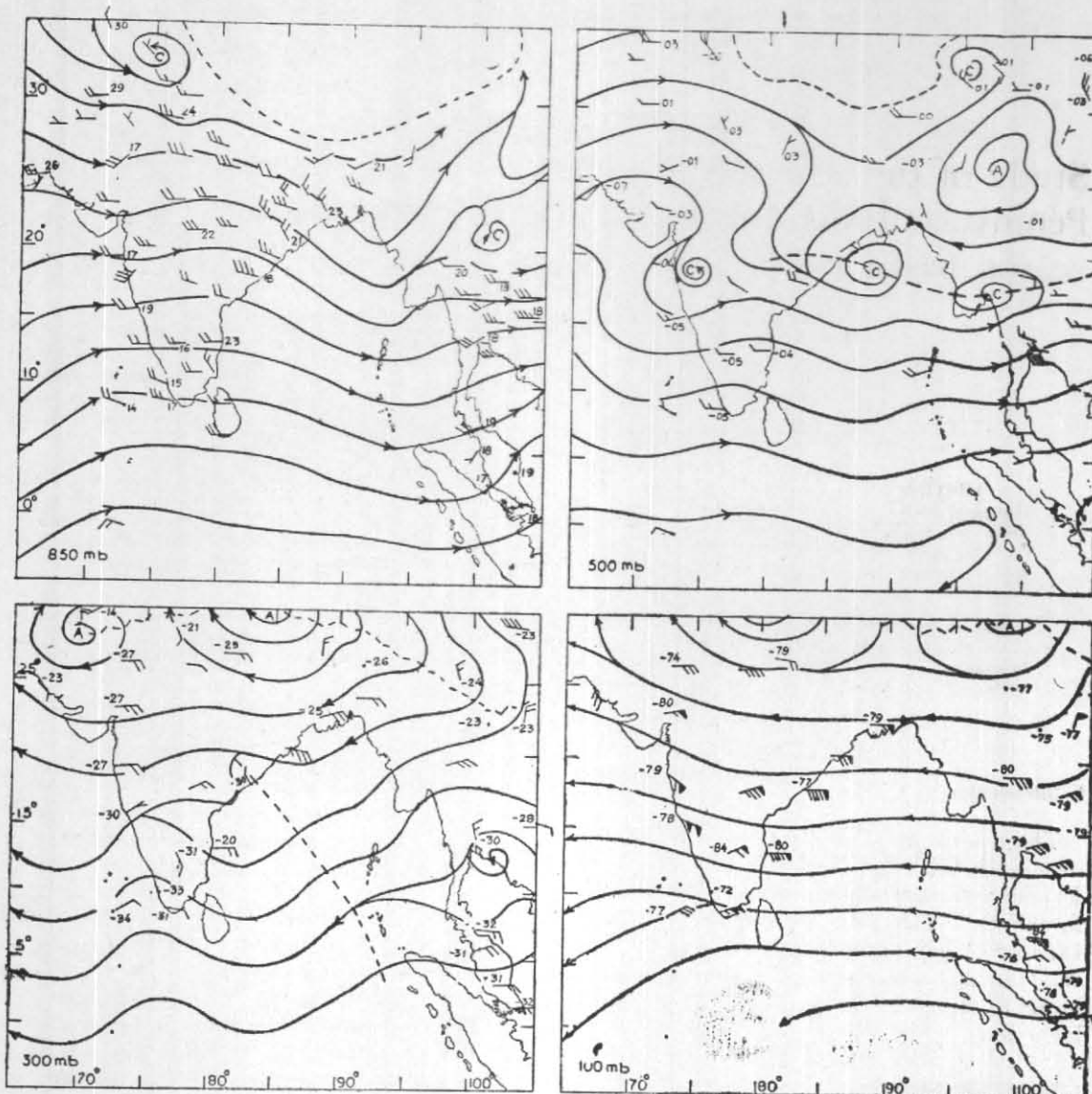


Fig. 1

Flow patterns at different levels at 0000 GMT on 25 July 1972

Continuous record of temperatures of the outside air is traced on a slow recorder which has time markers at every one second interval. For this study it was found sufficient if temperature data are extracted at one minute intervals. The temperature curve is generally fairly smooth for obtaining one minute average temperature values by graphically averaging the same on the record itself. The temperature thus obtained was then corrected for dynamic heating by using standard formulae which are briefly mentioned below for ready reference :

$$\delta = \frac{P}{P_{st}} = \left\{ 1 - \frac{\bar{\alpha} H}{T_{st}} \right\}^{g/\bar{\alpha} R} \quad (1)$$

$$M^2 = \frac{2}{\gamma-1} \left[\left\{ \frac{1}{\delta} \left(1 + \frac{\gamma-1}{2} \cdot \frac{V_i^2}{a_0^2} \right)^{\gamma/(\gamma-1)} - \frac{1-\delta}{\delta} \right\}^{(\gamma-1)/\gamma} - 1 \right] \quad (2)$$

where,

δ = Ratio of local static pressure, P , to the standard pressure at sea level P_{st} in the ICAN standard atmosphere.

P = Pressure at height H

P_{st} = Standard pressure at sea level (1013.2 mb)

g = Gravity (981 cm/sec²)

$\bar{\alpha}$ = Lapse rate of the atmosphere

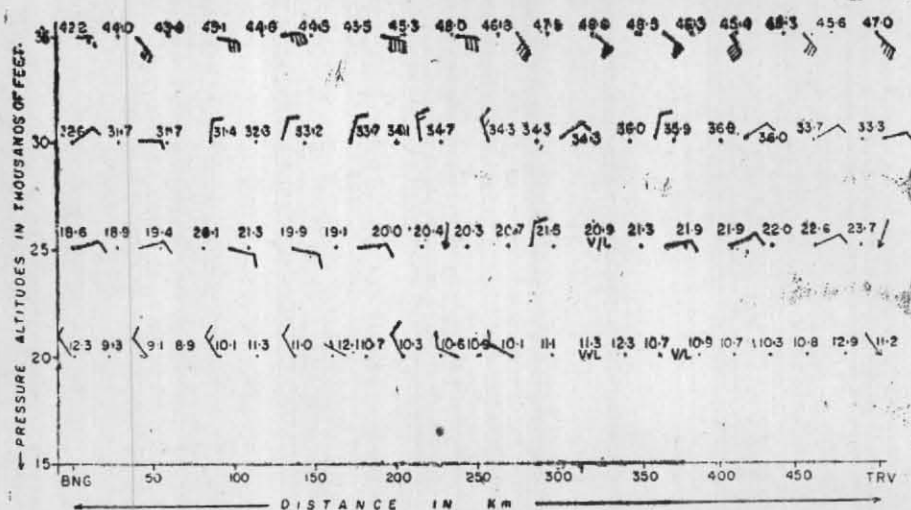


Fig. 2 (a)

Doppler winds and temperatures from slow recorder between Bangalore and Trivandrum on 25 July 1972.
All temperature values are negative

H = The pressure altitude

T_{st} = Standard sea level temperature (283°A)

R = The gas constant for air (2.87×10^6 ergs/deg or 2.87×10^6 cm²/deg)

γ = ratio of specific heats $c_p/c_v = 1.402$

V_i = Indicated air speed (in kt, as per calibration curve given)

a_0 = Speed of sound in air at 283°A and 1013.2 mb in kt (661.4 kt or 1117 ft/sec).

M = Mach number

$\bar{\alpha}$ is $6.5^{\circ}\text{C}/\text{km}$ in the ICAN atmosphere upto a height of 11 km a.s.l. (36091 ft) where the temperature is -56.5°C (216.5°A) and the pressure is 226.3 mb $\bar{\alpha}$ becomes zero above the height. If P_1 is the pressure, above which the $\bar{\alpha}$ become zero, δ is given by

$$\delta = \frac{P}{P_{st}} = \frac{P_1}{P_{st}} \times \frac{P}{P_1} = 0.22336 \times \frac{P}{P_1}$$

$$= 0.22336 \times \exp \left\{ \frac{g(H-H_1)}{RT_1} \right\} \quad (3)$$

where,

$$H_1 = 11.0 \times 10^5 \text{ cm}$$

$$T_1 = 216.5^{\circ}\text{A}$$

$$P_1 = 226.3 \text{ mb}$$

Once the true Mach number was obtained, the ambient temperature could be calculated from the equation:

$$\frac{T_0}{T} = 1 + \left(\frac{\gamma-1}{2} \right) M^2 \quad (4)$$

where, T_0 = Indicated outside air temperature
 T = True ambient temperature.

The aircraft was flown on 25 July 1972 between Trivandrum and Bangalore at flight levels (FL) 200, 250, 300, 350, 400, 430, 470 and 500 (Flight levels are pressure altitudes in hundred of feet). It was flown between Bangalore and Hyderabad on the 26th at the above levels. Unfortunately, the Doppler failed on the 26th and hence, useful wind data could not be obtained on this day. Hence the study is confined to the data from flights on 25th only.

3. Synoptic flow patterns

The flow patterns at 850, 500, 300 and 100 mb over India and neighbourhood on 25 July 1972 are shown in Fig. 1. It can be seen from the figure that the lower tropospheric westerlies prevail over the Peninsula upto 500 mb level. The easterly winds which were about 10 to 15 kt at 300 mb, increased in strength to 40 kt (on an average) at 200 mb. The 100 mb chart of that hour showed that the easterlies of strength 80 to 100 kt prevailed over most of the Peninsular India.

4. Aircraft data and analysis

The wind and temperature data as obtained from the aircraft observation are shown in Figs. 2 (a) and (b). The easterly maxima of over 100 kt was around 50,000 ft. The temperatures at all levels near Bangalore were higher than the corresponding levels at Trivandrum. The temperature gradient between Bangalore and Trivandrum was maximum at FL 350 and FL 470,

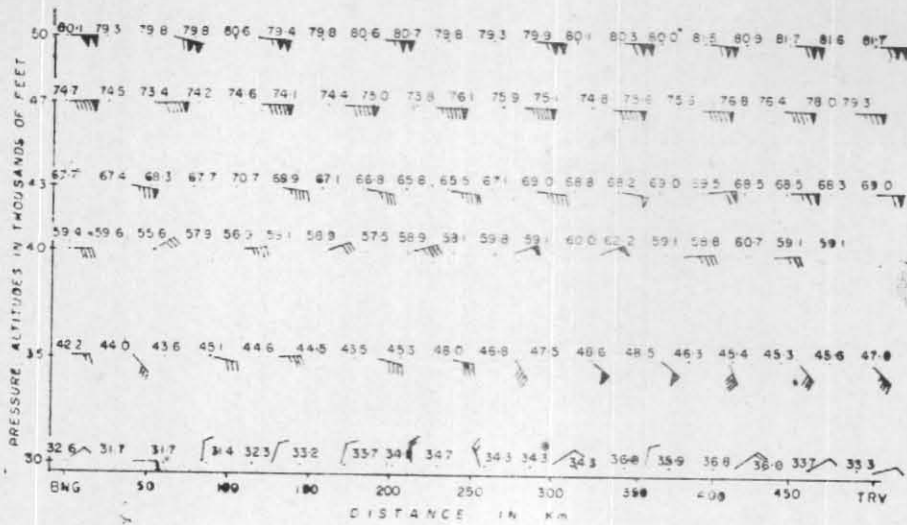


Fig. 2 (b)

Doppler winds and temperatures from slow recorder between Bangalore and Trivandrum on 25 July 1972
All temperature values are negative

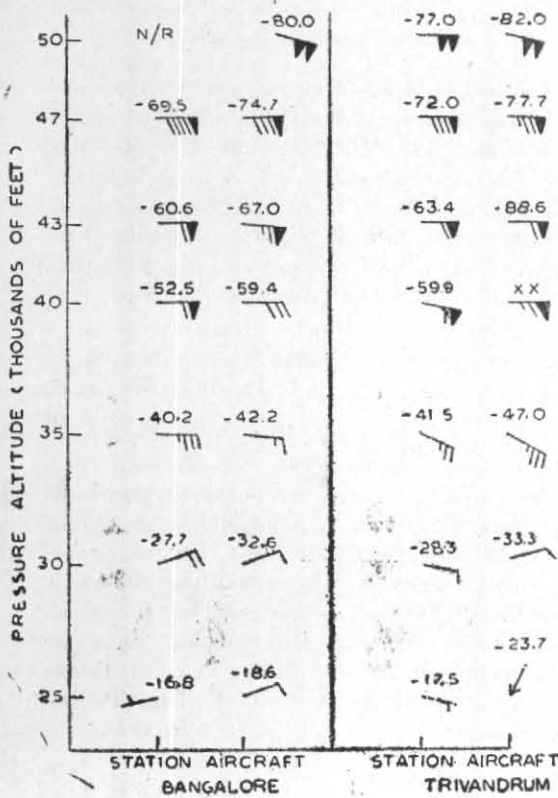


Fig. 2 (c)

Comparative observations on 25 July 1972

Fig. 2 (c) shows the Bangalore and Trivandrum upper air RS/RW data on that day with the aircraft data at the same positions. It may be seen that there was very good agreement between the two types of wind data at both stations, whereas the temperatures obtained with the aircraft are 5° to 8°C lower than the radiosonde data. In such comparison, morning radiosonde data were used for the flights in the forenoon which usually took place between 03 to 07 GMT and evening radiosonde data for flights between 08 and 14 GMT.

Under the geostrophic assumption the relationship between the vertical wind shears and the horizontal thermal gradients is given by

$$\frac{d\bar{V}}{dZ} = \frac{g}{fT} \left(\frac{dT}{dS} \right)_z \quad (5)$$

where $d\bar{V}/dZ$ is the vertical wind shear, f the Coriolis parameter ($f=2 \Omega \sin \phi$, where Ω is the angular velocity of the earth and ϕ the latitude). T is the mean temperature in the layer dZ , (dT/dS) is the temperature gradient in the direction perpendicular to the direction of the wind. Rewriting this equation in finite differences, we get

$$U_T = U_2 - U_1 = \frac{g(Z_2 - Z_1) (T_2 - T_1)_{m,y}}{fT_m(y_2 - y_1)} \quad (6)$$

$$V_T = V_2 - V_1 = \frac{g(Z_2 - Z_1) (T_2 - T_1)_{m,x}}{fT_m(x_2 - x_1)} \quad (7)$$

with the temperatures near Bangalore being 4°C higher than Trivandrum.

where x, y are directions in any horizontal orthogonal coordinate system, U_T and V_T are the thermal wind components respectively in the layer from Z_1 and Z_2 , T_m is the mean temperature in the layer. $(T_2 - T_1)_{m,y}/(y_2 - y_1)$ and $(T_2 - T_1)_{m,x}/(x_2 - x_1)$ are the mean temperature gradients in the layer in the y and x -directions respectively. At high latitudes (25° and above) the geostrophic winds agree well with actual winds and U_T and V_T generally represent the actual vertical wind shears to a fair degree of approximation. The relationship breaks down at very low latitudes, because f is small. Certain amount of ambiguity and doubt exists, as to how far the thermal wind equation holds good in the tropical latitudes (say, 5° to 25°). Conventional data are spaced too far apart, and are not of sufficient accuracy to resolve the doubt.

The following procedure was adopted to test the validity of the thermal wind equation. From the aircraft data wind velocities at points separated by 50 km between Bangalore and Trivandrum were interpolated at all levels. The shear winds between any two levels were determined by taking the vectorial difference between the winds at consecutive levels. These are shown in Fig. 3.

If y -axis is taken along the flight path and x -axis perpendicular to it, the thermal wind component U_T can be calculated from the observed temperature data on the flight using Eq. (6). U_T was calculated at points 100, 200, 300 and 400 km from Bangalore. While making these computations, a certain amount of smoothing was done to eliminate small scale fluctuations and random errors in the temperature data. As mentioned earlier, the basic temperature data (Figs. 2 a and 2 b) at different levels was derived at one minute intervals during the flight from the slow recorder chart. Then the smoothed temperatures at each level at points separated by 50 km between Bangalore and Trivandrum were determined by taking the mean of nearest three (one minute) temperature values. Temperature gradients at 100, 200, 300 and 400 km were determined by taking the differences between the above smoothed temperatures at points 50 km on either side of that point. The gradients were taken to be positive if the temperature towards the north was higher and negative if it was lower. The temperature gradient in any layer was taken as the mean of the temperature gradient at the two levels between which the layer lies. Taking these values of mean temperature gradients, the thermal wind U_T at points 100, 200, 300 and 400 km from Bangalore were worked out and are shown in Fig. 4.

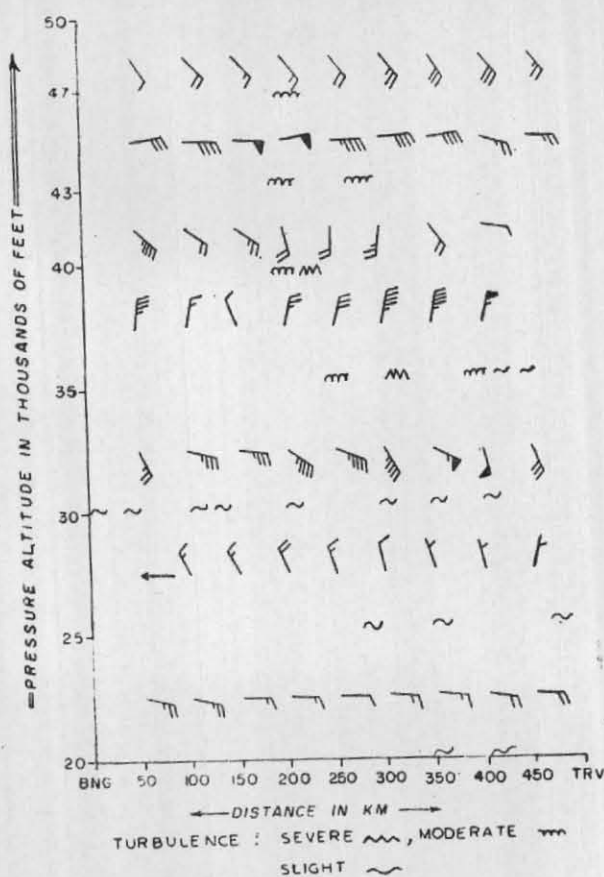
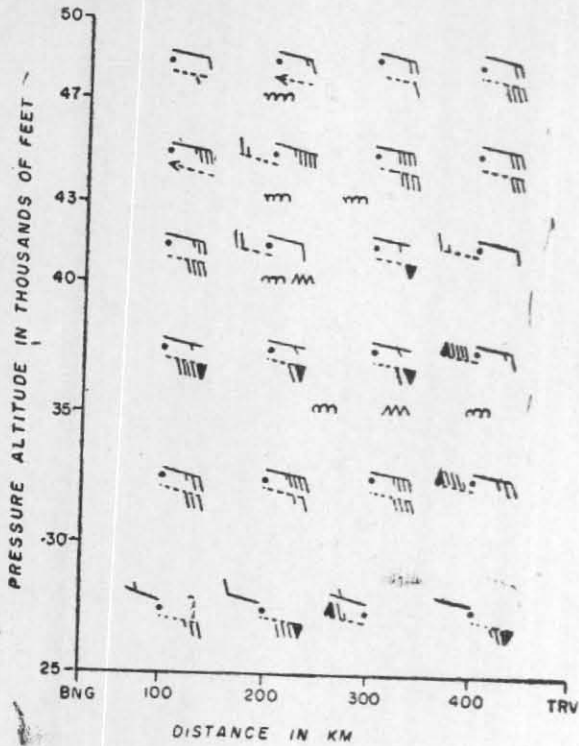


Fig. 3

Vertical wind shears at every 50 km between Bangalore and Trivandrum at different levels (25 July 1972)

Incidentally, as the vertical wind shears are known to be source of turbulence to aircraft, the places where the aircraft experienced clear air turbulence are also shown in Figs. 3 and 4.

The component of shear wind perpendicular to the flight path was derived at the same points (separated by 50 km) between Bangalore and Trivandrum. As a part of smoothing technique three successive shear vectors were taken and the mean values were determined. The mean values at points 100, 200, 300 and 400 km from Bangalore are also shown in Fig. 4. If Eq. (6) held good ΔU_0 and U_T should have agreed well at every point. But it was seen that there were large differences between the two at many points. Thus, we are led to infer that the thermal wind did not represent the true vertical wind shear. The surprisingly large differences are noteworthy. Even the order of magnitude was not the same in some cases. These large differences could not be attributed to observational errors, for even though the absolute value of aircraft data are subject to some



— OBSERVED COMPUTED
 TURBULENCE : SEVERE \sim , MODERATE \sim
 SLIGHT \sim

Fig. 4

Components of vertical wind shears perpendicular to flight path average for every 100 km from data shown in Fig. 3 and thermal wind from temperature data on 25 July 1972

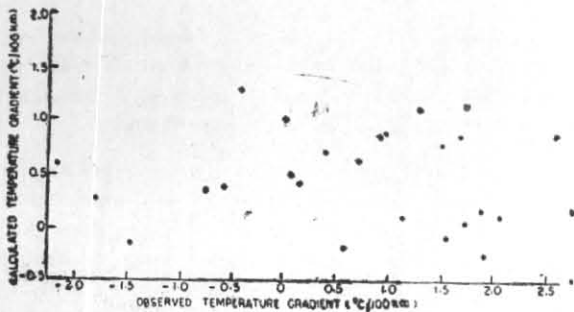


Fig. 5

Scatter diagram between the observed and calculated temperature gradients (25 July 1972)

amount of doubt, the horizontal temperature gradients obtained from temperature records are highly reliable.

Another method of testing the validity of the thermal wind equation was to compare the observed temperature gradients (ΔT_0) with calculated

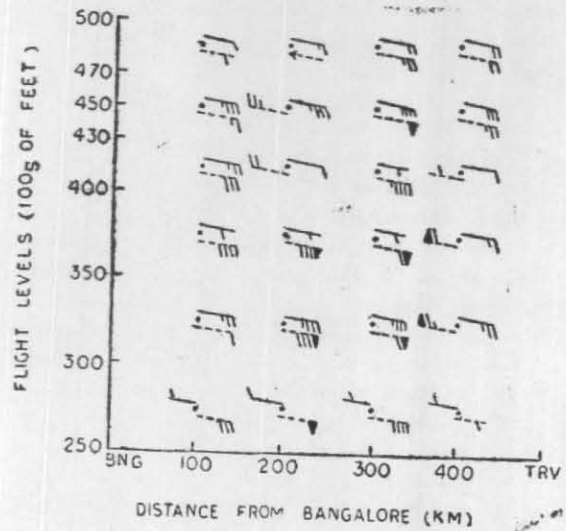


Fig. 6

Data processed on similar lines to the data shown in Fig. 4 except for the smoothing of temperature data for calculations of U_T by taking the five nearest values instead of three as in the case of Fig. 4 data

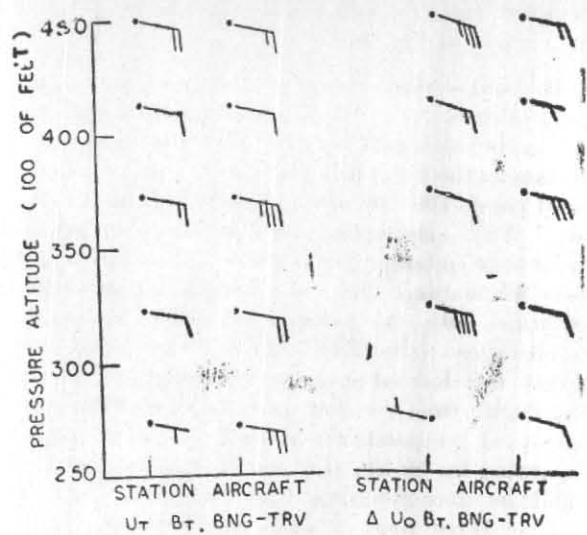


Fig. 7

U_T and U_0 calculated by taking the entire distance between Trivandrum and Bangalore

temperature gradients (ΔT_0), which were derived from the observed vertical wind shears (ΔU). Such computations were made and Fig. 5 shows the scatter diagram between ΔT_c and ΔT_0 . The diagram indicates that there was hardly any relationship between these two parameters.



Fig. 8

U_T and U_0 calculated by using the climatological data of pairs of adjacent upper air stations

In order to see if a slightly greater amount of smoothing of temperature data would lead to better correlation between the thermal winds and the actual wind shears, the smoothed temperatures were calculated by taking the five nearest (one minute) temperature values instead of three. U_T values were calculated using this temperature data and compared with ΔU_0 data. The results are shown in Fig. 6. As can be seen from the figure there is not much improvement.

It is apparent that the observed horizontal temperature gradients when taken over sub-synoptic scale distances (say 100 km) are greatly influenced by the small scale perturbations in the temperature field. Such small scale disturbances do not seem to contribute to the vertical wind shear.

If we take the entire distance between Bangalore and Trivandrum and calculate the thermal wind and compare it with the actual observed vertical wind shear averaged over this distance the agreement between the two appears to be far better even though significant difference still exists. Fig. 7 shows the U_T and ΔU_0 between Trivandrum and Bangalore at different levels as obtained from aircraft and conventional data. Apparently the temperature differences at different levels between Bangalore and Trivandrum have not been significantly affected by the small scale variations in the thermal fields on this particular day.

In the above discussion, the effect of small scale fluctuations in temperature data on the

validity of thermal wind equation have been pointed out as revealed by ESE data. The thermal wind equation being dependent on the geostrophic assumption, can be applied only in such cases where the geostrophic wind represents the actual wind field within acceptable limits. Ramage (1963) has pointed out that even though the geostrophic relationship between wind and pressure does not hold good in the lower latitudes on individual days, it holds good fairly well when applied to climatological data. If so, the thermal wind when derived from climatological data should also be in good agreement with the actual shears obtained by using the climatological wind data. To test whether this be true the mean data of the Indian stations were utilised. From the climatological data of pairs of adjacent stations, the thermal gradient along the line joining them was calculated at different levels. The average of the thermal gradients of two consecutive standard levels was then calculated. From this, the thermal wind component normal to the line joining them was determined. The wind data of the two stations was also taken and the average of the vertical wind shear at these stations between the standard levels was then evaluated. The component of this vertical wind shear perpendicular to the line joining the stations was then calculated. This component was then compared with the thermal wind component mentioned above. The results are shown in Fig. 8. It can be seen that there is a high degree of agreement between the actual shears and the thermal wind in most cases.

5. Conclusions

The project data have shown that small scale variations are present in the temperature field at all levels in the upper tropospheric easterly flow over Peninsular India during the southwest monsoon season. These variations are real and cannot be attributed to observational errors. They do not seem to contribute to the vertical stratification of the atmosphere as per hydrostatic assumption when this is gauged from data of standard isobaric levels. Therefore, the thermal wind and the vertical wind shear between standard isobaric levels calculated over short distances do not agree and sometimes these two differ by one order of magnitude. When the same comparison is made between the thermal wind and the actual wind shear using mean upper air data of the Indian stations, high degree of agreement is noticed, thereby confirming that geostrophic wind can be assumed to hold good in the mean even in lower latitudes (upto

7°-8°N), and the small scale variations in temperature data tend to cancel out when averaged.

As a corollary to the above conclusion, it follows that when such small scale variations of temperature affect synoptic upper air data of a station, the heights of standard isobaric levels would not fit in with synoptic scale analysis. Hitherto, such discrepancies were judged as instrumental or observational errors. However, the results of the present study indicate that such data may be correct but are not representative when synoptic systems are concerned.

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