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AN EVALUATION OF STRATOSPHERIC CAT FORECASTS FOR MID LATITUDES

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(Manuscript received May 1968)

ABSTRACT

The HICAT Program in Australia, which investigated the occurrence of CAT in the stratosphere, was carried out jointly by the U.S. Air Force and the Lockheed Company in July-August 1966.

Paucity of both temperature and wind gradients in the stratosphere made the identification of criteria associated with CAT in this region very difficult. However, parameters such as Richardson's number combined with an instability index which was a modification of the Endlich-McLean parameter $|V \Delta\alpha / \Delta Z|$, proved to be helpful in determining search areas for CAT. An example of the method used to forecast CAT is given together with a statistical analysis of the indicators used in this exercise.

1. INTRODUCTION

The joint U.S. Air Force - Lockheed "High Altitude Critical Atmospheric Turbulence" program, whilst investigating stratospheric turbulence on a world wide scale, made eleven flights in Australia between 19 July 1966 and 11 August 1966. Meteorological support for this operation was provided by the Commonwealth Bureau of Meteorology.

The frequency and intensity of stratospheric turbulence is required in connection with the design of supersonic aircraft. As well as contributing to the compilation of world wide turbulence statistics, this exercise also provided an opportunity for the verification or modification of existing CAT forecasting techniques. Experience gained from flights with Jindivik target aircraft between 200 mb and 50 mb over the Woomera Rocket Range in South Australia, formed the basis of the meteorological approach which was adopted during operation HICAT (Spillane 1967). Use was also made of the work done by Endlich and McLean (1964) and Endlich and Mancuso (1965).

A specially instrumented U2 research aircraft which was based at the RAAF Laverton aerodrome, Victoria, was used for the survey. As no support aircraft was provided in Australia, searches were made almost entirely over land and the maximum allowable seaward flying distance was 200 miles. In general, three survey flights were made each week, with no more than two on consecutive days. The first flight was usually made on a Monday and no search flights were carried out during the weekends. All flights were made during daylight hours and the maximum search range was 1200 miles from base. No searches were conducted below 50,000 ft.

2. DATA AND FORECASTING PARAMETERS

There were sixteen radiosonde stations within the prescribed range of operations. All of these carried out daily 2300 GMT radiosonde observations and three of them carried out routine 1100 GMT observations as well. In order to supplement this network special 1700 GMT radiosonde observations were obtained on request from selected stations close to the normal winter position of the jet stream. Radar wind observations were available four times daily from all stations.

To make the most use of available data, isopleths were drawn of all calculated indices. This established a basis for interpolation over areas where there were few or even no observations. For stations where radiosonde soundings were made at both 1700 GMT and 2300 GMT, features of the trace which were expected to be associated with turbulence, such as a "kink" or "saw tooth" pattern in the temperature profile (Spillane 1967), were found to be of a very transient nature. The maximum wind and its height were plotted to establish the axis and orientation of the jet stream. The Richardson number and the Scorer parameter were calculated using overlays designed by Spillane and Colquhoun (1966) for the Skew T-log p aerological diagram. Values of Richardson's number were calculated for each layer determined by a significant change in lapse rate, and or, wind shear. In routine observations at the particular levels considered, winds were reported at vertical separations of 8.4, 7.5 and 7.0 thousand feet. When one or more changes in lapse rate occurred over such intervals, the wind shears over these shallow layers were interpolated linearly from the reported winds. For each of the layers 150 to 100 mb, 100 to 70 mb, and 70 to 50 mb, the minimum value of Richardson's number in the layer and the height of the top of the sub-layer in which the minimum occurred, were charted.

Schwerdtfeger and Radok (1959) using the thermal geostrophic wind assumption proposed the use of differential advection as an indicator of the likely trend in vertical stability and hence in Richardson's number. Keitz (1959) also adopted a similar approach. With this principle in mind the simpler turbulence index, $V \Delta \alpha / \Delta Z$ as defined by Endlich and Mancuso (1965), was calculated for the layers 150 to 100 mb, 100 to 70 mb, and 70 to 50 mb. Here, for the height interval ΔZ, V is the mean speed in knots and $\Delta \alpha$ the change in wind direction in degrees. Although Endlich and Mancuso (1965) used the modulus of this index, the sign of the index was retained here to obtain an indication of the differential horizontal advection above 150 mb, on the grounds that this could result in the development of a "saw tooth" temperature profile in the stratosphere.

Spillane (1967), from a consideration of ageostrophic motions above the jet stream, has indicated that decreasing stability (and hence a low Richardson's number) can be expected to lead to the generation of turbulence in the unstable layer; this is then broken down, in the stable layer above, to a scale of turbulence sensed by aircraft as CAT.

Figure 1 illustrates the effect of differential thermal advection near and above the tropopause. As the planned search altitudes were from 50,000 ft to 70,000 ft, the regions marked X and Y in Fig. 1 were preferred to the region marked Z.

Search regions were chosen therefore on Richardson's number (actually $Ri \leqslant 5$) together with differential advection favouring increasing instability and hence the possibility of turbulence in regions X and Y of Fig. 1.

In the convention adopted cold air advection was taken as positive and warm air advection as negative. The value $V \Delta \alpha / \Delta Z$, for the 100 to 70 mb layer was subtracted from the value for the 150 to 100 mb layer in one case and the value for the 70 to 50 mb layer was subtracted from the 100 to 70 mb layer in the other; negative values of this indicator (I) were thus associated with increasing instability in the region of the interface of the layers under consideration.

The profile of the Scorer parameter, l^2, was plotted on the aerological diagram as it was calculated. The Scorer parameter was considered to be indicative of high level turbulence when the parameter decreased with height from a relatively high value in the lower levels to a point where a large increase was again observed. Above this point it was assumed that lee waves which were generated in the troposphere would break down into turbulence. The Scorer parameter was not a successful indicator of turbulence early in the program and was eventually abandoned as an aid.

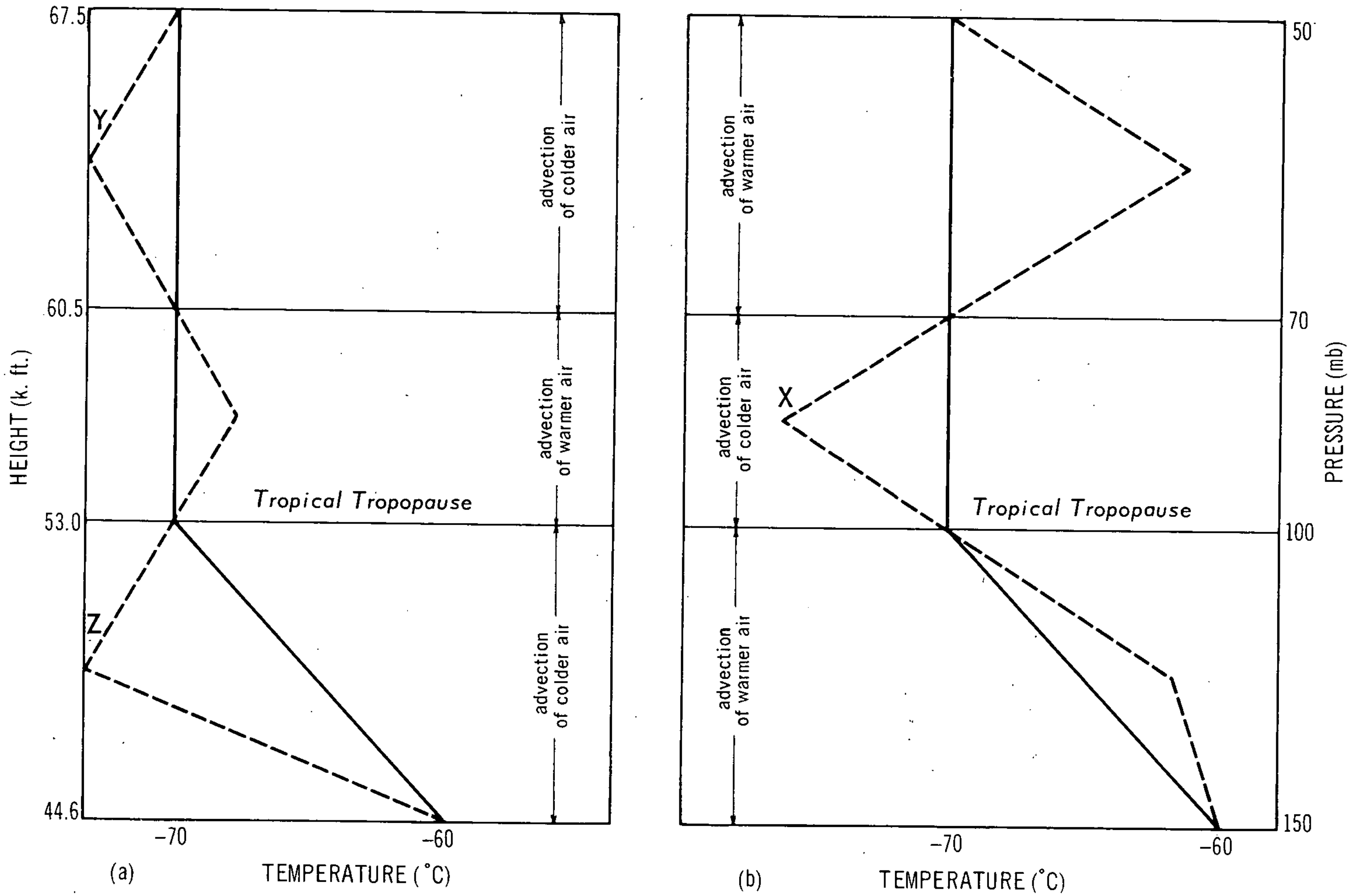

Fig. 1 Illustrating the effect of two types ((a) and (b)) of differential thermal advection. The continuous line represents the initial temperature profile and the broken line the profile after advection. Regions considered favourable for CAT are marked X, Y and Z.

3. TURBULENCE OCCURRENCE AND SYNOPTIC ASPECTS

Good volumes of turbulence were found both equatorward and poleward of the axis of maximum winds during the eleven search flights carried out over Australia. During operations seven flights encountered significant turbulence which exceeded 30 nautical miles in extent; these caused vertical accelerations equal to or greater than $\pm 0.25g$. Three flights recorded insignificant patches of CAT and the remaining case was intermediate. The efficiency of a flight can be defined as the ratio of the time spent in turbulence to the total time of the flight; this, of course, depends on the distance the plane has to travel to the target area. Based on this definition the efficiency for the entire Australian program was about 12 percent and the most successful flight defined on this basis had an efficiency of 36 percent. When particularly good turbulence areas were found, standard patterns of investigation were carried out by the aircraft. The standard pattern was in the form of a cross and was made up of a return run in the north-south and east-west directions.

Investigation of the maximum wind regime associated with occasions of turbulence showed that most occurrences of turbulence were above maximum winds with speeds greater than 100 knots. In all cases when significant turbulence was reported there was a marked lateral movement of the horizontal projection of the axis of maximum wind during the 6-hour period ending 2300 GMT. There was also a variation in the height of the maximum wind which was generally at a minimum height in the vicinity of turbulence; however, the occurrence of these features alone did not indicate turbulence.

The flight which spent the greatest percentage of time in turbulence was on the poleward side of a "jet exit" area and above maximum winds estimated between 60 and 80 knots. In the next two most successful flights, the main turbulence area was on the equatorward side of an east-west orientated jet with an adjacent southerly jet poleward (see Fig. 2). Jet stream configuration alone was insufficient to indicate turbulence; a jet stream pattern similar to that shown in Fig. 2, on another occasion was associated with practically no turbulence at all. Hence, although CAT in the stratosphere seems to occur in the vicinity of a jet stream, the presence of the jet stream alone is not sufficient to forecast the occurrence of CAT.

4. EXAMPLE OF THE METHOD USED TO SELECT A SEARCH AREA

The operational procedure adopted to choose a search route is illustrated by taking a specific example, for 28 July 1965. Features of the jet stream on this date are presented in Fig. 2 and referred to above. Extrapolation of 1700 GMT data was necessary in deciding the search route, as the 2300 GMT data were not available operationally until after the commencement of the search flight.

Isopleths of minimum Richardson's number were drawn firstly for the layers 150 to 100 mb and 100 to 70 mb; patterns of the instability index (I) were also constructed as described earlier. Due to the coarseness and paucity of measurements, a minimum Richardson's number of ≤ 5 within a layer was taken as indicating potential turbulence. Similarly, a negative value of the instability index between two layers was taken as being indicative of turbulence. Generally speaking, an area which was simultaneously selected by these two indicators was considered to have the greatest possibilities with regard to the occurrence of turbulence. Patterns for Richardson's number and the instability index appropriate to the mid-time of flight are shown in Fig. 3. In addition to these indicators, consideration was also given to topography and to the jet stream configuration (Fig. 2). The search path taken, which is divided into arbitrary intervals of 100 miles, is shown in Fig. 4. The maximum value of turbulence obtained in each of these intervals is shown in Table 1, together with the corresponding mean values, over each interval, of the minimum Richardson's number and the instability index.

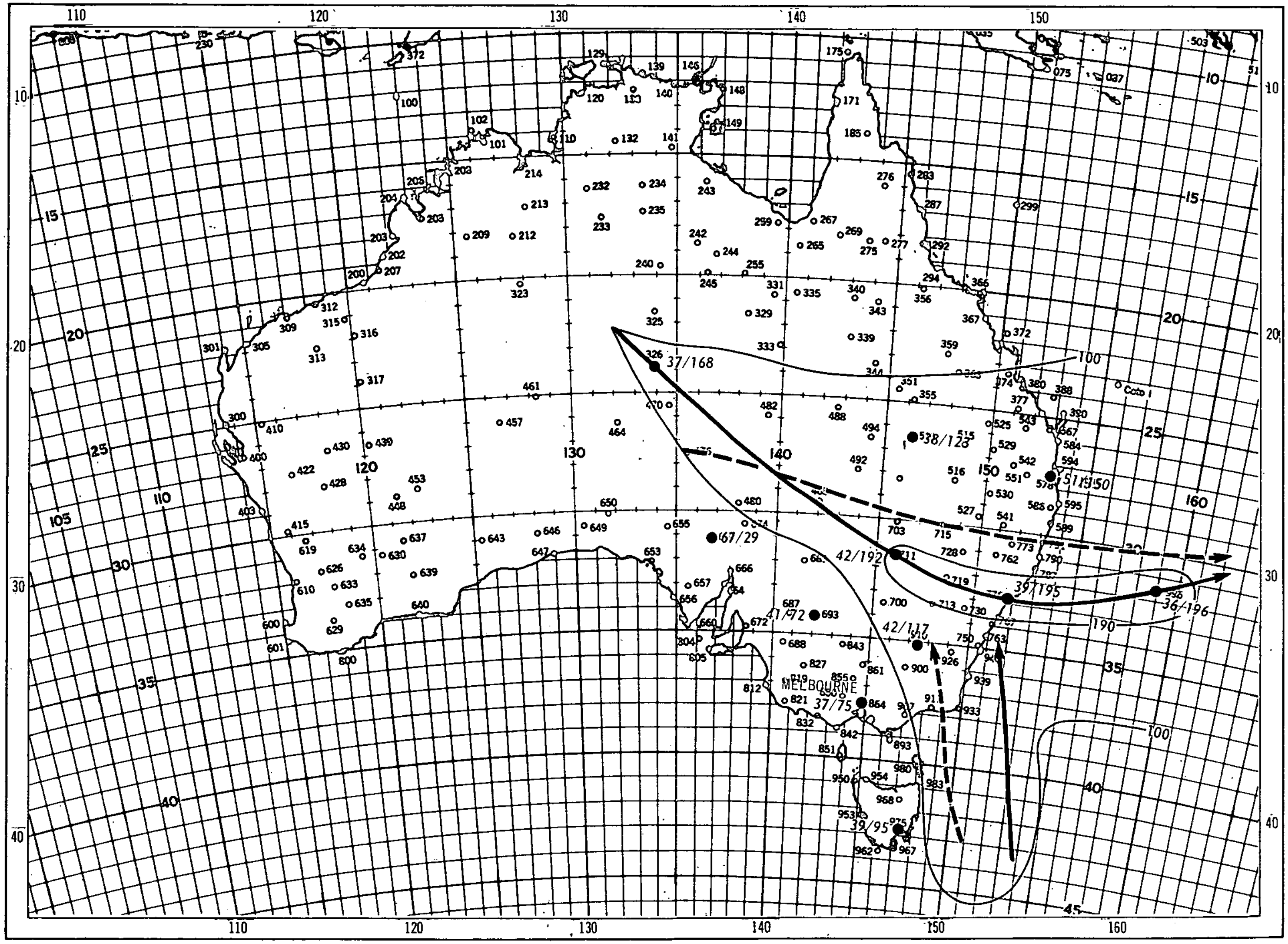

Fig. 2 Axes of jet streams for 1700 GMT (broken lines) and 2300 GMT (solid lines), 28 July 1965. The thin lines denote the isotachs (in knots) for 2300 GMT. The height at which the maximum wind occurs and the value of the maximum wind for selected stations are shown thus: *37/75* (at Melbourne); which indicates that the height of the maximum wind is 37,000 ft and the wind strength 75 knots.

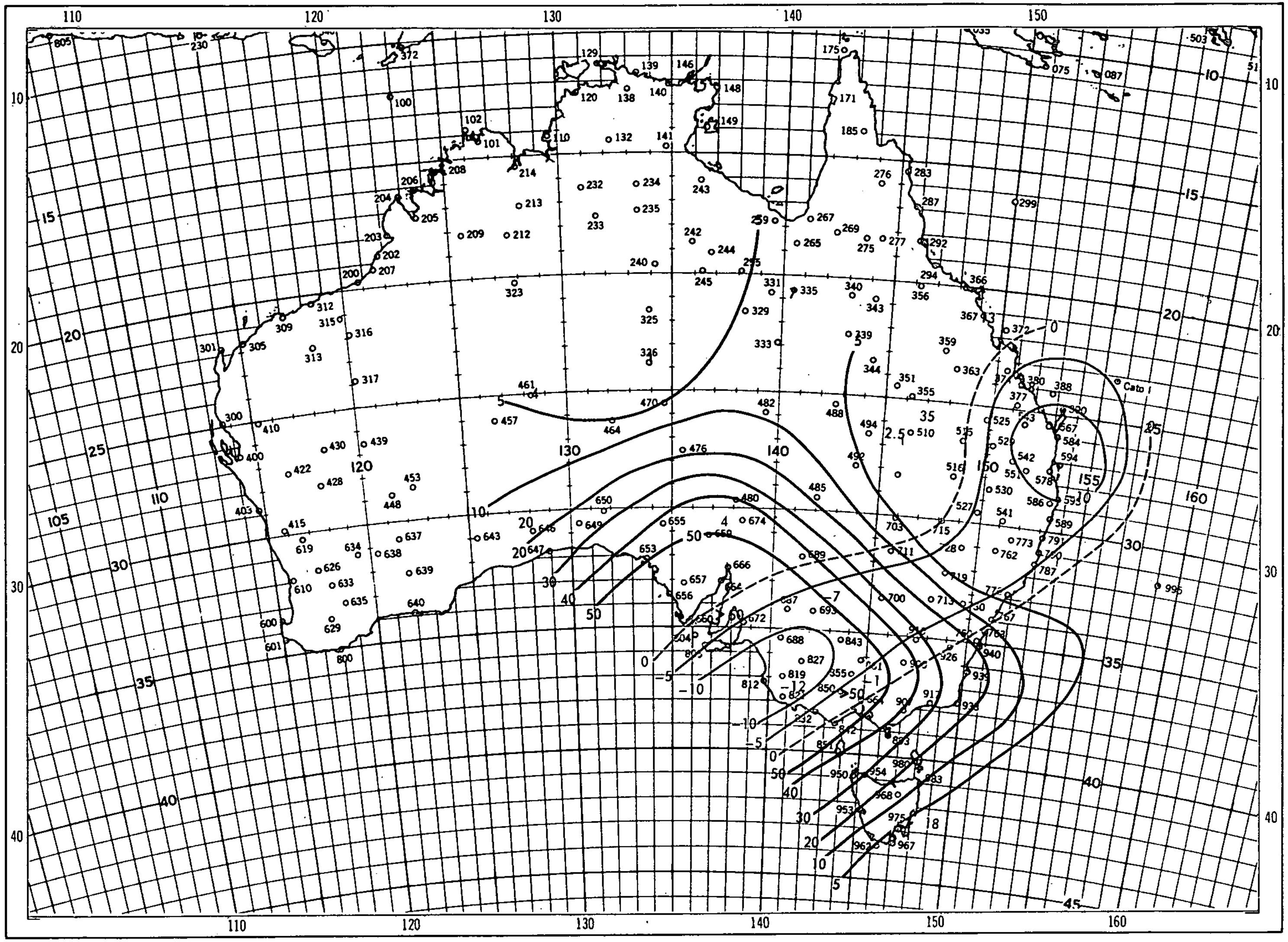

Fig. 3 Contours based on data for 28 July 1965. The minimum values of Richardson's number are for the 100 mb to 70 mb layer (red lines) Values for the instability index are shown as the algebraic difference between the values of $V.\alpha'.\Delta Z$ for the 100 mb to 70 mb layer and the 70 mb to 50 mb layer (black lines). Units for the latter are deg sec^{-1}

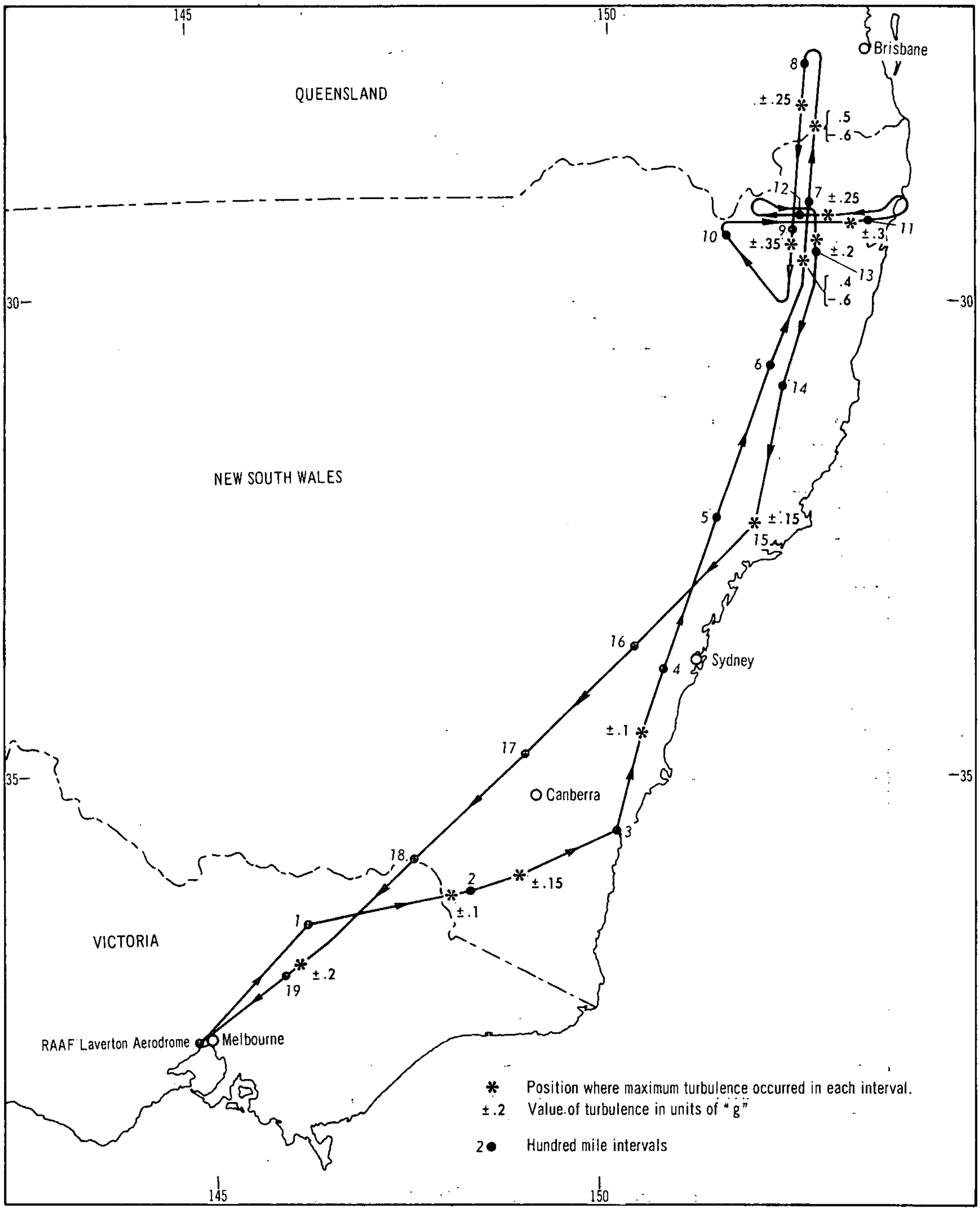

Fig. 4 The search route taken on 2300 GMT 28 July 1965. The number of miles flown and the maximum turbulence encountered in each hundred mile interval corresponds to the data set out in Table 1.

Table 1. Mean values of Richardson's number and the Instability Index are given for each 100 mile interval of the search flight on 28 July 1965. The corresponding maximum values of turbulence encountered together with the height are also shown for each interval.

Intervals 100 miles	Minimum Richardson's number between 100 mb and 70 mb	Instability Index ($V \Delta \alpha / \Delta Z$ for 100 mb to 70 mb) - ($V \Delta \alpha / \Delta Z$ for 70 mb to 50 mb). Units: deg sec^{-1}	Maximum value of turbulence in units of 'g'	Approximate height in thousands of feet
1	35	- 6	Nil	50
2	42	- 1	±.10	62.0
3	30	- 1	±.15	61.5
4	20	- 1	±.10	63.0
5	7	- 2	Nil	63.0
6	3	- 5	Nil	59 ±0.5
7	2	-10	+.40 -.60	59 ±0.5
8	2	-12	+.50 -.60	59 ±0.5
9	2	-12	±.25	59 ±0.5
10	2	-12	±.35	59 ±0.5
11	2	-12	±.30	59 ±0.5
12	2	-12	±.25	59 ±0.5
13	3	-10	±.20	59 ±0.5
14	3	- 5	Nil	59 ±0.5
15	4	- 2	±.15	62.5
16	10	- 1	Nil	62.5
17	25	- 1	Nil	62.5
18	40	- 1	Nil	62.5
19	50	- 1	±.20	56.0

5. STATISTICAL ANALYSIS OF TURBULENCE CRITERIA

Eleven flights were carried out during the period 19 June to 11 August 1965. The success of each flight was decided by dividing the search distance into intervals of 100 miles and scoring either turbulence or no turbulence for each interval against the average value of the instability index (I) and the Richardson's number (Ri) derived from the contours for the same interval. The turbulence index $|V \Delta \alpha / \Delta Z|$, as used by Endlich and McLean (1964) and represented here by $|i|$, was also evaluated for the series of test flights. In all, 204 cases were considered and the results are set out in Table 2.

Table 2. Occurrence of CAT against various parameters. Values of Chi-squared (χ^2) and skill score (S) against chance are also shown.

(a) Richardson's Number (Ri)

ANALYSED

	Ri $\leqslant$ 5	Ri > 5	
Turbulent	56	38	94
Non-turbulent	57	53	110
	113	91	

CHANCE

52	42
61	49

χ^2 = 1.28   S = 0.08

(b) Instability Index (I)

ANALYSED

	I < 0	I $\geqslant$ 0	
Turbulent	79	15	94
Non-turbulent	68	42	110
	147	57	

CHANCE

68	26
79	31

χ^2 = 11.90   S = 0.21

(c) Instability Index I < 0, Ri $\leqslant$ 5

ANALYSED

	Ri $\leqslant$ 5, I < 0	All remaining cases	
Turbulent	52	42	94
Non-turbulent	31	79	110
	83	121	

CHANCE

38	56
45	65

χ^2 = 16.10   S = 0.28

(d) Turbulence Index $|V \Delta\alpha / \Delta Z|$ represented by $|i|$

ANALYSED

	$\|i\| \leqslant 5$	$\|i\| > 5$	
Turbulent	50	46	96
Non-turbulent	39	69	108
	89	115	

CHANCE

42	54
47	61

$\chi^2 = 5.1$ $\quad\quad S = 0.16$

Using Richardson's number $\leqslant 5$ as an indicator, 53 percent of turbulence intervals were identified. The instability index (values <0) identified 59 percent of the turbulence, whilst a combination of the two parameters correctly identified 64 percent. The turbulence index $|V \Delta\alpha/\Delta Z|$ was evaluated subsequentially for the same data and it identified 58 percent of the reported turbulence.

To investigate the effectiveness of these various parameters in specifying CAT, the values of Chi-squared and a skill score were both calculated against chance.

Both the instability index, I, and the combination of this index with Richardson's number were significant at the one percent level, which was 6.64. The turbulence index ($|i|$) was significant at the three percent level, whilst Richardson's number alone was only significant at the 24 percent probability level.

Table 3 indicates the success of the various parameters in specifying CAT in intensity ranges, as compared with chance. For this purpose a vertical acceleration of $|\pm 0.2g|$ or more was taken as indicating moderate or severe turbulence. With six degrees of freedom the one percent probability level of Chi-squared is 16.81. Only the instability index, I, was significant at this level.

Table 3. Comparison of the number of cases of CAT in various categories, as indicated by different indices, with the values expected by chance as shown in brackets.

RICHARDSON'S NUMBER (Ri)

	Ri $\leqslant$ 5	5 < Ri $\leqslant$ 10	10 < Ri $\leqslant$ 15	Ri > 15	Total
No Turbulence	57 (61)	18 (20)	6 (4)	29 (24)	110
Light Turbulence	29 (27)	10 (9)	1 (2)	9 (11)	49
Moderate or Severe Turbulence	27 (25)	10 (8)	1 (2)	7 (10)	45
Total	113	38	8	45	204

$\chi^2 = 6.7$

INSTABILITY INDEX (I)

	$I \geqslant 10$	$0 \leqslant I < 10$	$-10 \leqslant I < 0$	$I < -10$	Total
No Turbulence	17 (11)	25 (20)	42 (45)	26 (34)	110
Light Turbulence	1 (5)	7 (9)	23 (20)	18 (15)	49
Moderate or Severe Turbulence	2 (4)	5 (8)	19 (19)	19 (14)	45
Total	20	37	84	63	204

$\chi^2 = 19.0$

TURBULENCE INDEX $|V\Delta\alpha/\Delta Z|$ or $|i|$

	$\lvert i\rvert \leqslant 5$	$5 < \lvert i\rvert \leqslant 10$	$10 < \lvert i\rvert \leqslant 15$	$\lvert i\rvert > 15$	Total
No Turbulence	39 (47)	41 (37)	13 (12)	15 (13)	108
Light Turbulence	28 (22)	17 (17)	4 (5)	2 (6)	51
Moderate or Severe Turbulence	22 (20)	11 (15)	5 (5)	7 (5)	45
Total	89	69	22	24	204

$\chi^2 = 8.7$

6. CONCLUSIONS

In this investigation use was made of the maximum winds in the troposphere to delineate the axis of strongest winds both in the horizontal and vertical. When turbulence was found, it was generally associated with rapid movement of the horizontal projection of this axis and in most cases it was above a maximum wind greater than 100 knots. There did not seem to be any preferred side of the jet axis for the occurrence of turbulence, although an area above a volume in the vicinity of a "jet exit" area seemed to be more favourable than a volume in the vicinity of a "jet entrance" area for the occurrence of turbulence in the stratosphere.

From a statistical analysis of the results obtained a combination of the two indicators used proved most successful, i.e. minimum Richardson's number $\leqslant 5$ over a layer of about 8,000 ft thickness, together with an instability index which was expressed as the algebraic difference of $V\Delta\alpha/\Delta Z$ (taking sign into account) between two layers of similar thickness. With the sparse data, this latter indicator proved to be more significant for forecasting purposes than the $|V\Delta\alpha/\Delta Z|$ index used by Endlich and McLean (1964). The combination of Richardson's number and the instability index was superior to any single indicator.

ACKNOWLEDGEMENTS

This project was carried out under the guidance of, and with continuous help from, Messrs. J.N. McRae and K.T. Spillane.

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