CLEAR AIR TURBULENCE ANALYSIS OVER THE SOUTH PACIFIC REGION FOR A FIVE-DAY PERIOD IN DECEMBER 1964

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ABSTRACT

As part of the ICAO short-term high-level turbulence reporting programme, data has been compiled and analysed for flights at or above 20,000 ft. Areas of non-occurrence as well as areas of occurrence of high level clear air turbulence (CAT) were determined over the South Pacific Region during a selected five-day period in December 1964. Latitude-longitude 'squares' of 2.5° were used to tabulate the flight data. Flights were divided into (1) flights at or below 30,000 ft and (2) flights above 30,000 ft. Frequency distributions and percentages of CAT occurrence were computed over individual 'squares', for flight elevations and also for various parameters mainly of a meteorological nature.

The percentage of CAT occurrences increases fairly uniformly with increasing "average" vertical wind shear and horizontal wind shear, and is more frequent near than away from the jet stream. No significant relationship was evident between CAT and Richardson's Number, maximum wind and the height and temperature of the tropopause. Most parameters were more successful for flights at and below 30,000 ft where the majority of CAT occurred.

No significant relationship was evident between CAT and flight direction but the presence of clouds above the flight level appears to be significant. Mean airspeed fluctuations at the onset of turbulence increase steadily with increasing severity of turbulence.

Six parameters - Endlich's turbulence index, vorticity, vorticity advection, "average" vertical wind shear, Richardson's number and the Colson-Panofsky turbulence index - were investigated in a study restricted to flights in the area bounded by latitudes 22°S and 40°S and longitudes 112°E and 160°E. Average vertical wind shear and Richardson's Number gave the best results.

1. INTRODUCTION

This study was undertaken in connection with the ICAO short-term high-level turbulence reporting programme during which clear air turbulence (CAT) data were collected on a world-wide basis. The data analysed here were collected in the South Pacific Region.

The programme consisted of four reporting periods, each of five days, with one period in each season. This paper covers the first of these periods, from 2300 GMT on 8 December to 2400 GMT on 13 December 1964.

Data for flight levels at 20,000 ft and above were received from,

(i) international flights by turbine powered IATA Member Airlines,
(ii) all other civil domestic flights and international civil flights by turbine powered aircraft,
(iii) flights by military or other government turbine powered aircraft.
Pilots were asked to submit data forms (see Fig. 1) whether or not turbulence was encountered. Thus the areas of non-occurrence as well as the areas of occurrence of CAT could be determined and analysed. The method of analysis of this data closely follows that carried out by Colson (1963 and 1964). The percentage occurrence of CAT with various values of different parameters has been estimated.

2. METHOD OF ANALYSIS

The South Pacific Region includes the Australian continent, air-routes to Singapore and over the Tasman Sea, and Pacific air-routes to Canton Island, Fiji and Tahiti. These areas were divided into 2.5° latitude and longitude 'squares'. Data forms were sorted into flights at or below 30,000 ft and flights above 30,000 ft and then examined for the intensity of CAT occurrences. The intensity classes were none, light, moderate, severe and extreme. Tabulations were made for 12-hour intervals centred on the synoptic hours of 2300 GMT and 1100 GMT. In the Australian region the main surface and upper air analyses were made at these times, rather than the standard WMO times of 0000 and 1200 GMT. These tabulations included the total number of flights, the number of occurrences of the different classes of CAT for both flight layers and time intervals over each 'square'. The percentages of the different CAT intensities were computed for time intervals, flight layers and geographical distribution.

As the analyses of CAT occurrences against "wind only" parameters were based on 12 hourly analyses while those for parameters such as Richardson's number were based on 24 hourly analyses, the totals of flight squares and CAT occurrences may differ due to several CAT occurrences spanning two periods.

The relation between CAT and such parameters as vertical wind shear, horizontal wind shear, jet stream, wind speed, tropopause height and temperature, and the Richardson Number, was investigated over the flight area. The percentage frequencies of various categories of CAT with varying values of the above meteorological parameters are given in Section 3. However, in some cases the numbers on which these percentages are based are too small to give representative values, therefore actual figures also are presented.

Over the restricted region bounded by latitudes 22.5°S and 40°S and longitudes 112.5°E and 160°E, a separate study was made of the relation between CAT and vertical wind shear, Richardson's Number, vorticity, vorticity advection and two turbulence indices. The results are presented in Section 4.

Since the aim of the programme was the study of CAT, occurrences of turbulence were excluded when they were reported to be in the vicinity of towering cumuli or thunderstorms, or where the surface map indicated well-developed thunderstorm areas, except that all turbulence occurrences were included in the study of fluctuations in the indicated airspeed of the aircraft.

3. RESULTS OF ANALYSIS

The areal distribution of the flight squares is shown in Fig. 2. The low flight density over the greater part of the area considered is evident from this chart. This greatly limits the value of this study.

(a) Analysis of CAT Occurrences with Time, Geographical Location and Height

Table 1 shows the actual distribution of the CAT occurrences in time during the five-day period for (i) flights at or below 30,000 ft, (ii) flights above 30,000 ft and (iii) flights at all levels. The peak period of CAT occurrence was from 1700 GMT on 9 December to 1700 GMT on 10 December 1964. After this period there were very few occurrences of moderate or severe turbulence. There were no extreme turbulence occurrences during the five-day period.

Tables 1(a) and (b) show that CAT was encountered more frequently at and below 30,000 ft than above 30,000 ft. From Table 1(c) it is seen that in 5.4 per cent of flight squares some degree of CAT was experienced, while in 2.0 per cent of flight squares moderate or severe CAT was encountered.

The geographical distribution of the percentage occurrences of all cases of CAT and of the moderate and severe cases are shown in Fig. 3.

To estimate the distribution of the incidence and severity of CAT at different flight levels, flights were divided into four layers and the number of flight squares with specified degrees of CAT in each layer counted. The results of this analysis are shown in Table 2. The highest frequency of all classes of CAT occurred in the lowest layer. All cases of severe CAT occurred below 26,500 ft.
HIGH LEVEL TURBULENCE REPORT
(FLIGHT LEVEL 200 OR ABOVE)

Return completed report to Bureau of Meteorology, P.O. Box 1289K, Melbourne, C.I., Australia

PLEASE READ CAREFULLY THE INSTRUCTIONS ON REVERSE SIDE

<table>
<thead>
<tr>
<th>TYPE OF AIRCRAFT:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROUTE: FROM TO</td>
</tr>
<tr>
<td>VIA: AIRWAY/PRINCIPAL REPORTING POINTS</td>
</tr>
<tr>
<td>CRUISING LEVEL:</td>
</tr>
<tr>
<td>DATE (GMT)</td>
</tr>
<tr>
<td>ALL FLIGHTS WITH NIL OR VERY LIGHT TURBULENCE, CHECK THIS SQUARE</td>
</tr>
</tbody>
</table>

ALL FLIGHTS WITH SIGNIFICANT TURBULENCE
(Fill out one column for each encounter)

<table>
<thead>
<tr>
<th>INTENSITY (Pilot's estimate):</th>
</tr>
</thead>
<tbody>
<tr>
<td>L—LIGHT</td>
</tr>
<tr>
<td>POSITION AT ONSET:</td>
</tr>
<tr>
<td>Longitude/Latitude</td>
</tr>
<tr>
<td>TIME (GMT) AT ONSET:</td>
</tr>
<tr>
<td>DURATION (minutes):</td>
</tr>
<tr>
<td>TYPE:</td>
</tr>
<tr>
<td>INTERMITTENT:</td>
</tr>
<tr>
<td>CONTINUOUS:</td>
</tr>
<tr>
<td>FLIGHT LEVEL AT ONSET:</td>
</tr>
<tr>
<td>INDICATED AIRSPEED (Knots)</td>
</tr>
<tr>
<td>AT ONSET:</td>
</tr>
<tr>
<td>AIRSPEED FLUCTUATIONS (Knots):</td>
</tr>
<tr>
<td>TRUE AIR TEMPERATURE °C AT ONSET:</td>
</tr>
<tr>
<td>WIND DIRECTION AND SPEED (Knots)</td>
</tr>
<tr>
<td>AT ONSET:</td>
</tr>
<tr>
<td>CLOUDS:</td>
</tr>
<tr>
<td>IN CLOUDS</td>
</tr>
<tr>
<td>IN AND OUT</td>
</tr>
<tr>
<td>IN THE CLEAR</td>
</tr>
<tr>
<td>IN OR ADJACENT:</td>
</tr>
<tr>
<td>TOWERING CUMULUS</td>
</tr>
<tr>
<td>THUNDERSTORM</td>
</tr>
<tr>
<td>CIRRUS</td>
</tr>
</tbody>
</table>

REMARKS: Any additional pertinent data such as abrupt changes in temperature or wind, fluctuations in temperature, any alleviating action such as reduction of airspeed, change of course or altitude and the consequences of such action, etc. Give position to which "Remarks" apply.


Fig. 1 Turbulence reporting form.
Fig. 2: Flight distribution over the 5-day period from 2100 GMT 8 December 1964 to 2400 GMT 13 December 1964.
Fig. 3 Geographical distribution of the percentage occurrence of C.A.T.—all levels combined
8 December 1964 to 13 December 1964.
Table 1 - Calendar of CAT occurrences during the period 2300 GMT 8 December to 2400 GMT 13 December 1964

(a) Flights at and below 30,000 ft

<table>
<thead>
<tr>
<th>Time and Date</th>
<th>Occurrence of CAT</th>
<th>Percentage of Flight Squares</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Flight Squares</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>None</td>
</tr>
<tr>
<td>GMT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2300; 8-0500, 9</td>
<td>92</td>
<td>80</td>
</tr>
<tr>
<td>0500, 9-1700, 9</td>
<td>112</td>
<td>106</td>
</tr>
<tr>
<td>1700, 9-0500, 10</td>
<td>155</td>
<td>131</td>
</tr>
<tr>
<td>0500, 10-1700, 10</td>
<td>93</td>
<td>81</td>
</tr>
<tr>
<td>1700, 10-0500, 11</td>
<td>197</td>
<td>175</td>
</tr>
<tr>
<td>0500, 11-1700, 11</td>
<td>61</td>
<td>60</td>
</tr>
<tr>
<td>1700, 11-0500, 12</td>
<td>66</td>
<td>64</td>
</tr>
<tr>
<td>0500, 12-1700, 12</td>
<td>67</td>
<td>65</td>
</tr>
<tr>
<td>1700, 12-0500, 13</td>
<td>132</td>
<td>131</td>
</tr>
<tr>
<td>0500, 13-2400, 13</td>
<td>103</td>
<td>101</td>
</tr>
<tr>
<td>Total</td>
<td>1078</td>
<td>994</td>
</tr>
</tbody>
</table>

Mod. = moderate; Sev. = severe

(b) Flights above 30,000 ft

<table>
<thead>
<tr>
<th>Time and Date</th>
<th>Occurrence of CAT</th>
<th>Percentage of Flight Squares</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Flight Squares</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>None</td>
</tr>
<tr>
<td>GMT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2300; 8-0500, 9</td>
<td>161</td>
<td>156</td>
</tr>
<tr>
<td>0500, 9-1700, 9</td>
<td>149</td>
<td>147</td>
</tr>
<tr>
<td>1700, 9-0500, 10</td>
<td>204</td>
<td>186</td>
</tr>
<tr>
<td>0500, 10-1700, 10</td>
<td>167</td>
<td>158</td>
</tr>
<tr>
<td>1700, 10-0500, 11</td>
<td>196</td>
<td>190</td>
</tr>
<tr>
<td>0500, 11-1700, 11</td>
<td>95</td>
<td>92</td>
</tr>
<tr>
<td>1700, 11-0500, 12</td>
<td>107</td>
<td>104</td>
</tr>
<tr>
<td>0500, 12-1700, 12</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>1700, 12-0500, 13</td>
<td>116</td>
<td>116</td>
</tr>
<tr>
<td>0500, 13-2400, 13</td>
<td>122</td>
<td>117</td>
</tr>
<tr>
<td>Total</td>
<td>1403</td>
<td>1352</td>
</tr>
</tbody>
</table>

Mod. = moderate; Sev. = severe
Table 1 - (Cont'd)  (c) Flights at all levels

<table>
<thead>
<tr>
<th>Time and Date</th>
<th>Occurrence of CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Flight Squares</td>
</tr>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>2300, 8-0500, 9</td>
<td>253</td>
</tr>
<tr>
<td>0500, 9-1700, 9</td>
<td>261</td>
</tr>
<tr>
<td>1700, 9-0500, 10</td>
<td>359</td>
</tr>
<tr>
<td>0500, 10-1700, 10</td>
<td>260</td>
</tr>
<tr>
<td>1700, 10-0500, 11</td>
<td>393</td>
</tr>
<tr>
<td>0500, 11-1700, 11</td>
<td>156</td>
</tr>
<tr>
<td>1700, 11-0500, 12</td>
<td>175</td>
</tr>
<tr>
<td>0500, 12-1700, 12</td>
<td>153</td>
</tr>
<tr>
<td>1700, 12-0500, 13</td>
<td>248</td>
</tr>
<tr>
<td>0500, 15-2400, 13</td>
<td>225</td>
</tr>
<tr>
<td>Total</td>
<td>2481</td>
</tr>
</tbody>
</table>

Mod. = moderate;  Sev. = severe

Table 2. Distribution of flight squares with and without CAT occurrence with height

<table>
<thead>
<tr>
<th>Flight Layers (ft)</th>
<th>No CAT Flight squares</th>
<th>Light Flight squares</th>
<th>Moderate Flight squares</th>
<th>Severe Flight squares</th>
<th>Total No.</th>
<th>% with CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>%</td>
<td>No.</td>
<td>%</td>
<td>No.</td>
<td>%</td>
</tr>
<tr>
<td>≤26,500</td>
<td>960</td>
<td>92</td>
<td>48</td>
<td>5</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>27,000 - 30,000</td>
<td>34</td>
<td>97</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>30,500 - 33,500</td>
<td>537</td>
<td>96</td>
<td>19</td>
<td>3</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>≥34,000</td>
<td>815</td>
<td>97</td>
<td>17</td>
<td>2</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>All levels</td>
<td>2346</td>
<td>95</td>
<td>85</td>
<td>3</td>
<td>40</td>
<td>2</td>
</tr>
</tbody>
</table>

Over the most intense period of CAT, from 1700 GMT on 9 December to 1700 GMT on 10 December 1964, there were 87 flights of which 45 (52 per cent) encountered some degree of CAT and 22 (25 per cent) encountered moderate or severe CAT. Examination of upper air charts during the most intense period of CAT shows some interesting features. The 300 mb charts for the period 2300 GMT on 8 December to 2300 GMT on 10 December 1964 (see Fig. 4) show an intensification of a major trough just off the east coast of Australia, with a subsequent equatorward displacement of the jet stream. Most of the CAT occurrences for the 24-hour period centred on 2300 GMT on 9 December were in the region of this trough. The horizontal wind shears in the region of the trough intensified to a maximum of 70 knots per 100 nautical miles between 2300 GMT on 8th December and 2300 GMT on 9th December and the vertical wind shear maintained a constant high value of 7 knots per 1000 ft over this area. There were also areas of CAT (mainly light) situated in or east of a high pressure ridge in the vicinity of New Zealand. The majority of CAT occurrences were on the cold side of the jet.
(b) Analysis of CAT against Vertical Wind Shear

Vertical wind shear has been regarded by many research workers as one of the most important parameters in forecasting CAT. The data were divided into two layers, squares with flights "at and below 30,000 ft" and squares with flights "above 30,000 ft". Analyses were carried out for these two layers separately and also for both combined, i.e. for flights "at all levels".

Two parameters of vertical wind shear are considered,

(i) the average of the magnitudes of the vector shears in the 10,000 ft layers above and below the level of maximum wind (the "average" shear),

(ii) the magnitude of the vector shear in the layer 10,000 ft below the level of maximum wind.

From these shears, values for the centres of flight squares were obtained by interpolation. Each shear parameter is graded in two ways, within specified limits and above specified limits (for values ≥4 kt/1000 ft).

The occurrences of CAT in flight squares are analysed according to classes of wind shear parameter (i) in Table 3, and according to classes of wind shear parameter (ii) in Table 4.

Table 3. Distribution of CAT occurrences against average of the vertical wind shears through the 10,000 ft layers above and below the level of maximum wind, i.e. parameter (i).

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
<th>Shear (Kt/1000 ft)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>319</td>
<td>14</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>&lt;4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>≥4 and &lt;6</td>
<td>369</td>
<td>17</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>≥4</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>≥6 and &lt;8</td>
<td>279</td>
<td>37</td>
<td>13</td>
<td>22</td>
<td>8</td>
<td>≥6</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>≥8</td>
<td>111</td>
<td>16</td>
<td>14</td>
<td>6</td>
<td>5</td>
<td>≥8</td>
<td>14</td>
<td>5</td>
</tr>
</tbody>
</table>

(b) Flights above 30,000 ft

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
<th>Shear (Kt/1000 ft)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
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<tbody>
<tr>
<td>&lt;4</td>
<td>819</td>
<td>19</td>
<td>2</td>
<td>4</td>
<td>0.5</td>
<td>&lt;4</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>≥4 and &lt;6</td>
<td>328</td>
<td>12</td>
<td>4</td>
<td>2</td>
<td>0.6</td>
<td>≥4</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>≥6 and &lt;8</td>
<td>176</td>
<td>11</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>≥6</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>≥8</td>
<td>80</td>
<td>9</td>
<td>11</td>
<td>4</td>
<td>5</td>
<td>≥8</td>
<td>11</td>
<td>5</td>
</tr>
</tbody>
</table>

(c) Flights at all levels

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
<th>Shear (Kt/1000 ft)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
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</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>1138</td>
<td>33</td>
<td>3</td>
<td>4</td>
<td>0.4</td>
<td>&lt;4</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>≥4 and &lt;6</td>
<td>697</td>
<td>29</td>
<td>4</td>
<td>9</td>
<td>1</td>
<td>≥4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>≥6 and &lt;8</td>
<td>455</td>
<td>48</td>
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<td>27</td>
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<td>≥6</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>≥8</td>
<td>191</td>
<td>25</td>
<td>13</td>
<td>10</td>
<td>5</td>
<td>≥8</td>
<td>13</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 4. Distribution of CAT occurrences against vertical wind shear in the 10,000 ft layer below the level of maximum wind, i.e. parameter (ii)

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>380</td>
<td>23</td>
<td>6</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>≥4 and &lt;6</td>
<td>354</td>
<td>30</td>
<td>7</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>≥6 and &lt;8</td>
<td>230</td>
<td>24</td>
<td>10</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>≥8</td>
<td>114</td>
<td>7</td>
<td>6</td>
<td>2</td>
<td>2</td>
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</table>

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>≥4</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>≥6</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>≥8</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

(b) Flights above 30,000 ft

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>814</td>
<td>26</td>
<td>3</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>≥4 and &lt;6</td>
<td>346</td>
<td>10</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>≥6 and &lt;8</td>
<td>187</td>
<td>11</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>≥8</td>
<td>56</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>≥4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>≥6</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>≥8</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

(c) Flights at all levels

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>1194</td>
<td>49</td>
<td>4</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>≥4 and &lt;6</td>
<td>700</td>
<td>40</td>
<td>6</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>≥6 and &lt;8</td>
<td>417</td>
<td>35</td>
<td>8</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>≥8</td>
<td>170</td>
<td>11</td>
<td>7</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shear (Kt/1000 ft)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>≥4</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>≥6</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>≥8</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

The results in Tables 3 and 4 suggest that the "average" vertical wind shear parameter (i), is a better indicator of CAT than the vertical wind shear below the maximum wind parameter (ii). Table 3 shows an increase in the percentage of CAT with increasing shear, whereas Table 4 only shows this tendency above 30,000 ft. The maximum percentage CAT of any category was 14 per cent for flights at and below 30,000 ft and for an "average" vertical wind shear of 8 knots or more per 1,000 ft.

(c) Analysis of CAT against Horizontal Wind Shear

An analysis of occurrence of CAT against various values of horizontal wind shear at 300 mb is shown in Table 5. Here too, the data has been divided into two layers, at and below 30,000 ft and above 30,000 ft. The wind shear is also graded within specified limits and above specified limits, separately.
Table 5. Distribution of occurrence of CAT with horizontal wind shear at 300 mb.

(a) Flights at and below 30,000 ft

<table>
<thead>
<tr>
<th>Shear (Kt/100 n mi)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
<th>Shear (Kt/100 n mi)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>383</td>
<td>19</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>&lt;10</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>10-19</td>
<td>358</td>
<td>30</td>
<td>8</td>
<td>13</td>
<td>4</td>
<td>≥10</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>20-29</td>
<td>186</td>
<td>13</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>≥20</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>30-39</td>
<td>68</td>
<td>5</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>≥30</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>40-49</td>
<td>54</td>
<td>6</td>
<td>11</td>
<td>5</td>
<td>9</td>
<td>≥40</td>
<td>21</td>
<td>13</td>
</tr>
<tr>
<td>50-59</td>
<td>8</td>
<td>3</td>
<td>37</td>
<td>2</td>
<td>25</td>
<td>≥50</td>
<td>38</td>
<td>21</td>
</tr>
<tr>
<td>≥60</td>
<td>21</td>
<td>8</td>
<td>38</td>
<td>4</td>
<td>19</td>
<td>≥60</td>
<td>38</td>
<td>19</td>
</tr>
</tbody>
</table>

(b) Flights above 30,000 ft

<table>
<thead>
<tr>
<th>Shear (Kt/100 n mi)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
<th>Shear (Kt/100 n mi)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>849</td>
<td>27</td>
<td>3</td>
<td>7</td>
<td>1</td>
<td>&lt;10</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>10-19</td>
<td>357</td>
<td>9</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>≥10</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>20-29</td>
<td>119</td>
<td>13</td>
<td>11</td>
<td>5</td>
<td>4</td>
<td>≥20</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>30-39</td>
<td>37</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>≥30</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>40-49</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>≥40</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>50-59</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>≥50</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>≥60</td>
<td>18</td>
<td>2</td>
<td>11</td>
<td>1</td>
<td>6</td>
<td>≥60</td>
<td>11</td>
<td>6</td>
</tr>
</tbody>
</table>

(c) Flights at all levels

<table>
<thead>
<tr>
<th>Shear (Kt/100 n mi)</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
<th>Shear (Kt/100 n mi)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>1232</td>
<td>46</td>
<td>4</td>
<td>13</td>
<td>1</td>
<td>&lt;10</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>10-19</td>
<td>715</td>
<td>39</td>
<td>5</td>
<td>15</td>
<td>2</td>
<td>≥10</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>20-29</td>
<td>305</td>
<td>26</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>≥20</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>30-39</td>
<td>105</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>≥30</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>40-49</td>
<td>77</td>
<td>6</td>
<td>8</td>
<td>5</td>
<td>7</td>
<td>≥40</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>50-59</td>
<td>8</td>
<td>3</td>
<td>37</td>
<td>2</td>
<td>.25</td>
<td>≥50</td>
<td>28</td>
<td>15</td>
</tr>
<tr>
<td>≥60</td>
<td>39</td>
<td>10</td>
<td>26</td>
<td>5</td>
<td>13</td>
<td>≥60</td>
<td>26</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 6. Distribution of occurrences of CAT against combinations of "average" vertical wind shear and 300 mb horizontal wind shear

(a) Flights at and below 30,000 ft

<table>
<thead>
<tr>
<th>Vertical Shear (kt/1000 ft)</th>
<th>Total</th>
<th>&lt;10</th>
<th>10-19</th>
<th>20-29</th>
<th>30-39</th>
<th>40-49</th>
<th>50-59</th>
<th>60+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
</tr>
<tr>
<td>≥8</td>
<td>25</td>
<td>0 / 0</td>
<td>49</td>
<td>12 / 0</td>
<td>15</td>
<td>3 / 0</td>
<td>13</td>
<td>0 / 0</td>
</tr>
<tr>
<td>6-7</td>
<td>77</td>
<td>6 / 2</td>
<td>87</td>
<td>8 / 6</td>
<td>52</td>
<td>6 / 12</td>
<td>7</td>
<td>1 / 14</td>
</tr>
<tr>
<td>4-5</td>
<td>124</td>
<td>3 / 2</td>
<td>119</td>
<td>9 / 5</td>
<td>57</td>
<td>2 / 4</td>
<td>20</td>
<td>3 / 15</td>
</tr>
<tr>
<td>&lt;4</td>
<td>159</td>
<td>6 / 4</td>
<td>106</td>
<td>5 / 5</td>
<td>57</td>
<td>2 / 4</td>
<td>28</td>
<td>1 / 4</td>
</tr>
</tbody>
</table>

(b) Flights above 30,000 ft

<table>
<thead>
<tr>
<th>Vertical Shear (kt/1000 ft)</th>
<th>Total</th>
<th>&lt;10</th>
<th>10-19</th>
<th>20-29</th>
<th>30-39</th>
<th>40-49</th>
<th>50-59</th>
<th>60+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
</tr>
<tr>
<td>≥8</td>
<td>28</td>
<td>4 / 2</td>
<td>22</td>
<td>3 / 14</td>
<td>7</td>
<td>0 / 0</td>
<td>6</td>
<td>0 / 0</td>
</tr>
<tr>
<td>6-7</td>
<td>61</td>
<td>2 / 0</td>
<td>62</td>
<td>2 / 30</td>
<td>41</td>
<td>7 / 17</td>
<td>2</td>
<td>0 / 0</td>
</tr>
<tr>
<td>4-5</td>
<td>128</td>
<td>2 / 1</td>
<td>119</td>
<td>2 / 21</td>
<td>55</td>
<td>4 / 7</td>
<td>21</td>
<td>0 / 0</td>
</tr>
<tr>
<td>&lt;4</td>
<td>642</td>
<td>21 / 4</td>
<td>143</td>
<td>0 / 0</td>
<td>16</td>
<td>2 / 15</td>
<td>8</td>
<td>0 / 0</td>
</tr>
</tbody>
</table>

(c) Flights at all levels

<table>
<thead>
<tr>
<th>Vertical Shear (kt/1000 ft)</th>
<th>Total</th>
<th>&lt;10</th>
<th>10-19</th>
<th>20-29</th>
<th>30-39</th>
<th>40-49</th>
<th>50-59</th>
<th>60+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
<td>Any %</td>
<td>M / S</td>
</tr>
<tr>
<td>≥8</td>
<td>53</td>
<td>4 / 2</td>
<td>71</td>
<td>15 / 21</td>
<td>22</td>
<td>3 / 14</td>
<td>19</td>
<td>0 / 0</td>
</tr>
<tr>
<td>6-7</td>
<td>138</td>
<td>8 / 2</td>
<td>149</td>
<td>10 / 75</td>
<td>93</td>
<td>13 / 14</td>
<td>9</td>
<td>1 / 111</td>
</tr>
<tr>
<td>4-5</td>
<td>252</td>
<td>5 / 2</td>
<td>238</td>
<td>11 / 56</td>
<td>112</td>
<td>6 / 13</td>
<td>41</td>
<td>3 / 7</td>
</tr>
<tr>
<td>&lt;4</td>
<td>801</td>
<td>27 / 4</td>
<td>249</td>
<td>5 / 2</td>
<td>73</td>
<td>4 / 6</td>
<td>36</td>
<td>1 / 3</td>
</tr>
</tbody>
</table>

M / S = Moderate or Severe.
Table 7. CAT occurrence against combinations of vertical wind shear and 300 mb horizontal wind shear. Numbers of expected chance occurrences are in brackets.

(a) At and below 30,000 ft

<table>
<thead>
<tr>
<th>Vertical shear (kt/1000 ft)</th>
<th>Horizontal shear &lt;30 kt/100 n mi</th>
<th>Horizontal shear ≥30 kt/100 n mi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No CAT</td>
<td>Light CAT</td>
</tr>
<tr>
<td>≥6</td>
<td>270</td>
<td>19</td>
</tr>
<tr>
<td>(309)</td>
<td>(13.9)</td>
<td>(8.2)</td>
</tr>
<tr>
<td>&lt;6</td>
<td>595</td>
<td>20</td>
</tr>
<tr>
<td>(556)</td>
<td>(25.1)</td>
<td>(14.8)</td>
</tr>
</tbody>
</table>

(b) Above 30,000 ft

<table>
<thead>
<tr>
<th>Vertical shear (kt/1000 ft)</th>
<th>Horizontal shear &lt;20 kt/100 n mi</th>
<th>Horizontal shear ≥20 kt/100 n mi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No CAT</td>
<td>Light CAT</td>
</tr>
<tr>
<td>≥6</td>
<td>203</td>
<td>10</td>
</tr>
<tr>
<td>(235)</td>
<td>(6.4)</td>
<td>(2.6)</td>
</tr>
<tr>
<td>&lt;6</td>
<td>1072</td>
<td>25</td>
</tr>
<tr>
<td>(1040)</td>
<td>(28.6)</td>
<td>(11.4)</td>
</tr>
</tbody>
</table>

(c) All levels

<table>
<thead>
<tr>
<th>Vertical shear (kt/1000 ft)</th>
<th>Horizontal shear &lt;4 kt/100 n mi</th>
<th>Horizontal shear ≥4 kt/100 n mi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No CAT</td>
<td>Light CAT</td>
</tr>
<tr>
<td>≥6</td>
<td>473</td>
<td>29</td>
</tr>
<tr>
<td>(555)</td>
<td>(19.2)</td>
<td>(9.6)</td>
</tr>
<tr>
<td>&lt;6</td>
<td>1667</td>
<td>45</td>
</tr>
<tr>
<td>(1585)</td>
<td>(54.8)</td>
<td>(27.4)</td>
</tr>
</tbody>
</table>
The results in Table 5 show no regular increase in the percentage of CAT with increasing horizontal wind shear but when the shear classes were grouped the percentages showed a regular increase. For flights below 30,000 ft, CAT was encountered on 37 and 38 per cent of cases with shears of 50-59 knots and 60 knots or more per 100 miles respectively.

(d) Analysis of CAT against Combined Vertical and Horizontal Wind Shears

The number of occurrences of CAT against combinations of "average" vertical wind shear and 300 mb horizontal wind shear is shown in Table 6. The same class intervals as in the earlier tables are used for wind shears, those above specified limits being omitted.

George (1961) used a combination of vertical with horizontal wind shear to predict CAT. A similar method has been tested in Table 7. "Average" vertical wind shear was combined with horizontal wind shear at 300 mb. The statistics in Table 6 are summarised in Table 7 for combinations of horizontal and vertical wind shear. Table 7 also compares the number of occurrences of the various classes of CAT with those obtained by chance. Particularly in the moderate to severe CAT category and in the left hand tables, the ratio of CAT occurrence to non-occurrence is greater than chance for the highest combined shear classes and less than chance for the lowest combined shear classes.

(e) Analysis of CAT against Jet Streams

The flight squares were checked for the presence of a jet stream at 200 mb. CAT occurrences were tabulated for squares along and for one square on each side of the jet axis. One square to the left (or right) refers to squares whose centres are not more than 2½ degrees of latitude from the jet axis but not cut by the axis. The results are given in Table 8.

Table 8. Distribution of occurrence of CAT against presence of a jet stream at 200 mb.

<table>
<thead>
<tr>
<th></th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev.</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left of Jet</td>
<td>64</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Along Jet</td>
<td>181</td>
<td>18</td>
<td>10</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Right of Jet</td>
<td>175</td>
<td>21</td>
<td>12</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Total Jet Cases</td>
<td>420</td>
<td>41</td>
<td>10</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>Total Non-Jet Cases</td>
<td>658</td>
<td>43</td>
<td>7</td>
<td>14</td>
<td>2</td>
</tr>
</tbody>
</table>

(b) Above 30,000 ft

<table>
<thead>
<tr>
<th></th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev.</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left of Jet</td>
<td>107</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Along Jet</td>
<td>163</td>
<td>12</td>
<td>7</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Right of Jet</td>
<td>97</td>
<td>6</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Jet Cases</td>
<td>367</td>
<td>21</td>
<td>6</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Total Non-Jet Cases</td>
<td>1036</td>
<td>30</td>
<td>3</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

(c) All levels

<table>
<thead>
<tr>
<th></th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev.</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left of Jet</td>
<td>171</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Along Jet</td>
<td>344</td>
<td>30</td>
<td>9</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>Right of Jet</td>
<td>272</td>
<td>27</td>
<td>10</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>Total Jet Cases</td>
<td>797</td>
<td>62</td>
<td>8</td>
<td>27</td>
<td>3</td>
</tr>
<tr>
<td>Total Non-Jet Cases</td>
<td>1694</td>
<td>73</td>
<td>4</td>
<td>23</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 8 shows that a greater percentage of CAT occurs along or to the right (or cold side) than to the left of the jet. The highest percentage of CAT was 12 per cent to the right of the jet for flights at or below 30,000 ft. The charts from which these figures were compiled show many segments of the jet axis with no turbulence, so the use of this parameter is limited. However, the percentage occurrence of CAT within one square of the jet axis was about twice as high as for other squares.

The combination of averaged vertical wind shear with presence of a jet stream (Table 9) gave little further discrimination over the analysis obtained from consideration of jet cases alone (Table 8).

Table 9. Distribution of occurrence of CAT against presence of a jet stream and "average" vertical wind shear (in kt/1000 ft)

<table>
<thead>
<tr>
<th></th>
<th>Jet with Shear</th>
<th>No. of Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT</th>
<th>No. of Mod. or Sev. Occ.</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>At and Below 30,000 ft</td>
<td>&lt;4</td>
<td>15</td>
<td>1</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>≥4</td>
<td>405</td>
<td>39</td>
<td>10</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>Above 30,000 ft</td>
<td>&lt;4</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>≥4</td>
<td>354</td>
<td>21</td>
<td>6</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>All levels</td>
<td>&lt;4</td>
<td>28</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>≥4</td>
<td>759</td>
<td>60</td>
<td>8</td>
<td>27</td>
<td>4</td>
</tr>
</tbody>
</table>

(f) Analysis of CAT against Maximum Wind Speed in the Vertical

Table 10 gives the distribution of CAT occurrence with the maximum wind speed in the vertical obtained for flight squares from maximum wind analyses. No discrimination is evident.

Table 10. Distribution of occurrence of CAT against maximum wind speed in the vertical (a) At and below 30,000 ft

<table>
<thead>
<tr>
<th>Max. Wind Speed (Knots)</th>
<th>Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT occurrences</th>
<th>No. Mod. or Sev. Occurrences</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25-49</td>
<td>105</td>
<td>8</td>
<td>8</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>50-74</td>
<td>308</td>
<td>18</td>
<td>6</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>75-99</td>
<td>330</td>
<td>28</td>
<td>9</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>100-124</td>
<td>255</td>
<td>27</td>
<td>11</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>125-149</td>
<td>77</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>≥150</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max. Wind Speed (Knots)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>5-75</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>8-100</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>≥100</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>≥125</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>
### Table 10. (Continued)

<table>
<thead>
<tr>
<th>Max Wind Speed (Knots)</th>
<th>Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT occurrences</th>
<th>No. Mod. or Sev. occurrences</th>
<th>% Mod. or Sev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>160</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>25-49</td>
<td>363</td>
<td>13</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>50-74</td>
<td>345</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>75-99</td>
<td>193</td>
<td>14</td>
<td>7</td>
<td>.7</td>
<td>4</td>
</tr>
<tr>
<td>100-124</td>
<td>262</td>
<td>9</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>125-149</td>
<td>67</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>≥150</td>
<td>13</td>
<td>1</td>
<td>8</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max Wind Speed (Knots)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥50</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>≥75</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>≥100</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>≥125</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

### (c) All levels

<table>
<thead>
<tr>
<th>Max Wind Speed (Knots)</th>
<th>Flight Squares</th>
<th>No. of CAT occurrences</th>
<th>% CAT occurrences</th>
<th>No. Mod. or Sev. occurrences</th>
<th>% Mod. or Sev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>160</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>25-49</td>
<td>468</td>
<td>21</td>
<td>5</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>50-74</td>
<td>653</td>
<td>24</td>
<td>4</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>75-99</td>
<td>523</td>
<td>42</td>
<td>8</td>
<td>21</td>
<td>4</td>
</tr>
<tr>
<td>100-124</td>
<td>517</td>
<td>36</td>
<td>7</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>125-149</td>
<td>144</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>≥150</td>
<td>16</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max Wind Speed (Knots)</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>≥50</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>≥75</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>≥100</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>≥125</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

### (g) Analysis of CAT against Tropopause Height and Temperature

The height and temperature of the tropopause was obtained from the 2300 GMT radiosonde reports and interpolated for other flight squares. Changes in tropopause height and temperature were taken over a 24-hour period centred on 2300 GMT. Changes in the tropopause were classified by,

(i) Changes in height: the tropopause was classified appropriately as higher or lower if the change in the 24-hour period was 50 mb or more; smaller changes were classified as "no change".

(ii) Changes in temperature: the tropopause was classified appropriately as colder or warmer if its temperature changed by 5°C or more; smaller changes were classified as "no change".

The analysis of occurrences of CAT against changes in height and temperature of tropopause is given in Table 11. For both flight levels the highest percentage of CAT occurred when the tropopause height rose in the 24 hours without change in temperature, but these larger percentages are based on fewer occurrences than most other classes.
Table 11. Distribution of occurrence of CAT against 24-hour changes in height and temperature of tropopause. All figures are percentages.

<table>
<thead>
<tr>
<th>Flight Levels</th>
<th>Tropopause</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Higher &amp; warmer</td>
<td>Higher &amp; colder</td>
</tr>
<tr>
<td></td>
<td>Any CAT</td>
<td>Mod. or Sev.</td>
</tr>
<tr>
<td>At or below 30,000 ft</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Above 30,000 ft</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>All levels</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 12 considers separately changes in height and changes in temperature of the tropopause. Again the highest percentage of CAT occurs with a higher tropopause, but the temperature study indicates nothing of significance.

Table 12. Distribution of occurrence of CAT against 24-hour changes in height and temperature of tropopause considered separately. All figures are percentages.

<table>
<thead>
<tr>
<th>Flight Levels</th>
<th>Tropopause Height</th>
<th></th>
<th>Tropopause Temperature</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Higher</td>
<td>No change</td>
<td>Lower</td>
<td>Warmer</td>
</tr>
<tr>
<td></td>
<td>Any CAT</td>
<td>Mod. or Sev.</td>
<td>Any CAT</td>
<td>Mod. or Sev.</td>
</tr>
<tr>
<td>At or below 30,000 ft</td>
<td>13</td>
<td>8</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Above 30,000 ft</td>
<td>11</td>
<td>6</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>All levels</td>
<td>12</td>
<td>7</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

The heights of the tropopause were read and tabulated for each square. Heights were divided into five ranges. The comparison of tropopause height with CAT occurrence (Table 13) shows that for flights at and below 30,000 ft the highest percentage of all CAT (21 per cent) occurs with the tropopause between 25,000 and 29,999 ft, but nothing of significance emerges for cases of moderate or severe CAT for such flights or for CAT in any category for flights above 30,000 ft.

Table 13. Distribution of occurrence of CAT against height of tropopause. All figures are percentages.

<table>
<thead>
<tr>
<th>Flight Levels</th>
<th>Tropopause Height</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Below 25,000 ft</td>
<td>25,000 - 29,999 ft</td>
</tr>
<tr>
<td></td>
<td>Any CAT</td>
<td>Mod. or Sev.</td>
</tr>
<tr>
<td>At or below 30,000 ft</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Above 30,000 ft</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>All levels</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
(h) Analysis of CAT against Richardson’s Number

Difficulties arise in determining the exact value of Richardson’s number at the location, level and time of reported CAT because of the widely spaced network of radiosonde stations and the 24-hour time interval between radiosonde flights.

CAT occurrences were grouped in 24 hours periods centred on 2300 GMT, the time of radiosonde flights. Approximations to Richardson number were computed for the layers 500-400mb, 400-300mb, 300-250mb and 250-200mb using the formula,

\[
Ri \approx \frac{g \Delta \theta / \Delta z}{\theta_M (\Delta u / \Delta z)^2}
\]

where \( \Delta \theta \) = difference of the potential temperatures at the extremes of the layer (°K),

\( g \) = acceleration due to gravity (ft/sec^2), (taken as 32.2 ft/sec^2),

\( \Delta z \) = thickness of the layer (gp ft),

\( \Delta u \) = magnitude of vertical wind shear in the layer (ft/sec),

\( \theta_M \) = mean potential temperature of layer (°K).

The Richardson numbers thus found were plotted at the stations and values in intermediate 2½ degree "squares" interpolated. Isolines with Ri values of 1 and 4 were drawn on each chart. The Richardson numbers for the layers 500-400mb and 400-300mb were classified as follows:

1. Both values below 1.
2. Only one value below 1.
3. Both values between 1 and 4.
4. One value between 1 and 4.
5. Both values above 4.

The same was done for the layers 300-250mb and 250-200mb. Analysis was then carried out of the occurrence or non-occurrence of CAT with Ri classified as above. This is given in Table 14 which shows that the combination of Richardson numbers for the 500-400mb and 400-300mb give a better indication of CAT than the combination for the higher layers (300-250mb and 250-200mb). However, the results are not encouraging from the forecasting aspect.

Richardson numbers were also combined for the layers 400-300mb and 300-250mb, but the results of this analysis (not presented here) were poor.

Table 14. Distribution of occurrences of CAT against Richardson Number. See text for classification of Ri numbers

(a) Flights at and below 30,000 ft

<table>
<thead>
<tr>
<th>Ri Numbers Classification</th>
<th>No. of Flight Squares</th>
<th>CAT occurrences</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
<th>% Mod.or Sev. CAT</th>
<th>No. of Flight Squares</th>
<th>CAT occurrences</th>
<th>% CAT</th>
<th>% Mod. or Sev. CAT</th>
<th>% Mod.or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>67</td>
<td>7</td>
<td>10</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>133</td>
<td>18</td>
<td>14</td>
<td>10</td>
<td>8</td>
<td>56</td>
<td>5</td>
<td>9</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>145</td>
<td>21</td>
<td>15</td>
<td>7</td>
<td>5</td>
<td>203</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>217</td>
<td>14</td>
<td>7</td>
<td>8</td>
<td>4</td>
<td>224</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>563</td>
<td>31</td>
<td>6</td>
<td>10</td>
<td>2</td>
<td>518</td>
<td>56</td>
<td>11</td>
<td>27</td>
<td>5</td>
</tr>
</tbody>
</table>
(b) Flights above 30,000 ft

<table>
<thead>
<tr>
<th>Ri Numbers Classification</th>
<th>No. of Flight Squares</th>
<th>500-400, 400-300 mb levels</th>
<th>300-250, 250-200 mb levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CAT</td>
<td>% CAT</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>74</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>156</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>239</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>848</td>
<td>24</td>
<td>3</td>
</tr>
</tbody>
</table>

(i) Frequency of, and Effect of Flight Direction on, CAT Intensity

A summary of flights in relation to CAT intensity is given in Table 15. 29 per cent of flights encountered some degree of CAT and 12 per cent encountered moderate or severe CAT.

Table 15. Distribution of flights in relation to CAT intensity

<table>
<thead>
<tr>
<th>CAT Intensity</th>
<th>Number of Flights</th>
<th>% of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>No CAT</td>
<td>188</td>
<td>71</td>
</tr>
<tr>
<td>Light CAT</td>
<td>44</td>
<td>17</td>
</tr>
<tr>
<td>Moderate CAT</td>
<td>27</td>
<td>10</td>
</tr>
<tr>
<td>Severe CAT</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>All Intensities</td>
<td>77</td>
<td>29</td>
</tr>
<tr>
<td>Moderate or Severe CAT</td>
<td>33</td>
<td>12</td>
</tr>
</tbody>
</table>

Reports of occurrences of different intensities of CAT for each predominant flight direction are given in Table 16; no preferred flight direction for CAT occurrence is evident.

Table 16. Distribution of CAT intensity against flight direction

<table>
<thead>
<tr>
<th>Flight Direction</th>
<th>Total Flights</th>
<th>CAT of All Intensities</th>
<th>Moderate or Severe CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Occ.</td>
<td>%</td>
<td>No. of Occ.</td>
</tr>
<tr>
<td>East</td>
<td>66</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>West</td>
<td>62</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>North</td>
<td>43</td>
<td>18</td>
<td>42</td>
</tr>
<tr>
<td>South</td>
<td>47</td>
<td>21</td>
<td>45</td>
</tr>
<tr>
<td>Combined East-West</td>
<td>128</td>
<td>55</td>
<td>43</td>
</tr>
<tr>
<td>Combined North-South</td>
<td>90</td>
<td>39</td>
<td>43</td>
</tr>
</tbody>
</table>

(ii) Analysis of Occurrence of CAT against Temperature Change and Clouds

Only seven report forms contained information on air temperature and CAT occurrence. One flight reported a 5°C fall in temperature initially with moderate wave-like CAT. Another flight reported a 3°C fall in temperature with moderate CAT. Three small rises in temperature were encountered with light CAT.

Overall, there were three falls in air temperature, three rises and one occurrence with no change in temperature. The data is too scanty to draw any useful conclusions.
In cases where turbulence was reported, pilots were asked to note whether they were flying in cloud, in and out of cloud, or in the clear; also if towering cumulus, thunderstorms or cirrus were present. A few report forms contained additional cloud information.

Table 17 shows that higher percentages of CAT of any type occurred in clear air than with the presence of middle or high cloud. As sky conditions were not reported for the "nil turbulence" cases, no analysis of occurrence and non-occurrence of CAT against sky condition was possible.

<table>
<thead>
<tr>
<th></th>
<th>In Clear</th>
<th>In or adjacent to Cirrus</th>
<th>In or adjacent to Middle Cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Occ.</td>
<td>% CAT</td>
<td>No. of Occ.</td>
</tr>
<tr>
<td>Any CAT</td>
<td>85</td>
<td>74</td>
<td>23</td>
</tr>
<tr>
<td>Mod. or Sev. CAT</td>
<td>28</td>
<td>78</td>
<td>5</td>
</tr>
</tbody>
</table>

(k) Analysis of Occurrence of CAT against Fluctuations in Air Speed at the Onset of Turbulence

Pilots were asked to indicate fluctuations in the indicated airspeed (knots) at the onset of turbulence. In the analysis of this data, turbulence in both clear air and cloud have been included. Of the 141 turbulence reports 22 did not specifically state whether or not there were fluctuations in the indicated airspeed at the onset of turbulence. These 22 cases have not been included in the analysis. Table 18 shows the distribution of severity of turbulence with fluctuations in the indicated airspeed. The mean airspeed fluctuation for each turbulence classification increases steadily with the severity of the turbulence.

<table>
<thead>
<tr>
<th>Airspeed Fluctuation at onset of turbulence (kt)</th>
<th>Number of cases of light turbulence</th>
<th>Number of cases of moderate turbulence</th>
<th>Number of cases of severe turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>22</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1-5</td>
<td>40</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>6-10</td>
<td>6</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>11-15</td>
<td>0</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>16-20</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>&gt;20</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>68</td>
<td>46</td>
<td>5</td>
</tr>
</tbody>
</table>

| Mean airspeed fluctuation (kt) | 2.5 | 7.5 | 11.0 |

One report gave an airspeed fluctuation of 30 knots with only moderate CAT. Another gave a fluctuation of 28 knots with moderate turbulence in a towering cumulus.

(l) Analysis of CAT against Wind Speed and Duration of CAT

The average windspeed at the onset of CAT and also the average duration of the three classes of CAT are shown in Table 19. The extremes of these distributions are shown in brackets. The table indicates a steady increase in wind speed at the onset of CAT with its increasing severity and a decrease in duration of CAT with increasing severity.
Table 19. Distribution of CAT intensity against average wind speed at onset of CAT and duration of CAT. Extreme values are shown in brackets.

<table>
<thead>
<tr>
<th>CAT Intensity</th>
<th>Average Wind Speed at onset of CAT (kt)</th>
<th>Average Duration of CAT (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>46 (2-90)</td>
<td>18 (1-100)</td>
</tr>
<tr>
<td>Moderate</td>
<td>52 (20-100)</td>
<td>10 (1-30)</td>
</tr>
<tr>
<td>Severe</td>
<td>58 (35-70)</td>
<td>5 (1-10)</td>
</tr>
</tbody>
</table>

4. ANALYSIS OF CAT AGAINST SIX PARAMETERS FOR A RESTRICTED AREA

In compiling the following tables the area under study was restricted to that bounded by latitudes 22.50S and 40°S and longitudes 112.5°E and 160°E. Distribution of CAT occurrence are analysed for six parameters, viz. Endlich turbulence index, "geostrophic" vorticity, "geostrophic" vorticity advection, "average" vertical wind shear, Richardson's number and Colson-Panofsky turbulence index. These parameters were calculated from the data at 2300 GMT on each day and correlated with turbulence occurrences for the 24-hour period centred on this hour.

(a) Endlich Turbulence Index \[ \nu \Delta \alpha / \Delta z \] (Endlich, 1964)

where \( \nu \) is the mean wind speed,
\( \Delta \alpha \) is the change in wind direction through the layer,
\( \Delta z \) is the depth of layer

\( \nu \Delta \alpha / \Delta z \) was computed for the layers 500-400, 400-300, 300-250 and 250-200 mb. Table 20 gives CAT occurrences at and below 30,000 ft against the largest value in the layers 500-400, 400-300 mb, while CAT occurrences above 30,000 ft are tabulated against largest value in the layers 300-250, 250-200 mb.

Table 20. Distribution of CAT occurrence against Endlich turbulence index \( \nu \Delta \alpha / \Delta z \)

<table>
<thead>
<tr>
<th>( \nu \Delta \alpha / \Delta z ) (deg sec(^{-1}))</th>
<th>Flights at and below 30,000 ft</th>
<th>Flights above 30,000 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &lt;4 )</td>
<td>No. of Flight Squares</td>
<td>CAT occurrences</td>
</tr>
<tr>
<td>( \geq 4 ) and &lt;6</td>
<td>558</td>
<td>41</td>
</tr>
<tr>
<td>( \geq 6 ) and &lt;8</td>
<td>78</td>
<td>6</td>
</tr>
<tr>
<td>( \geq 8 )</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

(b) "Geostrophic" Vorticity

In Table 21 CAT occurrences are tabulated against "geostrophic" vorticity at 300 mb.
Table 21. Distribution of CAT occurrence against 300 mb vorticity

<table>
<thead>
<tr>
<th>Vorticity x 10^7 (sec^-1)</th>
<th>Flight Squares</th>
<th>CAT occurrences</th>
<th>% CAT</th>
<th>Mod. or Sev. CAT occurrences</th>
<th>% Mod or Sev. CAT</th>
<th>Flight Squares</th>
<th>CAT occurrences</th>
<th>% CAT</th>
<th>Mod. or Sev. CAT occurrences</th>
<th>% Mod or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤-600</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-599 to -400</td>
<td>6</td>
<td>1</td>
<td>17</td>
<td>1</td>
<td>17</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-399 to -200</td>
<td>33</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>75</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-199 to 0</td>
<td>133</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>122</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1 to 200</td>
<td>128</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>129</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>201 to 400</td>
<td>170</td>
<td>9</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>97</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>401 to 600</td>
<td>117</td>
<td>15</td>
<td>13</td>
<td>8</td>
<td>7</td>
<td>57</td>
<td>11</td>
<td>6</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>&gt;600</td>
<td>57</td>
<td>6</td>
<td>11</td>
<td>3</td>
<td>5</td>
<td>64</td>
<td>4</td>
<td>6</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

(c) "Geostrophic" Vorticity Advection

In Table 22 CAT occurrences are tabulated against 300 mb "geostrophic" vorticity advection.

Table 22. Distribution of CAT occurrence against 300 mb vorticity advection

<table>
<thead>
<tr>
<th>Vorticity Advection x 10^11 (sec^-2)</th>
<th>Flight Squares</th>
<th>CAT occurrences</th>
<th>% CAT</th>
<th>Mod. or Sev. CAT occurrences</th>
<th>% Mod or Sev. CAT</th>
<th>Flight Squares</th>
<th>CAT occurrences</th>
<th>% CAT</th>
<th>Mod. or Sev. CAT occurrences</th>
<th>% Mod or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤-150</td>
<td>58</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>62</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>-149 to -100</td>
<td>73</td>
<td>6</td>
<td>8</td>
<td>5</td>
<td>7</td>
<td>35</td>
<td>4</td>
<td>11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-99 to -50</td>
<td>100</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>58</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-49 to 0</td>
<td>91</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>76</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1 to 50</td>
<td>98</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>91</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>51 to 100</td>
<td>109</td>
<td>11</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>89</td>
<td>8</td>
<td>9</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>101 to 150</td>
<td>67</td>
<td>9</td>
<td>13</td>
<td>4</td>
<td>6</td>
<td>56</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&gt; 150</td>
<td>48</td>
<td>15</td>
<td>31</td>
<td>8</td>
<td>17</td>
<td>91</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

(d) "Average" Vertical Wind Shear

CAT occurrences in both layers are given against "average" vertical wind shear in Table 23.

Table 23. Distribution of CAT occurrence against "average" vertical wind shear

<table>
<thead>
<tr>
<th>&quot;Average&quot; Vertical Wind Shear (kt/1000 ft)</th>
<th>Flight Squares</th>
<th>CAT occurrences</th>
<th>% CAT</th>
<th>Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
<th>Flight Squares</th>
<th>CAT occurrences</th>
<th>% CAT</th>
<th>Mod. or Sev. CAT occurrences</th>
<th>% Mod. or Sev. CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>202</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>127</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&gt;4 and &lt;6</td>
<td>242</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>223</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>≥6 and &lt;8</td>
<td>118</td>
<td>19</td>
<td>16</td>
<td>11</td>
<td>9</td>
<td>128</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>≥8</td>
<td>82</td>
<td>15</td>
<td>18</td>
<td>10</td>
<td>12</td>
<td>80</td>
<td>11</td>
<td>14</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>
(e) Richardson's Number

CAT occurrences at and below 30,000 ft are classed in Table 24 against the Richardson Number (Ri) classifications (see Section 3(h)) for the layers 500-400 and 400-300 mb, and occurrences above 30,000 ft against the classifications for the layers 300-250, and 250-200 mb.

Table 24. CAT occurrence against Richardson's number classification

<table>
<thead>
<tr>
<th>Ri, Number Classification</th>
<th>Flights at and below 30,000 ft.</th>
<th>Flights above 30,000 ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flight Squares</td>
<td>CAT occurrences</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>151</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>368</td>
<td>14</td>
</tr>
</tbody>
</table>

(f) Colson-Panofsky Turbulence Index

This Turbulence Index, $I, = (\Delta \mathbf{v})^2 (1 - \text{Ri}/0.75)$, where $\Delta \mathbf{v}$ is the vector wind shear over the layer, and 0.75 is the critical Richardson number (Colson and Panofsky (1965)).

CAT occurrences for flights at and below 30,000 ft are classed in Table 25, against the largest of the $I$ values calculated for the layers 500-400 and 400-300 mb, and those above 30,000 ft against the largest $I$ values in the layers 300-250 and 250-200 mb.

Table 25. CAT occurrence against Turbulence Index, $I$.

<table>
<thead>
<tr>
<th>$I$ (Kt/1000 ft)</th>
<th>Flights at and below 30,000 ft.</th>
<th>Flights above 30,000 ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flight Squares</td>
<td>CAT occurrences</td>
</tr>
<tr>
<td>$&lt;$ 25</td>
<td>466</td>
<td>20</td>
</tr>
<tr>
<td>$\geq$ 25 and $&lt;$ 0</td>
<td>155</td>
<td>25</td>
</tr>
<tr>
<td>$\geq$ 0 and $&lt;$ 25</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td>$\geq$ 25 and $&lt;$ 50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\geq$ 50</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Most parameters gave the best results for flights at or below 30,000 ft. Average vertical wind shear and Richardson's number were the most promising parameters. With both vorticity and vorticity advection most CAT occurred when the parameter was positive.

5. CONCLUSIONS

The importance of using probability in forecasting CAT is demonstrated by this study. With most parameters the maximum percentage of CAT occurrences, when these parameters had values which indicated the presence of CAT, was about 15 per cent.
In the general study covering all flight squares, the highest percentage of CAT was 38 per cent with a horizontal wind shear of 50 knots per 100 nautical miles or greater, for flights at and below 30,000 ft. Most of the parameters were more successful in the layer at and below 30,000 ft, where the majority of the CAT occurred, than in the layer above 30,000 ft.

Of the relationships between the frequency of CAT and meteorological parameters, that for the "averaged" vertical wind shear was the most regular. Although there was a fairly general increase in CAT frequency with decreasing Richardson number classification for the layers 500 to 400 mb and 400 to 300 mb, the results were not encouraging from a forecasting point of view. This is probably due to the inaccuracies arising from the method of interpolating values for flight squares from the rather sparse upper air network (a difficulty associated with most other parameters). In the analysis connected with tropopause data, the only significant feature was the higher frequency of CAT for flights at or below 30,000 ft with tropopause heights in the layer 25,000 - 29,999 ft.

A major trough at 300 mb on 9 December was associated with a large number of CAT reports.

The mean airspeed fluctuations at the onset of turbulence showed a steady increase with increasing severity of the turbulence, but the use of this as an indication of the severity of turbulence is limited because of the large range of fluctuations at each turbulence intensity.

In the study covering a restricted area, the best results were obtained with "average" vertical wind shear and Richardson's number. The Richardson number results are better than those in the general study covering all flight squares, because the restricted area of analysis is better served with upper air observations than the area of the general study. No comparison can be made between the "average" vertical wind shear results of the two studies because the data were grouped in different time intervals, 12 hours for the general study and 24 hours for the restricted study. With both vorticity and vorticity advection most CAT occurred when the parameter was positive. The Endlich and Colson-Panofsky turbulence indices gave poor results.

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REFERENCES


