551·515·8 : 551·524

Correlation between Clear Air Turbulence and Temperature Gradients at standard isobaric levels

N. S. BHASKARA RAO and A. SADAGOPAN

Meteorological Office, Bombay Airport

(*Received 16 August 1966*)

ABSTRACT. The forecasting offices which render service to turbo-prop and jet aircraft have to indicate the probable area of Clear Air Turbulence (CAT) and if possible the intensity of the CAT which is likely to be encountered by the aircraft. Forecasting of CAT from synoptic data is beset with many problems which have been discussed in Section 2 of this paper. There is, however, an apparent correlation between the occurrence of CAT and the increase of thermal gradient. This was statistically tested in the case of all flights for which post-flight reports were available at the Main Meteorological Office, Santacruz for the year 1964. The results of the test are discussed in this paper. Briefly the results show that the method based on thermal gradients is a good guide for delineating probable areas of CAT occurrence but the method was not very sensitive for discriminating different intensities of CAT. The method has a good potentiality to be used as a forecasting tool.

1. Introduction

Clear air turbulence is encountered by aircraft at all levels. In the lower levels (below 4·5 km) the turbulence is caused by thermals due to ground heating, mountain waves and eddies and by vertical wind shear. In the higher levels (above 4·5 km) turbulence is caused by the latter two only. This paper deals with clear air turbulence of the shear type at high levels. The definition of CAT is same as that given by Clodman (1961) with the exception that the level (lower) has been brought down to 4·5 km.

Vertical wind shear is the most important factor in the production of small-scale motions which cause CAT (Colson and Panofsky 1960). Thermal wind gives a good measure of the vertical wind shear in a layer. Nat. Weath. Analysis Centre, Wash. (1960) has found that the thickness between two standard isobaric levels and the temperature field at the lower of these two isobaric levels are highly correlated. As the thickness gradients give a measure of the thermal wind, there apparently exists a correlation between the thermal wind and the gradients of temperature at the standard isobaric levels.

2. Present study

Fig. 1 shows the routes served by Bombay M.M.O. and the upper air observatories which lie in the area of the chart. It was noticed from the routine analysis of extended charts that areas from which aircraft reported CAT seem to coincide with areas of tight temperature gradients at standard isobaric levels. This coincidence was noticed in cases where turbulence was experienced over small distances as well as in those where turbulence was reported over long stretches of the route. Fig 2 shows the contours and isotherms at the 500-mb level along with the actual winds at 1200 GMT on 26 August 1964. The isotherms were drawn at intervals of 5°C. A commercial aircraft flying from Istanbul to Bomaby reported severe turbulence in that sector of the route where its flight cross the tight temperatures gradient associated with a trough of low between the Black Sea and the Caspian Sea. The aircraft was flying at F. L. 175 and at approximately the chart time. The actual wind and temperature reported by the aircraft are also shown in the diagram. Fig. 3 shows the contours, isotherms and the winds at 300-mb level at 0000 GMT of 26 February 1964. A jet commercial airliner (AI. 102/16) started Beirut at 1930 GMT of 25 February 1964 and reached Bombay at 0005 GMT of 26 February 1964. The aircraft was flying at F.L. 380. It encountered light to moderate turbulence intermittently over the entire stretch of the route from 43° to 63° E. It can be seen from the chart that fairly tight temperature gradients were present over the sector. Thus even turbulence encountered at fairly high altitudes above the chart level seems to be correlated to the temperature gradient at this standard isobaric level.

It is this apparent correlation which was taken for statistical examination to evolve an easy and quick method of forecasting CAT with the available data. Also the forecasting of the future position of such areas of high thermal gradients is less difficult than the prognostication of areas of high wind shear directly.

In our study instead of using the thermal gradients as such for comparison with the intensities of CAT reports, we have defined two thermal wind vectors, *viz.*, V_5 and V_3.

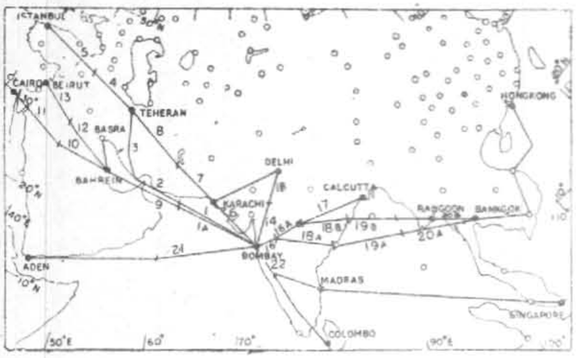

Fig. 1. The air routes served by Santacruz (Bombay)

The limits of the sectors are marked by small perpendicular lines. The sectors have been numbered. The filled circles show the location of R.S. / Rawin stations

V_5 and V_3 = The speeds of the thermal wind vectors in layer of 1000-ft thickness with 500 and 300-mb level respectively in the middle (expressed in kt per thousand ft).

Comparisons were made for CAT reports from flights between 600 and 400-mb levels with V_5 and from flights between 400 and 200-mb levels with V_3. This was done to avoid the latitudinal effect and also to bring the comparisons in line with the works done elsewhere.

The meteorological office at Bombay airport receives post flight reports from most of the international aircraft which land at Bombay. We have taken the reports received in 1964 which number about 755. The routes were divided into sectors of approximately 7° of latitude/longitude (as shown in Fig. 1). The sector units come to about 2350 in number. V_5 or V_3 was evaluated whenever a flight took place in any of the sectors, V_5 in case of flights between 600 and 400-mb levels and V_3 in case of flights in the layer between 400 and 200-mb levels. The constant pressure charts nearest to the times of flights were used in the evaluation of V_3/V_5. In 150 of the above 2350 sector units V_3/V_5 could not be evaluated due to paucity of data.

As a geostrophic wind scale prepared by Northern Hemisphere Analysis Centre, New Delhi, for the Asian charts now in use for constant pressure data was already available, we used it for evaluating V_3 and V_5 by suitably re-graduating the same. The relationship between thermal wind and geostrophic wind is given by the formula, when the distances between consecutive isotherms and isobars are identical —

$$\frac{V_T}{V_g} = \frac{g \rho \triangle T (Z - Z_0)}{T \triangle P} \text{ (Hewson and Longley)} \quad (1)$$

where, $\triangle T$ is the interval between isotherms in degrees Centigrade/Absolute, $\triangle P$ is the interval between isobars in dynes for which the scale has been constructed, T is mean temperature in the layer Z_0 to Z in °A.

Equation (1) becomes —

$$\frac{V_T}{V_g} = \frac{\triangle T (Z - Z_0)}{T \cdot \triangle Z} \quad (2)$$

when used for constant pressure charts and $\triangle Z$ is the height interval between the contours for which the scale has been constructed. In the case of V_5/V_3, the $Z - Z_0$ is taken as 1000 ft (300 m) which gives the speed of the thermal winds in knots per thousands feet (original scale is in kt). The mean temperature T is the temperature at the corresponding constant pressure charts.

The absolute annual and synoptic range of temperatures for the area concerned at 500 and 300-mb levels is about 25°A, *i.e.*, the temperature range from 0°C to —25°C for the 500-mb level and from —25°C to —50°C for the 300-mb level. So a mean temperature of —12°C (261°A) for the 500-mb and —37°C (236°A) for the 300-mb level were taken as the values of T of equation (2). The maximum error involved is about 4 per cent and on most days it is far less. This error does not affect the results to any significant extent and is far less than the subjectivity involved in the analysis of upper air charts.

3. Results

Table 1 gives the number of cases of CAT reported in Winter (December, January, February), Spring (March, April, May), Summer (June, July, August) and Autumn (September, October, November) arranged according to the corresponding values of V_5/V_3.

Winter — It is seen that out of the 565 route sectors considered 457 had values of V_3/V_5 between 0 to 4 kt/km and only 7 cases of CAT were reported, whereas out of the 107 remaining units, 64 CAT cases were reported. Another noteworthy point is CAT of some magnitude was always encountered in those sectors where the values of V_3/V_5 worked out to be 6 to 8 kt/1000 ft.

Spring — The occurrence of CAT has fallen from 71 in winter to 37 in this season whereas the number of sectors considered has fallen only from 565 in winter to 508 in this season. This is in keeping with the general weakening of the westerlies from winter to spring. The other features reflect the same tendencies as in winter and in fact the correlation between the intensity of CAT and the speeds of V_5/V_3 are better than in winter.

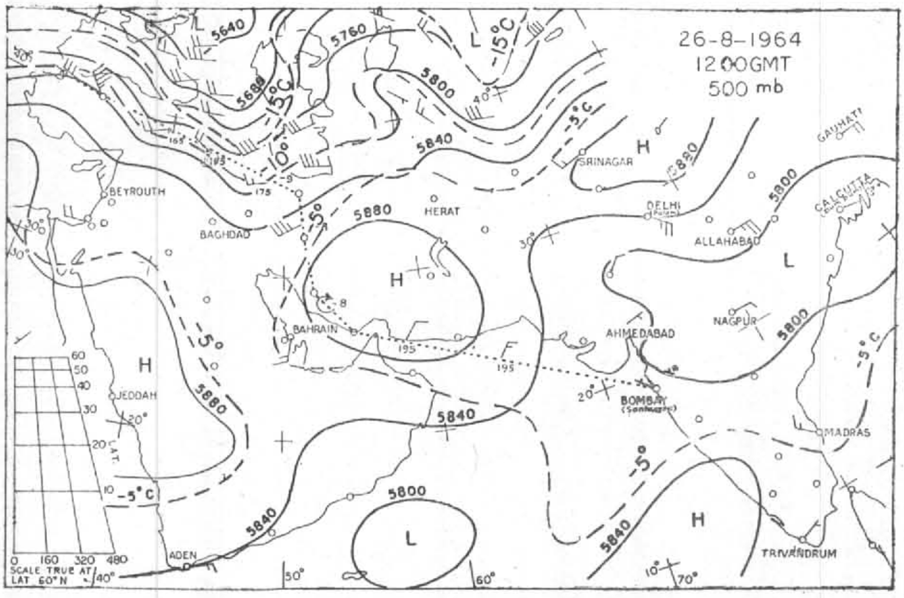

Fig. 2. 300-mb contours and isotherms (broken lines) at 1200 GMT on 26 September 1964

The flight path and the met. information supplied by the aircraft which experienced CAT is also shown

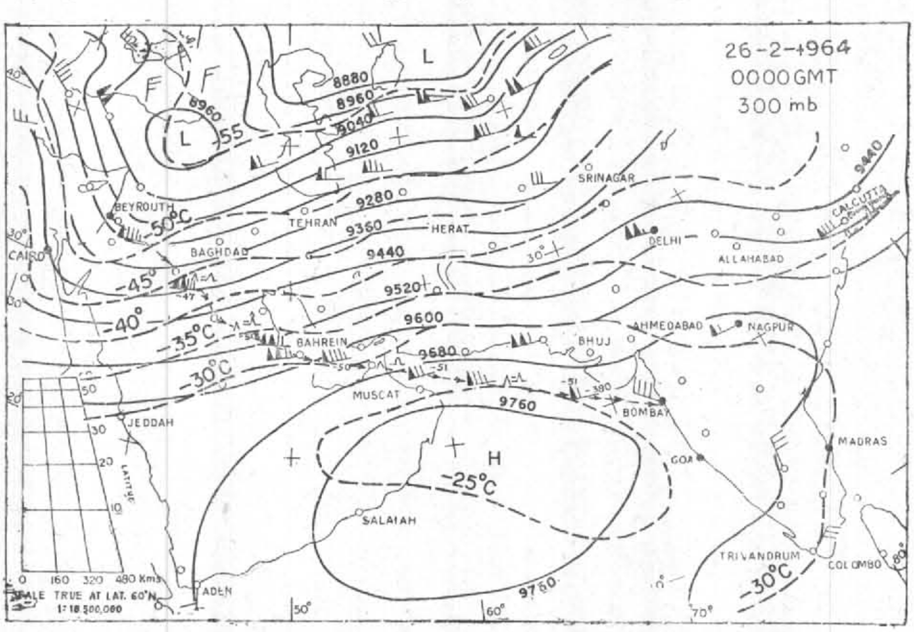

Fig. 3. 300-mb contours and isotherms (broken lines) at 0000 GMT on 26 February 1964

The flight path and the met. information supplied by the aircraft which experienced CAT is also shown

Summer — There is a sharp fall in the cases of CAT. Out of the 493 route sectors considered CAT was reported from only 11 of them. This is to be anticipated as the circulation is generally weak in this season over most of the areas covered by the flights whose data are utilised in this study.

The number of route sectors with V_5/V_3 values of 4 kt/1000 ft or more also fell from 108 in winter to 47 in spring and to 20 in summer. But the distribution of CAT intensity with respect to V_5/V_3 values remains in general the same.

Autumn — The number of cases of moderate or severe turbulence is greater than in summer but the percentage frequency remains the same. V_3/V_5 values of 6 to 8 kt/1000 ft were encountered in 4 route sectors as against 10 in winter and 3 in spring and summer. In all these sectors turbulence of some intensity was reported.

The data for the middle tropospheric levels (600 to 400 mb) for all seasons is shown in Table 2. About 25 per cent of the route sectors were considered and 19 per cent of the CAT reports are from

TABLE 1

Occurrence and intensity of turbulence as compared to the vertical wind shear (kt/1000 ft) for all levels

	Vertical wind shear (kt/1000 ft) at appropriate level (V_3 or V_5 values)									
	0-2	2-4	4-6	6-8	8-10	0-2	2-4	4-6	6-8	8-10
			WINTER					SPRING		
No. of cases of severe turbulence	Nil	1	9	2	Nil	Nil	Nil	1	3	Nil
No. of cases of moderate turbulence	Nil	2	24	5	Nil	Nil	1	21	Nil	Nil
No. of cases of light turbulence	1	3	21	3	Nil	Nil	1	8	Nil	Nil
Total No. of route sectors considered	140	317	98	10	Nil	206	255	45	3	Nil
Percentage occurrence of moderate and severe turbulence	Nil	0·95	33·67	70·00	Nil	0·0	0·39	49·00	100·0	Nil
Percentage occurrence of all types turbulence	0·71	1·90	55·10	100·00	Nil	0·0	0·78	66·70	100·0	Nil
			SUMMER					AUTUMN		
No. of cases of severe turbulence	Nil	Nil	1	Nil	Nil	Nil	Nil	Nil	1	Nil
No. of cases of moderate turbulence	Nil	1	4	Nil	Nil	Nil	Nil	9	2	Nil
No. of cases of light turbulence	Nil	1	3	Nil	Nil	Nil	1	8	1	Nil
Total No. of route sectors considered	383	90	20	Nil	Nil	363	218	43	4	Nil
Percentage occurrence of moderate and severe turbulence	0·0	1·1	25·00	Nil	Nil	0·0	0·0	20·93	75·00	Nil
Percentage occurrence of all types turbulence	0·0	2·2	40·00	Nil	Nil	0·0	0·46	39·53	100·00	Nil

TABLE 2

Occurrence and intensity of turbulence as compared to the vertical wind shear (kt/1000 ft) for all seasons for levels between 600 and 400 mb, and 400 and 200 mb

No. of cases of	Vertical wind shear (kt/1000 ft) at 500-mb level$=V_5$					Vertical wind shear (kt/1000 ft) at 300-mb level$=V_3$				
	0–2	2-4	4–6	6–8	8–10	0–2	2–4	4–6	6–8	8–10
Severe turbulence	Nil	Nil	1	Nil	Nil	Nil	1	11	6	Nil
Moderate turbulence	Nil	2	2	Nil	Nil	Nil	2	56	7	Nil
Light turbulence	1	3	14	Nil	Nil	Nil	3	26	4	Nil
Total route sectors considered	251	270	33	Nil	Nil	841	610	173	17	Nil
Moderate and severe turbulence(%)	0·0	0·74	9·09	Nil	Nil	0·0	0·5	38·72	70·60	Nil
All types turbulence(%)	0·4	1·85	51·51	Nil	Nil	0·0	0·99	53·75	100·00	Nil

TABLE 3

Occurrence and intensity of turbulence as compared to the vertical wind shear (kt/1000 ft) for all seasons for all levels

	Vertical wind shear (kt/1000ft) at appropriate levels (values of V_3 or V_5)				
	0–2	2–4	4–6	6–8	8–10
No. of cases of severe turbulence	Nil	1	12	6	Nil
No. of cases of moderate turbulence	Nil	4	58	7	Nil
No. of cases of light turbulence	1	6	40	4	Nil
Total No. of route sectors considered	1092	880	206	17	Nil
Percentage occurrence of moderate and severe turbulence	0·0	0·57	34·0	70·60	Nil
Percentage occurrence of all types turbulence	0·1	1·25	53·4	100·00	Nil

TABLE 4

Average values of vertical wind shear for different intensities of turbulence

Intensity of turbulence	Average vertical wind shear (kt/1000 ft) (V_3 or V_5)
Severe	5·5
Moderate	5·1
Light	4·8

these levels. Of the CAT reports only 5 out of 88 cases of moderate to severe turbulence are from these layers. Most of the turbulence encountered in these layers are light (18 cases out of 23). Only 1 out of 19 cases of severe turbulence reports was from these layers.

Table 2 also gives the data for the 400 to 200-mb levels. 1641 route sectors were studied for the data of these layers. Data shown in row 6 show a high amount of correlation between the occurrence of CAT of moderate to severe intensity and values of V_3.

Table 3 shows the data of all seasons for the two levels (contained in Table 2) and summarises the total data studied under all conditions. It can be seen that there is a sudden jump in the occurrence of CAT as V_5/V_3 crosses the values of 4 kt/1000 ft, which is well in agreement with results published by earlier workers who computed direct vertical wind shears and compared them with CAT data. 53 per cent of the route sectors with V_3/V_5 values of 4 to 6 kt/1000 ft have turbulent conditions in one place or other. This figure jumps to 100 per cent for those sectors with V_3 values between 6 to 8 kt/1000 ft.

However, it should be pointed out that percentages quoted here of rough air embedded sectors to the total sectors are not comparable with percentage of rough air distances to total sector distances given and discussed by earlier workers. The present figures refer to sector units in which turbulent regions form only a small percentage of the sector region. The actual distance over which rough air was encountered could not be evaluated with any degree of confidence due to the fact that the data from commercial flights do not give reports of turbulence in detail. And the resolution allowed by meagre upper air data also do not allow the evaluation of V_3/V_5 over areas of smaller extent.

4. Discussion on the results

(*a*) *The quality of correlation*

The data presented in Tables 1–3 show that there is a good correlation between the areas of synoptic scale extent in which turbulent patches can develop and the temperature gradients at standard isobaric levels. The critical value of 4 kt/1000 ft when CAT can be expected also agrees well with results obtained by earlier workers, who used direct method of evaluation of vertical wind shear using upper wind data.

Out of the 2195 sector units considered 1972 had V_3/V_5 values of less than the critical values. In other words only 10 per cent of the sectors had higher shear conditions. Out of the 139 cases of turbulence, 127 (90 per cent) were reported from these high shear sectors. The data indicate that thermal gradients at isobaric levels can be used as an aid in forecasting the general areas of CAT and the precision and accuracy of such forecasts will be satisfactory.

Comparing the data presented in Table 2, it can be seen that the frequency of sectors with CAT of moderate to severe intensities is about 9 per cent for the lower layer where V_5 is 4 to 6 kt/1000 ft and about 39 per cent for the upper layer where V_3 has the same value. This is a significant difference and needs explanations. The average level of flights in the lower layer (600-400 mb) works out to be nearly the 500-mb level itself. So V_5 gives nearly the actual shear conditions being experienced by the aircraft. On the other hand the flight levels in the upper layer (400-200 mb) average around 35,000 feet that is around 5000 ft above the 300-mb level. So the V_3 with which these CAT data in this layer are compared, is generally an under estimate of the actual shear conditions in which the flights are taking place. The correlation sought between V_3 and CAT in this layer is based on the assumption that the V_3 will be correlated to $(\partial v/\partial z)_{Z_f}$, where Z_f is the flight level. The statistics indicate that such a correlation is present. On the other hand the values of V_3 and V_5 have to be interpreted with respect to actual levels of the intended flights.

(*b*) *Limitations, exceptions and applicability of the correlation as a forecasting tool*

The average values of V_3 and V_5 for different intensities of CAT — severe, moderate and light — are shown in Table 4. It can be seen that correlation is not as sensitive as the correlations obtained with vertical wind shear as calculated directly from upper wind data. The discrimination between different degrees of CAT given by the present method compares unfavourably with that obtained with I by Colson and Panofsky (1965). The main reason is due to the fact that this is a second order correlation, as the V_3/V_5 are not the shears at the flight levels, as explained in the last para of the above sub-section.

Secondly, the shears computed by earlier workers are spot values. In the present case the V_3/V_5 are evaluated from the analysed charts. The analysis smoothens out the spot data and reduces the sensitivity. But it has other advantages which will be discussed later.

Thirdly, in this study no allowances have been made for the effect of orography. On scrutiny of individual cases, it was noticed that most of the cases of CAT which occurred with V_3/V_5 values below the critical value are from the mountainous regions of western Persia, north Iraq and eastern Turkey. The only case of severe CAT of this type was also from this region. Apparently the orography was chiefly responsible for the occurrence of these CAT cases. These cases naturally have their effects on the average values.

Fourthly, the thermal wind equation is derived from the geostrophic wind equation and its evaluation does not take into consideration the curvature of the upper air flow. The effect of curvature becomes pronounced as the wind speed increases. So very high shears can often develop in the upper air which are not reflected in the thermal structures. Many cases of moderate to severe CAT which we came across in this study were associated with jets with anticyclonic curvature and on such cases, the V_3 values did not indicate satisfactorily the intensity of CAT.

So forecasts based on the thermal gradients at standard isobaric levels have to be subjectively modified and supplemented for the above mentioned factors.

Fifthly, the subjective assessment of CAT reported by pilots has its own limitations which need no elaboration.

Most of the above mentioned shortcomings of using V_3/V_5 as forecast tools for CAT will be present in any method to be employed as long as synoptic data are the only basic material from which the forecasts are to be prepared.

The applicability of the method is also restricted to those parts of the globe where the geostrophic wind field is a good approximation of the actual wind field. This limits the utility of the method to north of 18°N with a doubtful zone between 13° to 18°N. So the data used for the present study were taken only from the area north of latitude 17°N. Fortunately very few cases of CAT occur in the region south of 17°N as the wind speed and vertical wind shear are generally low at the flying levels.

(c) *Advantages of the method*

The correlation shown by the study shows that V_5/V_3 with all their limitations (mentioned in the earlier sub-section) have good potentiallity as forecast tools, for CAT occurrence. Being a statistical method, it does not go into the basic physics of the occurrence of CAT. It is a practical solution for an operational need.

Even at a glance at the thermal field on the analysed chart will show the probable areas. These areas can then be studied in details.

As the V_3/V_5 reflect the shears both due to changes in speed and in direction with height, they incorporate the two in one parameter.

No special charts need be prepared for the purpose of CAT forecasts. No elaborate calculations are involved.

Lastly and most imporant of all is that thermal field for a future time can be more easily forecast than the direct vertical wind shear field. This is being done already for routine supply of chart form of documentation at the E.A.P. centres. So no special additional effort is needed.

6. Conclusion

The statistical study of the relationship between the occurrence of CAT and the temperature gradients at standard isobaric levels shows that there is a fairly good correlation between them and that this can be used as an aid to forecasting probable areas of CAT.

7. Acknowledgements

We wish to thank Dr. T. M. K. Nedungadi, Director, Regional Meteorological Centre, Bombay and Dr. A. K. Mukherjee, Meteorologist-in-charge, M.M.O., Santacruz for encouragement during this study.

REFERENCES

Clodman, J.	1961	*WMO Tech. Note*, 38, WMO-No. 109 T.P. 47.
Colson and Panofsky	1965	*Quart. J.R. met. Soc.*, **91**, pp. 505-517.
Hewson, E. W. and Longley, R. W.	1944	*An Introduction to Theoretical Meteorology*, John Wiley and Sons Inc., New York, p. 298.
Nat. Weath. Analysis Centre, Wash. D.C.	1960	*Manual on Weather Analysis and Prognostication*, U.S. Weath. Bur., Washington D.C.