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Clear air turbulence over south Asia and neighbourhood

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ABSTRACT. Over 9000 aircraft reports have been studied to estimate the frequency of occurrence of Clear Air Turbulence (CAT) along various routes diverging from Bombay and to assess the usefulness of the Richardson's number (*Ri*) in the identification of areas favourable for CAT occurrence. It is found that for smaller layers *Ri* can be a useful indicator of CAT prone areas. It is also observed that among the different air routes emanating from Bombay, the Bombay-Aden and Bombay-Bangkok routes show the highest frequency of CAT occurrence. The stability factor in *Ri* is of considerable importance at lower latitudes as the variation of potential temperature with height near the normal jet flight levels in this area is small enough to produce *Ri* less than 1 even with comparatively less wind shear. A nomogram for easy and quick examination of the 300, 250 and 200 mb levels for prediction of areas susceptible to CAT has been suggested.

1. Introduction

Clear air turbulence (CAT) and related atmospheric motions have attracted much attention in recent years. With the advent of high speed and high-flying aircraft this phenomenon has assumed greater importance.

CAT is also said to present a problem in communication since it scatters signals transmitted by electro-magnetic waves.

In view of these, a number of studies based on all available data have been undertaken during the past two decades to determine the environmental conditions necessary for the occurrence of CAT and the turbulence characteristics themselves. Several papers and review articles on research done on this subject are available. Srinivasan (1961) and Rai Sircar and Varghese (1963) have attempted case studies on the basis of aircraft reports confining their attention only to the horizontal wind field at the cruising level. Their findings were that CAT was experienced generally in association with trough lines and in areas of horizontal wind shear. The contribution of vertical wind shear towards the occurrence of CAT was not examined by them. Rai Sircar and Varghese could not find any significant relationship between the horizontal temperature distribution and clear air turbulence. Bhaskara Rao and Sadagopan (1968) have on the other hand concluded that the occurrence of CAT and the horizontal temperature gradient at standard isobaric levels are well correlated. They have, however, realised that the temperature gradient obtained at standard isobaric levels may not be applicable to the flight levels of aircraft. Gupta *et al.* (1972) have studied the occurrence of CAT in association with features like westerly and easterly jets, wind discontinuity, bending of jets in cyclonic and anticyclonic shears and changing synoptic patterns. Their approach has mainly been a physical identification of the synoptic patterns causing CAT. They have not used any index in their study.

The use of Richardson's Number (R_i) as an indication of conditions favourable for clear air turbulence has by now been widely recognised, as it takes into account both the static stability and vertical wind shear. Low values of R_i have been associated with clear air turbulence. Joseph and Ranjit Singh (1966) and Sastry (1966) have evolved nomograms for calculating R_i as a parameter for the prediction of CAT. The tables given by former authors relate only to the standard isobaric levels of 300 and 200 mb and the levels of maximum wind if available in between these levels. Apart from one example cited by them of CAT on the Bombay-Aden route, the results of further utility-studies of this parameter do not appear to have been published so far.

In this paper the occurrence of clear air turbulence over some important routes from Bombay has been studied. It is found that the Richardson's

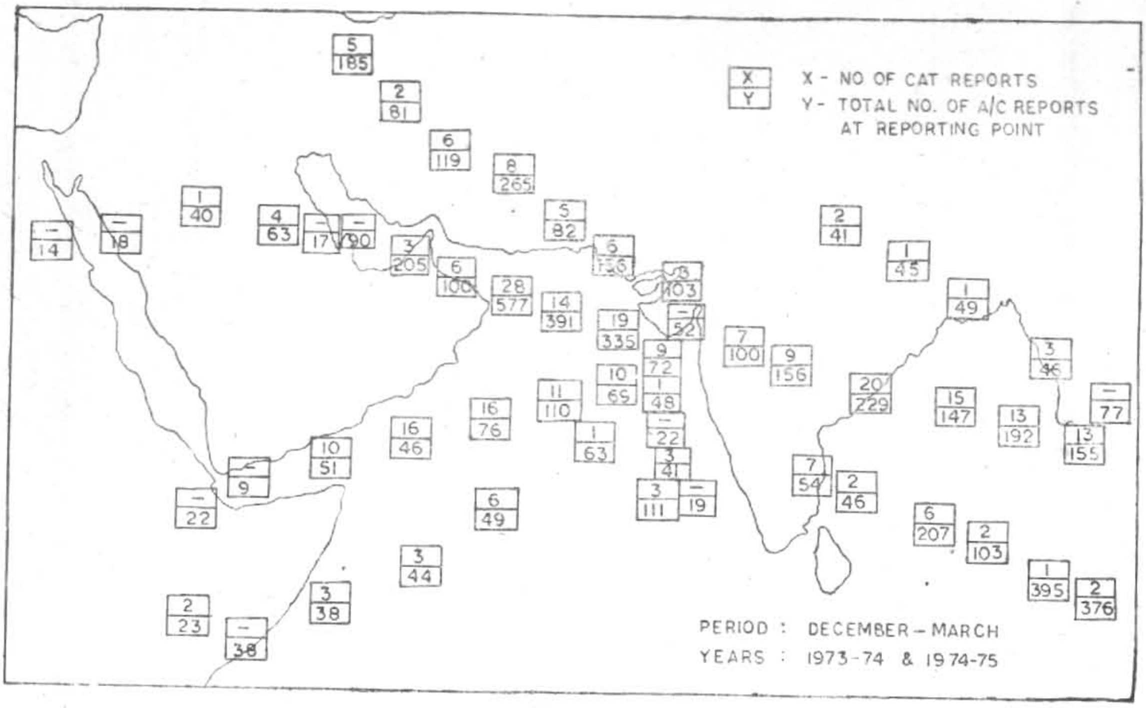

Fig. 1

Number when calculated for smaller layers is a good indicator for outlining areas susceptible to CAT. A nomogram for easy assessment of whether the required criterion is satisfied on daily synoptic charts has been drawn up. This could serve as a ready reckoner in aviation forecasting offices for the prediction of CAT.

2. Data

Of late, there has been marked increase in aircraft activity and consequently wind, temperature and weather reports over international air routes are available in greater number. Reports made by different aircraft at more than one flight level at the same reporting point at about the same time are now available. Generally these flight levels are between the 300 mb and 200 mb levels and with the introduction of 250 mb as a mandatory level in the international TEMP data exchange, charts for this additional level are now being prepared and data are available for utilisation with the aircraft reports. Detailed study of the finer structure of the atmosphere in this region can now be attempted. Calculation of R_i values for layers varying between 1000 to 4000 ft using the above data have become possible.

A large number of aircraft reports (over 9000) from December 1973 to October 1975 have been taken into account in this study. These reports cover both in-flight and post-flight. Special arrangements were made to collect as many post-flight reports as possible from the offices of Airlines operating through Bombay. The accuracy of temperature measurements by modern aircraft is of the order of ±1 to 2°C. However, whenever aircraft temperature data have been utilised, they have been checked against each other or with soundings of nearby stations as recommended by WMO (*see* Ref). As far as wind observations made by aircraft are concerned an accuracy of ±5° in direction and ±5 kt in speed has been assumed as most aircraft of international airlines flying through Bombay are equipped with either the Doppler or the Inertial Navigation system. These are also the limits of accuracy mentioned in the WMO publication.

3. Analysis

Out of over 4000 aircraft reports received during a full year (November 1974 to October 1975) 108 reported CAT. The monthwise distribution of these CAT reports are given in Table 1 for three different routes from Bombay. It may be seen that CAT reports are a maximum in the months of January and February in the Aden route and in January in the other routes. In the pre-monsoon, monsoon and post monsoon seasons there could be clouding in this area and the isolation of CAT cases from turbulence encountered between cloud layers or between cloud cells can become a difficult matter. It was, therefore, decided to confine the detailed study of CAT

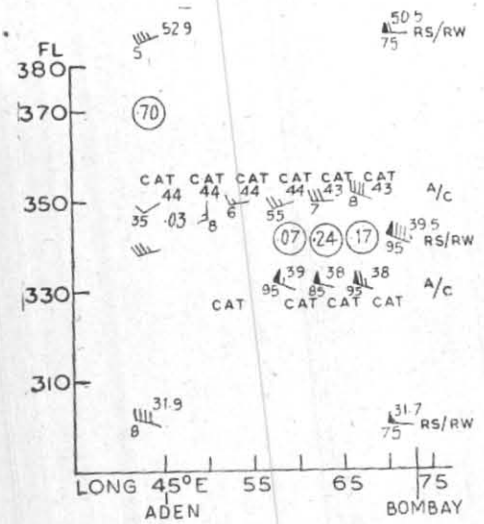

Fig. 2. Route Aden—Bombay on 9 Feb 1975 CAT reported near 60°E at FL 350 & 60°E to Bombay at FL 330

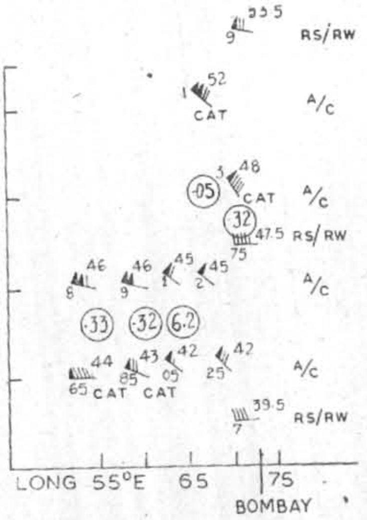

Fig. 3. Route Dubai to Bombay on 28 Jan. 1975. CAT reported beginning and end route

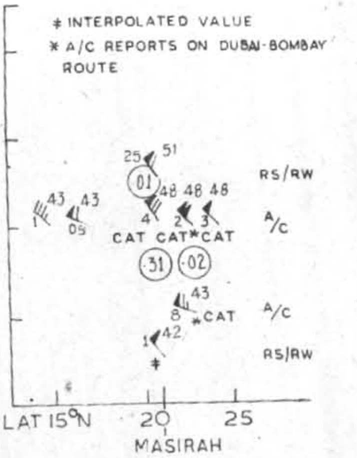

Fig. 4 Route Nairobi—Karachi overflying Masirah on 20 Feb 1975. CAT reported near Masirah.

to the eight months from December 1973 to March 1974 and from December 1974 to March 1975.

Fig. 1 shows the frequency of occurrence of CAT along various air routes from Bombay within the area where the largest proportion of aircraft reports are received. The data combines all intensities of CAT since on a majority of cases the aircraft reports do not mention the intensities and even when reported, they are likely to be subjective in the absence of instrumented observations. The figure reveals the interesting feature of a large number of CAT reports on Bombay-Aden and on the Bombay-Bangkok routes. There are fewer reports elsewhere.

In order to examine the features in greater detail, case studies were made along selected air routes by constructing vertical cross-section charts utilising aircraft reports and soundings from nearby meteorological stations. These charts are shown in Figs. 2-6 along with the values of R_i computed for different layers. Locations where clear air turbulence was encountered are also marked.

3.1. *Case 1—Route* : *Bombay to Aden*

East African Flight EC-864 from Nairobi to Bombay reported CAT at FL 330 from 9°N 50°E to 18°N 68°E between 082128 GMT and 090000 GMT of February 1975. Air India flight from Bombay to Addis Ababa at FL 350 on 9 February 1975 and the same Air India plane on its return flight to Bombay over the same route at FL 330 on 10th February 1975, also reported CAT over most of the route. Fig. 2 shows the vertical cross section from Aden to Bombay with the available aircraft observations at FL 330 and FL 350 recorded within a period of 12 hours and the computed values of R_i for different layers. On this day the core of sub-tropical jet with wind speeds exceeding 140 kt was about 10° latitude north of the area where CAT was reported.

3.2. *Case 2—Route* : *Bombay to Dubai*

Air India Flight AI-823 left Bombay at 0039 GMT of 28 January 1975 and on encountering moderate to severe CAT at the top of the climb (FL 350) descended to FL 310. However, the aircraft began experiencing CAT even at this level as it approached Barnacle (23°N 61°E) which became severe between Muscat and Abudhabi. The flight touched Dhahran at 0402 GMT. TWA flight No. TW-810 flying into Bombay at FL 370 reported CAT at Billet (21°N 68°E) at about 2130 GMT of 27 January 1975. Fig. 3 shows a vertical cross-section chart for the route Bombay-Dubai with the observations of the above two aircraft and another one flying into Bombay at FL 330 at about the same time. The figure also shows the computed values of Ri for various layers.

3.3. *Case 3—Route*: *Nairobi to Karachi overflying Masirah*

East African Airways flight EC-840 reported CAT between Salalah and Masirah at FL 330 from 1414 to 1458 GMT on 20 February 1975. The aircraft report over Masirah was utilised along with the available 0000 GMT Temp. data of Masirah of 21 February 1975 to compute R_i at various

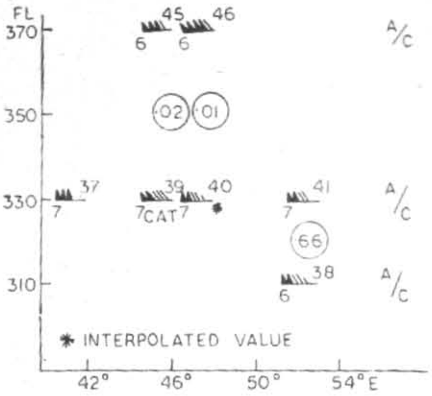

Fig. 5. Route Cairo-Bombay on 10 Feb 1975. Moderate CAT reported near Long. 46°E.

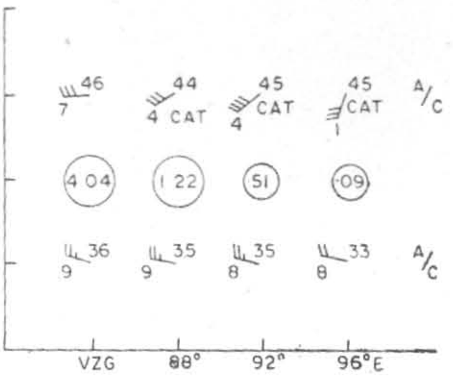

Fig. 6 Route Bangkok—Bombay on 10 Jan. 1974. Moderate CAT reported from Long. 96°E to 88°E at FL 350

layers over Masirah (*vide* Fig. 4). Two Air India flights AI 827 and AI 826 in the forward and reverse direction on the Bombay-Dubai route crossing the Masirah-Karachi route at Barnacle (23°N and 61°E) reported CAT at FL 310 and FL 330 at 0329 GMT and 0955 GMT on the same day. The winds and temperatures recorded by them at this point as well as the computed values of R_i for this layer are also shown in Fig. 4.

3.4. *Case 4 — Route : Cairo to Bombay*

Air India flight AI-116-C from Cairo to Bombay on 10 February 1975 reported moderate CAT at Shayib (27°N 46°E) at 0629 GMT while flying at FL 330. The winds and temperatures reported by this aircraft have been utilised along with the reports of another aircraft flying at FL 370 at 1728 GMT on the same day for the calculation of *Ri* between these levels. The vertical section (Fig. 5) shows the corresponding reports and the corresponding values of R_i in this area. A wind and temperature report from another aircraft flying in the area at FL 310 is also shown in the figure.

3.5. *Case 5 — Route : Bangkok to Bombay*

Air France flight from Bangkok to Bombay on 10 January 1974 reported moderate CAT at the reporting points of Urchin (15°N 96°E) Whitefish (16°N, 92°E) and upto Conger Eel (17°N, 89°E) between 1637 GMT and 1732 GMT while flying at FL 350, on this day the temperature and wind data at the same reporting points were available for FL 310 from the reports of a Swiss Air flight following the same route from Bangkok to Bombay about 4 hours earlier. The reports of both these aircraft may be seen in Fig. 6 along with the calculated *Ri* values. The core of the jet with speeds exceeding 100 kt was more than 10°latitude north of the area where CAT was reported.

In all the above case studies it may be seen that *Ri* values were less than 1 wherever CAT was reported. It may be also noted that in cases 1 and 5 the core of jet was far away from the areas of CAT report.

4. Nomogram

The introduction of the 250 mb chart enables us to compute R_i for the layers 300 to 250 mb and 250 to 200 mb. It was decided to examine whether the above criterion of R_i being less than one for CAT to occur is satisfied by the 252 cases of CAT reported during the period under study. A nomogram was drawn up to find out from the winds and temperatures of the 250 and 300/200 mb charts which are being regularly prepared and analysed at main forecasting offices, whether R_i was greater or less than 1 at various points.

Richardson's number (*Ri*) for a layer of thickness $\triangle Z$ is given in finite difference form by

$$R_i = \frac{g}{\bar{\theta}} \frac{\triangle\theta}{\triangle z} \frac{(\triangle z)^2}{(\triangle V)^2} \tag{1}$$

where, $\bar{\theta}$ is the mean potential temperature of the layer

$\triangle\theta$ — difference between the potential temperature at the top and bottom of the layer, and

$\triangle V$ — shear vector between the top and bottom of the layer considered.

Using the climatological mean value of potential temperatures for the 300 to 250 mb layer and the 250 to 200 mb layer, the speed of the shear vector wind $\triangle V$ which would provide an $Ri = 1$ in these layers was computed for various values of differences in temperature between them. These values are shown in Table 2. Since the generally accepted theory regarding CAT is that it occurs

TABLE 1

Monthwise statistics of CAT reports along different routes from Bombay

Routes	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Bombay – Aden	$\frac{13}{67}$	$\frac{19}{65}$	$\frac{3}{66}$	$\frac{0}{54}$	$\frac{1}{62}$	$\frac{2}{59}$	$\frac{0}{58}$	$\frac{0}{66}$	$\frac{0}{49}$	$\frac{1}{48}$	$\frac{0}{33}$	$\frac{0}{56}$
Bombay – Dubai	$\frac{21}{261}$	$\frac{6}{166}$	$\frac{8}{192}$	$\frac{5}{202}$	$\frac{2}{202}$	$\frac{0}{135}$	$\frac{0}{160}$	$\frac{4}{188}$	$\frac{0}{178}$	$\frac{0}{140}$	$\frac{3}{191}$	$\frac{8}{228}$
Bombay – Tehran	$\frac{9}{158}$	$\frac{1}{140}$	$\frac{1}{166}$	$\frac{0}{102}$	$\frac{2}{161}$	$\frac{0}{127}$	$\frac{0}{100}$	$\frac{0}{121}$	$\frac{0}{184}$	$\frac{0}{160}$	$\frac{2}{99}$	$\frac{0}{134}$

TABLE 2

For determining the minimum shear wind speed to produce $R_i = 1$ for various values of differences in temperatures between (1) 250 and 200 mb and (2) 300 and 250 mb levels

Difference in temp. (°K)	Minimum shear wind speed (kt)	Diffrerence in temp. (°K)	Minimum shear wind speed (kt)
(a) 250 and 200 mb		*(b) 300 and 250 mb*	
$T_{200}-T_{250}$		$T_{250}-T_{300}$	
−12	27	−10	21
−10	35	−8	29
−8	42	−6	35
−6	48	−4	41
−4	54	−2	45
−2	58	0	50
0	62	+2	54
+2	67	+4	58
+4	71		

TABLE 3

Sample ready reckoner for finding out limits of difference in wind directions between two levels to produce the shear wind specified

Shear wind value (kt) $\triangle V$	V_1	V_{21}	ϕ_1 (°)	V_{22}	ϕ_2 (°)	V_{23}	ϕ_3 (°)
30	20	20	97	10	180	—	—
	30	30	60	20	71	10	80
	40	40	44	30	48	20	47
	50	50	35	40	37	30	34
	60	60	29	50	30	40	26
	70	70	25	60	25	50	22
	80	80	22	70	22	60	19
	90	90	19	80	19	70	16
	100	100	17	90	17	80	14
	110	110	16	100	15	90	13
	120	120	14	110	14	100	12
	130	130	13	120	12	110	11
	140	140	12	130	12	120	10
	150	150	11	140	11	130	9
	160	160	10	150	10	140	9

V_1—Windspeed at level 1 (kt)

V_{21}, V_{22}, V_{23}—Wind speeds at second level

ϕ_1, ϕ_2, ϕ_3—Angle of separation between directions of V_1 and V_{21}, and V_1 and V_{22} etc.

in thermally stable layers where the vertical wind shear is large enough to favour the formation of eddies, the temperature difference given in Table 2 are limited only to stable lapse rates where $\triangle\theta$ is always > 0.

If V_1 and V_2 are the wind speeds at two levels and ϕ the angle between the wind directions at these levels $\triangle V$, the shear vector between the two levels is given by

$$(\triangle V)^2 = V_1^2 + V_2^2 - 2V_1\ V_2\ \cos\phi$$

$$\text{or } \mathrm{Sin}^2\ \frac{\phi}{2} = \frac{(\triangle V)^2-(V_1-V_2)^2}{4\ V_1V_2} \qquad (2)$$

Using Eq. (2), values of ϕ have been computed for given values of $\triangle V$, V_1 and V_2. A sample tabulation for a shear vector wind of 30 kt is given in Table 3. The nomogram is used in the following way. Let us assume that the possibility of occurrence of CAT in the layer 300 to 250 mb is being examined. The prognostic charts for the 300 mb and 250 mb levels are superposed and the temperature difference between the two levels picked out for various areas. Suppose the value of the temperature difference at a particular point is 8°C between these layers. From Table 2 it may be seen that the minimum wind shear ($\triangle V$) required to produce an $Ri = 1$ with the temperature difference of 8°C is 29 kt (say 30 kt). Table 3 which provides the tabulation for the 30 kt shear wind vector can now be used. Let the wind speed at this point on the 250 mb chart be 80 kt and the same point on the 300 mb chart be 60 kt. 80 is chosen under V_1 in Table 3, and the minimum angle ϕ required for producing an $Ri = 1$ is read off against 60 along this line. It may be seen that it is 19° in this case. If, therefore, the difference in wind direction between the wind at 300 mb and 250 mb is larger than 19° conditions favourable for CAT formation can be considered to exist over this point.

TABLE 4

Use of Richardson's number as a criterion for CAT

No. of cases showing $Ri < 1$	No. of cases showing $Ri \approx 1$	No. of cases showing $Ri > 1$
(*a*) Total No. of CAT reports verified : 252		
155	64	33
(62%)	(25%)	(13%)
(*b*) Total No. of non-CAT reports verified : 464		
85	23	356
(18%)	(5%)	(77%)

The above method was utilised to examine each of the 252 cases of CAT reports, at aircraft reporting points, received at Bombay during the period December 1973 to March 1974 and December 1974 to March 1975. The results are shown in Table 4(a). In 87 per cent of the cases the values of R_i were nearly equal to or less than 1. The nomogram was also used for verifying whether on occasions when CAT was not reported, Ri was greater than 1. The results of verification of 464 such reports in January 1975 in the neighbourhood of India are given in Table 4(b). It may be seen that on 77 per cent of these cases Ri was greater than 1. Areas where R_i is less than 1, are considered to be areas which are susceptible to CAT formation. However, since CAT generally occurs in a transient fashion, an aircraft may not experience CAT unless it passes through the area at the time when CAT is occurring. Hence even the 23 per cent cases when CAT was not reported inspite of R_i being near or less than 1 need not necessarily be considered as signifying a failure of the applied criterion.

Considering that CAT prediction has been a difficult problem, the authors feel that the nomogram outlined above could be a useful tool to forecasters in the absence of any better or quicker method.

5. Discussion

5.1. *Criterion for forecasting CAT*

From the studies mentioned above it may be seen that whenever aircraft have reported CAT, the R_i in the area of the report has been generally less than 1. It is now fairly well-established that most of the CAT occurrences in the free atmosphere are caused in stable layers by vertical wind shears that are large enough to produce super critical flow conditions which could favour eddy formation. The R_i which takes into account both the vertical wind shear and the hydrostatic stability is, therefore, considered to be the best indicator of the synoptic scale areas where conditions favourable for CAT formation exist. The usual complaint about the use of Richardson's number is that it is being calculated with data of poor resolution. This drawback has been overcome to a large extent now due to the availability of the 250 mb data. There have been cases, such as the one on 1 February 1975, when an aircraft flying at FL 350 experienced CAT and descended to FL 310 at which level it had a CAT-free flight. The R_i calculated between 250 to 200 mb on this day at this point was less than 1 while the R_i calculated between 250 and 300 mb was much greater than 1. A more realistic use of Richardson's criterion is, therefore, possible when the smaller layers (300 to 250 mb and 250 to 200 mb) are taken into account.

There is a popular belief that vertical wind shear (or horizontal thermal gradient) is a sufficiently good or even better indicator of CAT than R_i. Endlich (1964) and Colson and Panofsky (1965) are quoted to support this view. Colson and Panofsky have mentioned that "of all the parameters tested, the probability of moderate to severe turbulence was best related to vertical wind shear and Richardson's number with the wind shear being the better discriminant". Admittedly vertical wind shear does play the major role, but the hydrostatic stability factor *i.e.*, the variation of potential temperature with height is also important. During the course of the present investigation, plenty of evidence supporting this view has been found. Taking for instance, a case on 11 February 1975, the vertical wind shear between two aircraft reports (FL 350 and FL 390) over the same point near Bahrein was about 25 knots. In spite of this wind shear, the calculated R_i was greater than one due to the large increase of potential temperature with height over this point as a result of inversion (about 18° K/km). No CAT was reported by either aircraft at this point. The same 25 knots vertical wind shear occurred at a lower latitude over Aden on 9 February 1975 (*vide* case No. 2 Fig. 3) between FL 350 and FL 390. R_i worked out in this case was less than 1 since the rate of change of potential temperature with height was quite low (about 3° K/km). CAT was actually reported near Aden by aircraft flying in the area on 9 February 1975 and 10 February 1975. This goes to show that it is not only the wind shear that is to be considered but also the degree of stability. The Richardson's number which includes both these factors appears to be best indicator available for forecasting CAT.

5.2. *CAT prone areas*

According to Reiter (1969) several authors have observed that CAT occurs more frequently near the jet than away from it. The present study on the other hand indicates that CAT occurs very rarely near the sub-tropical jet but occurs quite frequently over the Bombay-Aden and Bombay-Bangkok routes during the period December to March. Rai Sircar and Varghese (1963) have also found similar results but could not offer any explanation. It is felt that the higher frequency observed at the lower latitudes is due to the lapse rates here, being more favourable for providing lower R_i even with moderate vertical wind shears compared to the higher latitudes near Bahrein or Tehran where the lapse rates are much smaller and $\triangle\theta/\triangle Z$ larger, particularly at 300 mb and aloft, due to closer proximity to the tropopause at these latitudes. The comparatively low vertical wind shear required for lowering the R_i to less than 1 along the Bombay-Aden and Bombay-Bangkok routes can be provided by the tilt of the subtropical ridge with height or the difference in boundaries and sharpness of outline of the sub-tropical highs between 300 and 200 mb

To examine the nature of variation of $\triangle\theta/\triangle Z$ from low to high latitudes the mean values of $\triangle\theta/\triangle Z$ in the layer 300 to 250 mb for the latitudinal belt 11° to 15°N and the latitudinal belt 26°N to 30°N were computed for all the days taken into account during the study. The mean $\triangle\theta/\triangle Z$ value for the belt 11° to 15°N is of the order of 1° K/1000 ft. with a variation from 0·1 to 1·6°K/1000 ft while that for the belt 26° to 35°N is about 2°K/1000 ft with a variation from 0·4 to 4·1°K/1000 ft. The lowest value of $\triangle\theta/\triangle Z$ (0·1) in the belt 11 to 15°N will require only a vertical wind shear of about 2 kt/1000 ft to give an $R_i=1$ while the highest value of $\triangle\theta/\triangle Z$ (4·1) encountered in the belt 26 to 35°N will require a vertical wind shear of about 12 kt/1000 ft to give an $R_i=1$.

5·3. *Nature of CAT*

There is a general feeling that CAT could be only a transient phenomenon lasting not more than a few hours. It is also opined that it could occur only in patches not more than 100 miles in extent. This may be so for each CAT outbreak but it is believed by the authors that conditions favourable for CAT occurrence (*i.e.*, with R_i=near or less than 1) can exist over larger areas and may continue to exist even up to 24 hours or more. This is shown for example by the CAT reports received from several aircraft flying along the Bombay-Aden and Bombay-Bangkok routes covering periods of day and night from 8 February 1975 to 10 February 1975. Although CAT itself may be a transient phenomenon, CAT might have occurred frequent enough during this period, to be observed by a number of aircraft traversing the area.

Conditions favourable for CAT formation may therefore, continue over a period of time in some areas, while CAT itself may develop and fade in a patchy or transient fashion in such preferred locations.

5·4. *Orographic effects*

A good percentage of the cases out of the 13 per cent in Table 4(a) that showed $Ri>1$ were cases where CAT was reported just east of Vishakapatnam in a strong westerly wind field with little vertical wind shear. These cases may be due to the effect of the eastern mountain ranges and this aspect is being separately examined. It, however, only indicates that the fairly high reliability of the suggested nomogram for forecasting CAT areas can be at times further enhanced by the forecast of CAT over such preferred areas on the lee of mountain ranges on occasions when the wind speed exceeds a particular value which can be determined after further study of this problem with the help of more aircraft reports.

6. Conclusion

(1) In the area considered CAT occurs quite frequently on the Bombay-Aden and Bombay-Bangkok routes which are away from the core of the subtropical jet stream during the period December to March. The occurrence of CAT near the core is comparatively less.

(2) CAT generally occurs in areas where R_i is near or less than 1, when calculated between the available levels of 300 to 250 mb or 250 to 200 mb. Vertical wind shear by itself is not a sufficient indicator of CAT. The difference in stability conditions between lower and higher latitudes implies that while large vertical wind shears are required to produce CAT at higher latitudes comparatively smaller wind shears may suffice at lower latitudes.

(3) The suggested nomogram could be a useful tool for the forecaster for quick delineation of CAT susceptible areas on the significant weather chart by using the routine analysed 300, 250 and 200 mb chart. It would also enable him to indicate with greater confidence the levels where they are likely to occur.

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REFERENCES

Bhaskar Rao, N. S. and Sadagopan, A. 1968 *Indian J. Met. Geophys.*, **19**, pp. 59—64.

Colson, B. and Panofsky, H. 1965 *Quart. J. R. Met. Soc.*, **91**, pp. 507—517.

Endlich, R. M. 1964 *J. App. Met.*, **3**, pp. 261·276.

Gupta, G. R., Nayasthani, M. M. and Verma, R. K. 1972 *Indian J. Met. Geophys.*, **23**, pp. 379—384.

Joseph, P. V. and Ranjit Singh 1966 *Ibid.*, **17**, pp. 411—414.

Rai Sircar, N. C. and Varghese, K. P. 1963 *Ibid.*, **14**, pp. 433—440.

Reiter, E. R. 1969 Proceedings of a symposium on Clear Air Turbulence and its Detection—Plenum Press, New York.

Sastry, P. S. N. 1966 *Indian, J. Met. Geophys.*, **17**, pp. 415—418.

Srinivasan, V. 1961 *Ibid.*, **12**, pp. 279—282.

W. M. O .. Tech. Note No. 80.