Clear air turbulence over South Africa

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Clear air turbulence (CAT) at high altitude remains a hazard to aviation which can result in passenger injury and aircraft damage. Two limited surveys of CAT events over South Africa, 1993-1995 (inclusive) and 1998, are used to illustrate the most likely synoptic conditions under which CAT can be expected. A case study of CAT associated with an upper-air trough and a mountain wave is presented. The study also evaluates the effectiveness of the Ellrod Turbulence Index (ETI) derived from model data provided by the UK Met. Office. A forecast of ETI derived from the Global Spectral Model of the United States National Center for Environmental Prediction (NCEP) is also reviewed.

1. Introduction

High altitude clear air turbulence (CAT) has been the cause of numerous incidents in which commercial aircraft passengers have been injured and deaths have sometimes occurred. On rare occasions aircraft suffer structural damage and temporary loss of pilot control. Other effects of CAT are increased fuel consumption and late arrival due to reduced airspeed (Ellrod, 1992). CAT is turbulence encountered by aircraft when flying through air space devoid of clouds and is caused by marked changes in wind speed and/or direction, either vertically or horizontally (American Meteorological Society, 1989; Met. Office, 1991).

According to the US Department of Commerce (1966) and Met. Office (1994), CAT is divided into three categories: light, moderate and severe.

- During light turbulence passengers may be required to use seat belts, but loose objects within the aircraft remain at rest.
- Moderate turbulence results in passengers being required to wear seat belts and occasionally being thrown against the seat belt. Loose objects in the aircraft move about. Frequent rolling occurs and there is difficulty in walking about in the aircraft.
- Occurrences of severe turbulence may cause the aircraft to be momentarily out of control and it is difficult to maintain flight altitude. Passengers are thrown violently against the seat belt and back into the seat and loose objects are tossed about. Under extremely severe turbulent conditions, which fortunately rarely occurs, the aircraft is violently tossed about and is almost impossible to control. Structural damage is also likely.

In April 1993 a flight from Shanghai to Los Angeles encountered severe CAT over the northern Pacific Ocean at 33,000 ft. Of the 265 passengers on board, 169 were injured, several were severely injured and one passenger died. The aircraft suffered no external damage but the interior was badly torn up. In November of the same year another aircraft, flying a similar route, encountered severe turbulence which damaged its elevators. In South Africa, during January 1994, two stewardesses were injured when a flight between Durban and Cape Town flew into CAT.

According to Godson (1970) for every crash or incident of severe structural damage and injury caused by CAT, 'it is believed that there have been at least a hundred near encounters'. In addition, Stack (1991) states that there were 96 CAT events from 1985 to 1991, which 'included passenger death, major and minor injuries and aircraft damage'. He also adds that nearly half of the injuries occurred to flight attendants.

Given the potential for serious harm, it seemed surprising that no research into the occurrence of CAT over South Africa had been undertaken, especially considering the marked increase in commercial air traffic over the country in recent years. The number of airlines operating into South Africa, for example, has risen from approximately 20 in 1993 and to 80 in 1997. With this in mind it was considered essential to know more about CAT over South Africa so that it could be predicted more accurately.

To this end, a survey was made of all pilot reports of CAT between 1993 and 1995, and later, during 1998, a further more detailed survey was conducted during the winter months of May to September inclusive, to determine the conditions under which CAT is most likely to occur over South Africa. A summary of the results of the earlier survey is presented in this paper along with a more detailed analysis of the 1998 survey.

A forecast CAT index was introduced by the South African Weather Bureau (SAWB) to assist the aviation forecaster in forecasting CAT over the country. This took the form of the dimensionless Ellrod Turbulence

Index (ETI) which is derived from the Global Spectral Model (GSM) of the United States National Center for Environmental Prediction (NCEP). An example of a weather system that produced high altitude CAT associated with an upper-air trough over central South Africa and mountain wave turbulence is presented. The role played by the Ellrod Turbulence Index (Ellrod & Knapp, 1992) in predicting the turbulence, derived from numerical weather prediction models, is also given.

Without going into detail, the ETI was selected because two independent evaluations found it to be the most suitable (McCann, 1993; Smith *et al.*, 1995). It was already in use by NCEP, and trial use over South Africa produced favourable results.

A drawback of all indices is that they cannot successfully predict all cases of CAT and its severity. However, they often alert forecasters to areas that normally would not be considered high threat regions. Ellrod & Knapp (1992) also state that there is a tendency for the ETI to predict CAT through too deep a layer.

Note that places mentioned in the text are given in Figure 1.

2. The 1993–1995 survey

The meteorological conditions at the time of all available reports of CAT over South Africa, from 1993 to 1995 inclusive, were studied in order to determine local characteristics (de Villiers, 1997). This was by no means a comprehensive survey and consisted of 15 events. Only those that came to the attention of the author were researched and there were doubtless other CAT events that went unreported or unrecorded. For example, a mountain wave event on 10 January 1994 was discovered by chance when it was reported in a Cape Town newspaper. Nevertheless, the samples helped to give an idea of the local conditions suitable for CAT.

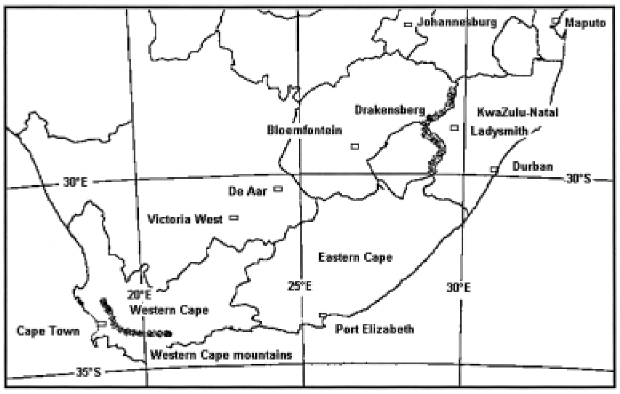

Figure 1. *Map of South Africa showing the places mentioned in the text.*

A jet stream was present in all of the 15 incidents when CAT was reported (Table 1), although in the mountain wave events the reports of CAT were at a level well below the jet stream. They were also sometimes well ahead of the jet stream and consequently on the warm or high pressure side. In the case of the one cut-off low, when a turbulence report was received, the jet was well to the north around the northern edge of the low. A trough was present most of the time, including in the two mountain wave instances (80%). Of these, 58% of the CAT observations (including the two mountain wave cases) were in the north-westerly flow east of the trough, 25% at the trough axis and 17% in the post-trough southerly flow. Two events were associated with an anticyclone, with one on the warm, or high pressure side of the jet and also at the same level as the jet. Including one mountain wave event, this meant that only 20% of the CAT incidents were in the warm sector. By far the most occurrences were below the jet on the cold and low pressure side (67%) and 13% directly below. Most of the reports were within 5,000 ft of the jet (53%) and 67% within 10,000 ft. These results were consistent with the findings of Briggs (1961).

With respect to vertical shear, most events were in the lower vertical wind shear range of 4 to 5 kn/1000 ft, while only one exceeded 8 kn/1000 ft. This is supported by the fact that no CAT reports in excess of moderate were received, although with shear greater than 8 kn/1000 ft it is surprising that there was not at least one report of severe CAT.

Horizontal velocity (speed and/or directional) shear was noted on nine occasions (60%), but it was difficult to classify due to the distances between observations, which are at least 3° latitude apart and often about 7°. Therefore the results are not to be trusted. In assessing the horizontal shear the overall synoptic pattern was considered. There were also instances where significant shear was evident, but not where the CAT was experienced. A significant horizontal shear yardstick of 100 kn/100 miles (Colson, 1963) was used and under these conditions shear was noted on four out of the nine occasions. If the UK Meteorological Office (UKMO) limits of 20 kn/° latitude for moderate CAT and 30 kn/° latitude for severe CAT (from Starr, 1996) had been used, the figures would no doubt have been higher.

Most of the 15 events were associated with moderate stability, i.e. a positive potential temperature change of 1.5–4.5 °K/1000 ft. Two were associated with high stability, one of which was 10 °K/1000 ft (de Villiers, 1997).

3. The 1998 survey

A more detailed survey was conducted during the winter months of 1998 from May to September, inclusive.

Table 1. *Analysis of the synoptic conditions at the time of 15 CAT events during the 1993–1995 survey.*

Characteristic	Number
CAT east of upper-air trough	5
CAT at trough axis	3
CAT in post-trough southerly flow	2
CAT due to an upper-air cut-off low	1
CAT due to mountain wave	2
CAT in an anticyclonic flow	2
CAT below the jet on the cold/low pressure side	10
CAT below the jet on the warm/high pressure side	3
CAT below the jet	2
CAT above the jet on the cold/low pressure side	0
CAT above the jet on the warm/high pressure side	0
Distance of CAT from jet <5 000 ft	8
Distance of CAT from jet 5 000–10 000 ft	2
Distance of CAT from jet >10 000 ft	5

Table 2. *Analysis of the synoptic conditions at the time of 34 CAT events during the 1998 survey.*

Characteristic	Number
CAT east of upper-air trough	9
CAT at trough axis	9
CAT in post-trough southerly flow	5
CAT due to an upper-air cut-off low	1
CAT due to mountain wave	10
CAT in an anticyclonic flow	3
CAT below the jet on the cold/low pressure side	21
CAT below the jet on the warm/high pressure side	10
CAT below the jet	7
CAT above the jet on the cold/low pressure side	1
CAT above the jet on the warm/high pressure side	0
Distance of CAT from jet <5 000 ft	15
Distance of CAT from jet 5 000–10 000 ft	11
Distance of CAT from jet >10 000 ft	12

Prior to beginning the survey of 1998, a special appeal was made to airline pilots, air traffic controllers and SAWB personnel to observe and pass on information to the author. This had a positive effect, because during the three-year period from 1993 to 1995 only 15 reports were received on 15 different days, whereas during the 1998 five-month long survey, reports totalling 49 were received on 34 days. On 28 May 1998 as many as six reports of CAT were received (de Villiers, 1997).

A high number of CAT reports occurred at a trough axis and downwind east of the axis. The high number of CAT reports at the trough axis suggests that directional shear is an important factor in producing CAT (Table 2). Unfortunately, the SAWB, because of financial constraints, has had to cut the number of upper-air soundings made at stations around the country, with some stations carrying out only one ascent a day. This made the computation of horizontal shear nearly impossible. Hence, the data on horizontal shear in Table 2 should be treated with caution.

CAT occurred on one occasion on 11 July 1998 (Table 2) in the throat of an upper-air cut-off low. Another incident occurred where a cut-off low was present to the west of the country over the Atlantic Ocean, but the CAT occurred in mountain wave activity in a north-westerly flow, well in advance of the low, over the Western Cape mountains in the south-western part of the country.

Consistent with the findings reported in Starr (1996) and the research of Ellrod (1993), Hopkins (1977) and Endlich (1964), by far the highest number of CAT reports were received below the core and to the south below the core on the cold side (Table 1). Nevertheless, a high number of CAT reports were in the warm air below the jet stream. Five of them were associated with mountain wave activity well ahead of an approaching trough. Three reports were in developing anticyclonic flow. That is, where the circulation was in the process of changing from a post trough southerly circulation to westerly and north-westerly.

As in the 1993–1995 survey, the distance of CAT from the jet stream core was mostly within 5,000 ft. However, inclusion of mountain wave events meant that the report was often much greater than 10,000 ft below the core (Table 2).

Most (six) of the lower flight level reports of turbulence came from the lee of the Drakensberg mountains (in the east), with three from the Eastern Cape mountains in the south and one in the vicinity of the Western Cape mountains. However, with respect to the last, there seems to be a connection between the passage of trough systems and the mountains in the area because numerous reports of CAT at high altitude were received in this area (nine reports). Shutts (1997), quoting Smith (1979), states that a steep lee slope relative to the windward side of a mountain range is also a criteria for strong lee waves. This may help to explain the high number of reports over KwaZulu-Natal in the lee of the Drakensberg.

Most of the CAT reports occurred with 4 to 8 kn/1000 ft vertical wind shear (Table 3). What is interesting is that although a 4 kn/1000 ft vertical wind shear is usually considered the cut-off point for moderate turbulence there were seven occasions when the shear was below this threshold and yet light to moderate CAT was reported (Table 4). All seven of the CAT reports were associated with light to moderate stability. Three of the events were associated with mountain waves and two with a trough axis (which suggests horizontal directional shear). The remaining reports were of light/moderate CAT east of the trough axis.

Low to moderate stability was present during most CAT reports (Table 3). This corresponds to the preponderance of vertical wind shear <8 kn/1000 ft. In other words, lower stability is necessary where large vertical shear is absent (Colson, 1961).

By and large, pilot reports of moderate turbulence and moderate to severe turbulence coincide with moderate vertical wind shear and moderate stability (Table 4). However, there were occasions when vertical wind shear and stability were less favourable for CAT development and yet severe CAT was reported (Table 4). For example, on 7 May 1998 a pilot reported severe turbulence with a 4 to 5 kn/1000 ft vertical wind shear and a low potential temperature change of <+1.5 °K/1000 ft. On 12 June 1998 a stewardess was injured when the pilot reported no more than moderate CAT in the lee of the Drakensberg. The aircraft, on route from Durban to Johannesburg, was ascending through FL210 to FL250 in winds of 40 to 50 kn, while the vertical wind shear was less than 4 kn/1000 ft with low stability. The conclusion is that mountain waves were the cause of the turbulence. The author has noted similar turbulence on numerous commercial flights when climbing or descending on the sector of the flight between Durban and Ladysmith, particularly with Berg wind conditions. A Berg wind is the local name for the hot and dry Fohn wind which descends from the mountains to the coast. These incidences support the assumption that a steep lee slope is a factor in producing mountain wave CAT.

Table 3. *Analysis of the vertical and horizontal wind shear and atmospheric stability at the time of the 34 CAT events during the 1998 survey. PPTC is the positive potential temperature change.*

Characteristic	Number
Vertical shear <4 kn/1000 ft	6
Vertical shear 4–5 kn/1000 ft	19
Vertical shear 6–8 kn/1000 ft	8
Vertical shear >8 kn/1000 ft	1
Horizontal (directional and/or speed) shear	2
Horizontal shear >100 kn/100 miles	0
Wind shift ≥75°	6
PPTC <1.5°K/1000 ft, low stability	12
PPTC 1.5–4.5°K/1000 ft, moderate stability	19
PPTC >4.5°K/1000 ft, high stability	3

In contrast to the 1993 to 1995 survey, where vertical wind shear >8 kn/1000 ft occurred but no reports of CAT were received, during the 1998 survey there were five reports of severe CAT, but vertical wind shear >8 kn/1000 ft was observed on only one occasion (Table 4). However, a report of severe CAT was received when the air was very stable (>+4.5 °K/1000 ft potential temperature change) with vertical wind shear of 4 to 5 kn/1000 ft.

From the above it is apparent that hard and fast rules cannot be made about when and how differing levels of severity of CAT occur. Confirmation of this is apparent from research by Colson (1963) where reports of moderate to severe CAT were received with vertical wind shear as low as 4 kn/1000 ft. However, Ellrod (1990) states that moderate CAT usually occurs with vertical wind shear of 6 to 9 kn/1000 ft and severe CAT at higher levels of shear, but that the severity of CAT is compounded by the presence of directional shear.

4. High altitude CAT and mountain wave CAT

4.1. Method

Shortly after GSM aviation products were introduced in the SAWB Central Forecast Office (CFO), an opportunity presented itself to view the effectiveness of the ETI (Ellrod & Knapp, 1992) using the GSM model. The situation arose when a baroclinic system with a marked cold front and negative vorticity centre associated with a pronounced upper-air trough passed over the country on 18 September 1996.

Three CAT reports were received. Two reports were of moderate to severe CAT in the lee of the Drakensberg over the eastern part of the country. The first at FL170 at 0805 UTC (10:05 SAST), followed by a report at a similar level at 0900 UTC (11:00 SAST). The last report was of moderate to severe CAT over Victoria West between FL310 to FL330 at 1030 UTC (12:30 SAST).

Observed upper-air data from atmospheric soundings and numerical model wind analysis from the UK Meteorological Office (UKMO) from 1200 UTC on 18 September 1996 were used to analyse the upper-air conditions nearest to the time of the CAT incidents.

Table 4. *Severity of CAT reports in relation to vertical wind shear and stability during the 1998 survey.*

Severity of CAT	Vertical wind shear (kn/1000 ft)				Stability(°K/1000 ft)		
	<4	4–5	6–8	>8	<1.5	1.5–4.5	>4.5
Light/Moderate	2	3	1		3	3	
Moderate	5	16	7		7	16	5
Moderate/Severe		6	4		1	8	1
Severe		4		1	2	2	1

The ETI was then calculated, from the wind analysis fields, to determine if the index would have given advance warning of the CAT conditions. This was compared with the same ETI forecast derived from the NCEP GSM data received on the Global Transmission Service (GTS). An example of the model field is given in Figure 2.

The ETI is based on horizontal stretching deformation (DST) and shearing deformation (DSH) at the 300, 250 and 200 hPa levels (collectively the DEF) with vertical wind shear (VWS) in the 400–300, 300–250 and 250–200 hPa layers (see equations (1) and (2) below). The index has been used by NCEP in Washington since 1988 (Bakker, 1993). It originates from Pettersen's frontogenetic intensity equation which relates frontogenesis with increased vertical shear and therefore the likelihood of turbulence (Ellrod & Knapp, 1992):

$$ETI = DEF \times VWS \tag{1}$$

where:

$$DEF = \left(DST^2 + DSH^2\right)^{\frac{1}{2}} \tag{2}$$

$$DST = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \qquad DSH = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

with u and v the east/west and north/south horizontal wind components.

VWS uses the resultant layer difference in u and v wind components from model forecast data so that:

$$VWS = \frac{\left(\Delta u^2 + \Delta v^2\right)^{\frac{1}{2}}}{\Delta z}$$

with Δu and Δv changing in east/west and north/south direction in the vertical layer z.

4.2. Results

Figure 3 reveals that the CAT report over Victoria West is near the trough axis with cold air advection at FL300 (approximately 300 hPa) evident from the fact that the FL300 winds cross the isotherms at a large angle. Comparison with the winds 5,000 feet lower, at FL250, shows that the vertical shear was about 8 kn/1000 ft with directional shear. The report is also close to the jet stream and tropopause shear (Figure 4). Increased stability is also apparent in the form of a temperature inversion at the level of CAT at De Aar (Figure 5). According to Hopkins (1977) and Colson (1961) these are all favourable CAT conditions.

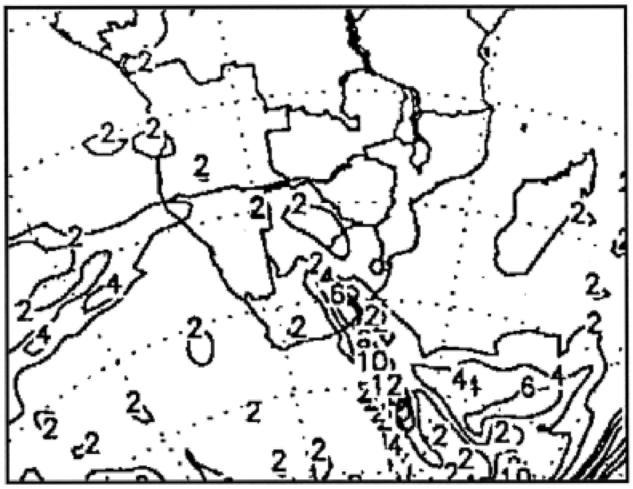

Figure 2. *Ellrod Turbulence Index (ETI) for the 24-hour forecast from the GSM model valid at 1200 UTC on 18 September 1996.*

The other two turbulence reports were much further to the east in the lee of the Drakensberg mountains (FL150 in Figure 3) with a strong north-westerly wind and more-or-less under the jet stream (Figure 4). The wind speed increased with altitude and it was virtually 90° to the Drakensberg mountain range. The air was also stable, as indicated by the sounding at Durban (Figure 5). In other words the criteria for the generation of mountain waves were met (Alaka, 1958) and this was the cause of the turbulence experienced in the lee of the Drakensberg.

The ETI values, using UKMO analysis data (Figure 3), produced a band of moderate to severe levels of ETI, which straddled the report of turbulence over the western interior. Figure 6 gives the corresponding 12-hour GSM forecast, valid at 0000 UTC on 18 September, of ETI values at 250 and 300 hPa (approximately FL350 and FL300); these compare favourably with the UKMO analysis. The GSM prognosis, therefore, presented a more than adequate indication of CAT. As a result of this CAT was included in local aviation significant weather charts. By 1800 UTC (T+18) the GSM CAT prognosis showed a marked decrease, with maximum values of 2 over the south-western part of the country at 250 hPa and it was assumed that the system had passed its peak. This also led to the exclusion of CAT on the aviation forecast significant weather charts in the evening and underlines the transitory nature of CAT. It is worth noting in Figure 2, that CAT was already indicated nearly 24 hours in advance, albeit a bit too far to the east.

GSM ETI values are not calculated for levels below 300 hPa, but they were calculated using UKMO analysis data (Figure 3). These showed turbulence well to the west in the vicinity of wind shear, but gave poor results in the vicinity of the mountain range where horizontal and vertical wind shear was less evident. The conclusion is that orographic influence in a steady flow cannot be detected by the ETI.

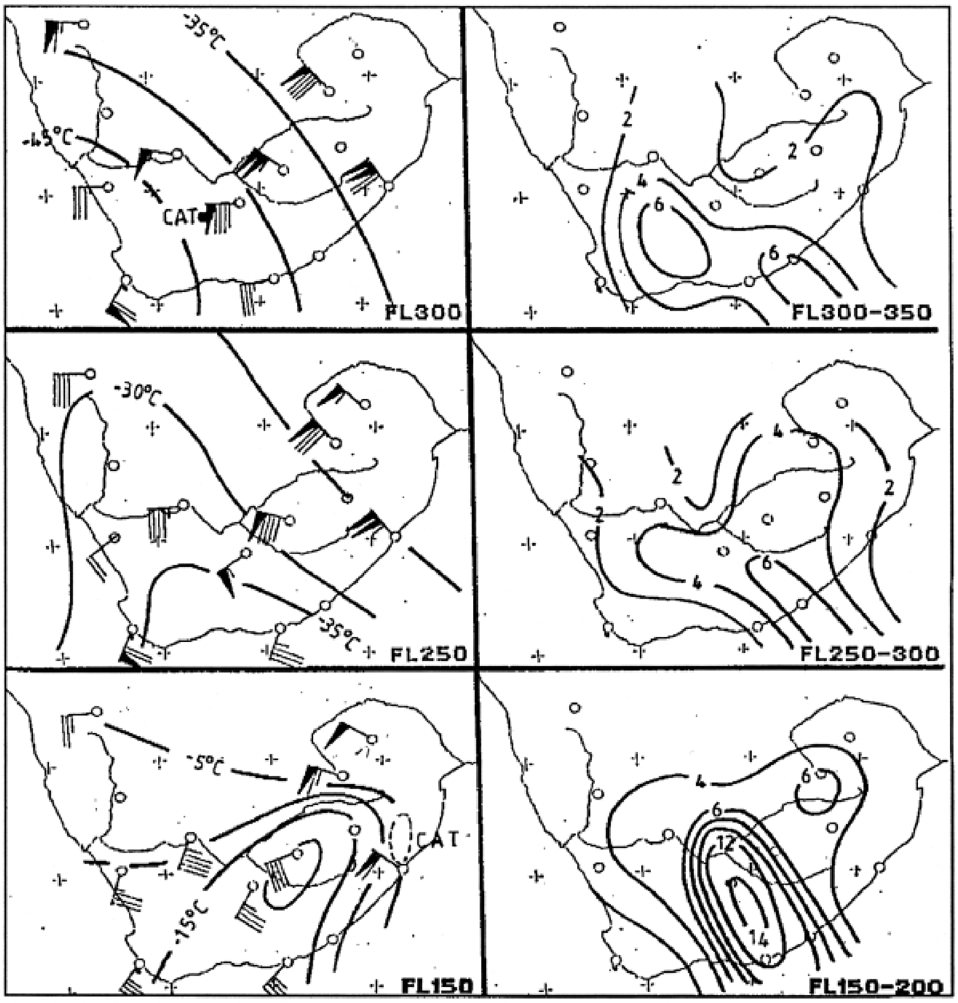

Figure 3. *Analysis of upper winds and temperature (left) and ETI (right) for 1200 UTC on 18 September 1996.*

5. Conclusions

Analysis of the two surveys reveals that CAT over South Africa occurs under conditions similar to those elsewhere in the world.

- The jet stream is a dominant factor in the occurrence of CAT and the probability of CAT in association with a jet stream is increased when it passes over a mountain range. This is particularly evident in a pre-trough north-westerly flow over the Drakensberg and the Eastern Cape mountains.
- CAT is most likely within 5,000 to 10,000 feet below the jet stream core and on the cold or low pressure side of the core. However, mountain wave CAT is often likely to occur sufficiently far ahead of the trough for it to occur in the warm air of the jet stream.
- In general increased vertical wind shear and greater stability are indicative of more severe CAT, but this is not a strict rule. For example, reports of moderate to severe and severe mountain wave CAT were received with weak vertical wind shear and low stability. This emphasises the increased effect of mountains in the path of the air flow.
- An upper-air trough is the dominant synoptic feature and the high number of reports at the axis of the trough emphasises the importance of directional shear. However, it is difficult to determine the effect of horizontal shear on CAT reports due to the large distances between observing points. This is particularly so during the 1998 survey.

The results of the limited surveys are in agreement with overseas research in that most CAT occurred with curved segments of jet streams associated with troughs and ridges and vertical wind shear. In accord with the research of Ellrod & Knapp (1992), moderate CAT is associated with ETI values of 4–8 and severe CAT with values above 8.

The limited number of events during the three-year period is believed to be in part due to the fact that the incidents are not always passed on to the SAWB. The other consideration is that, because of South Africa's sub-tropical position, occasions of moderate to severe CAT are not as prevalent as would be the case in more temperate latitudes nearer to the polar jet stream.

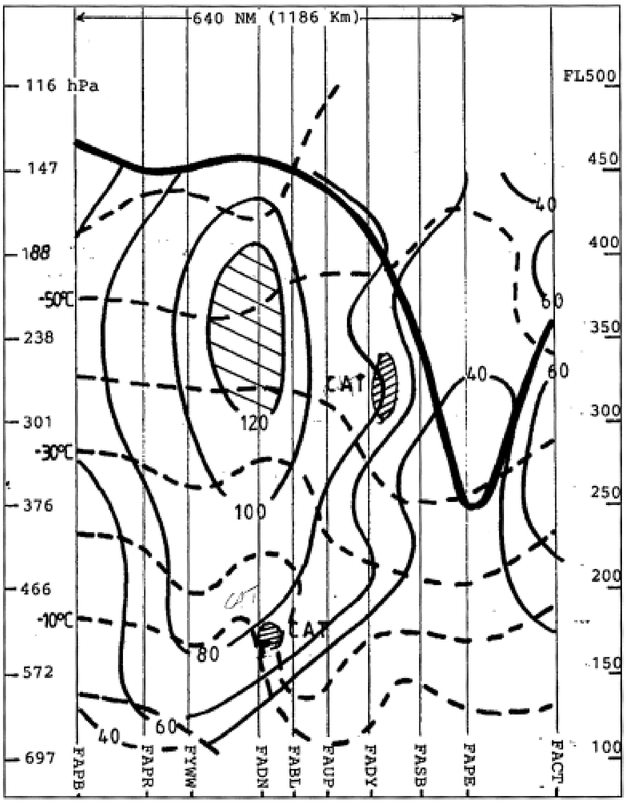

Figure 4. *Cross-section of wind (knots, solid lines), air temperature (°C, dashed lines), tropopause (dark solid line), jet stream core (widely spaced hashed lines) and CAT locations (closely spaced hashed lines) for 1200 UTC on 18 September 1996.*

In the study presented, the GSM ETI performed well as an indicator of CAT where vertical and horizontal wind shear were present. In practice, in the CFO, the ETI has been found to be a reliable indicator of CAT areas. This must be qualified by stating that no detailed evaluation has been made. Confidence in the ETI is simply because reported CAT events (when received) have supported the ETI prognosis. However, the ETI does not appear to be a reliable indicator of mountain wave turbulence and in this respect it would be best to use traditional forecasting methods.

In the introduction it was pointed out that high altitude CAT has been the cause of numerous incidents in which aircraft passengers have been injured and sometimes even died. On rare occasions aircraft have suffered structural damage and temporary loss of pilot control. It is the responsibility of the aviation forecaster to be conscientious in providing pilots with a warning of potential areas of clear air turbulence, especially severe turbulence, at the flight planning stage. This enables suitable advance changes in flight route to be made. Furthermore, forewarned is forearmed and a pilot who encounters CAT is more likely to immediately recognise it for what it is and take suitable corrective action.

Acknowledgements

The authors are indebted to Mr G. Schulze, Chief Director of the SAWB, without whose support this

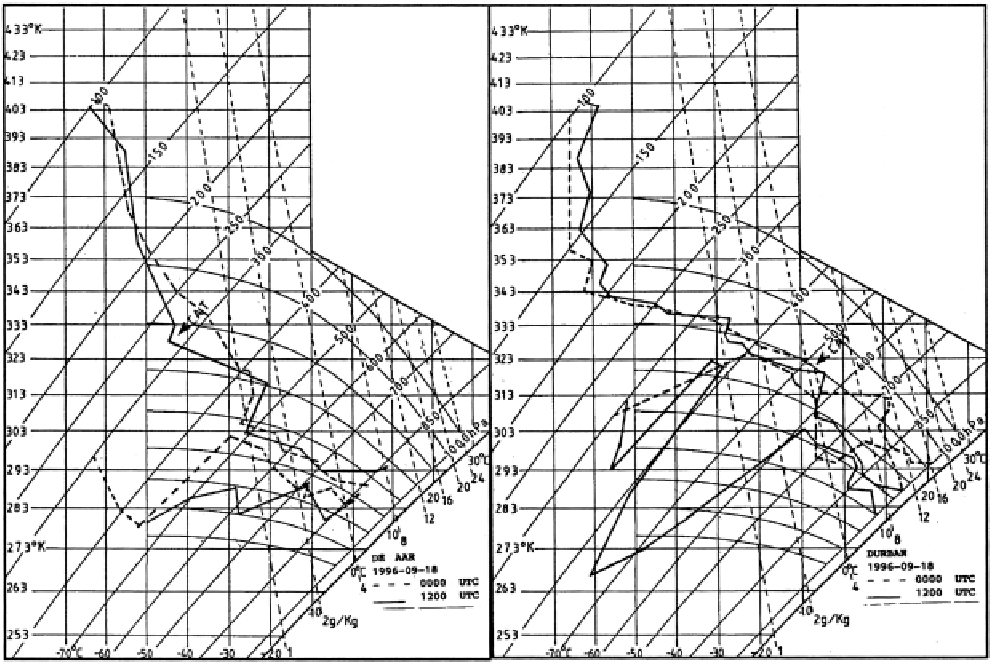

Figure 5. *Atmospheric soundings from De Aar (left) and Durban (right) showing the air temperature and dew-point temperature for 0000 UTC (dashed lines) and 1200 UTC (solid lines) on 18 September 1996, plus the location of CAT reports.*

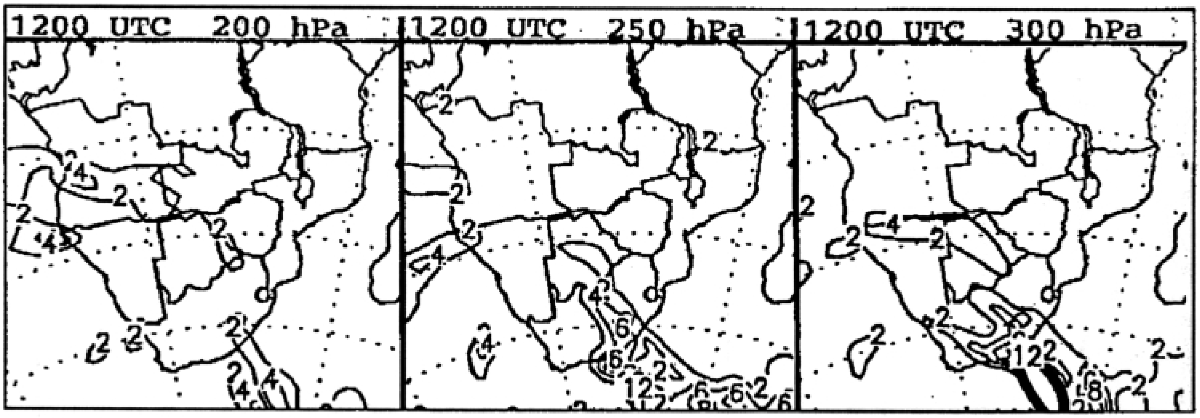

Figure 6. *12-hour forecast of ETI from the GSM valid for 1200 UTC on 18 September 1996.*

paper would not have been possible. Appreciative thanks also go to South African Airways for providing the aircraft data recorder technical information concerning the CAT incident on 10 January 1994; to the pilots of British Airways (Comair), SA Airlink, Sabena/Nationwide, SA Express, South African Airways and Sun Air for their observation and reports of CAT; and to Air Traffic Navigation Services for their efforts in relaying information from pilots to SAWB Weather Offices for the transmission of CAT reports to the Central Forecast Office.

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