Aust. Met. Mag. 47 (1998) 321-326

A marked upper tropospheric temperature anomaly observed by an aircraft near a thunderstorm over inland Western Australia

Gary Foley
Regional Office, Bureau of Meteorology, Perth, Western Australia

(Manuscript received June 1997; revised January 1998)

A marked positive temperature anomaly of up to 18°C was encountered by a commercial passenger aircraft near Meekatharra, Western Australia at an altitude of around 9500 m. The aircraft was diverting around the up-wind side of a large thunderstorm at the time and experienced difficulties maintaining power. The meteorological aspects of the situation are examined and evidence is presented that similar anomalies have been observed at other times, in other parts of the world. Adiabatic warming of air returning from the stratosphere as a result of interactions between the thunderstorm outflow and the environmental airflow is shown to be consistent with the magnitude of the anomaly observed.

Introduction

A four-engine jet aircraft was scheduled to fly from Perth to Karratha and return on the evening of 22 March 1992 (see Fig. 1). The initial leg to Karratha was completed without incident. At 1235 UTC on the return journey the aircraft, which had been cruising at flight level FL310* (approximately 9500 m), experienced a loss of power in all engines. This occurred initially when the aircraft was located approximately 500 km (270 nm) to the northwest of Meekatharra.

The aircraft was in the process of diverting, at a distance of about 55 km (30 nm), around the western edge of a 'strong' (pilot's description) radar return associated with thunderstorm activity when an abnormal and rapid warming was experienced in the outside air temperature (OAT). A plot of Total Air Temperature (TAT)† measurements from the aircraft's flight data recorder shows the magnitude and rapidity of the rise and subsequent fall in temperature (Fig. 2). The OAT is a more familiar meteorological parameter. This rose from minus 39°C to minus 26°C in 50 seconds with the onset of the warming and fell from minus 19°C to minus 37°C in 25 seconds as conditions returned to normal. The warming lasted approximately 8 minutes. The aircraft lost altitude and descended through FL280 (approximately 8500 m) during this time.

The aircraft entered stratiform cloud at FL190 (approximately 5800 m). Control of the aircraft's engines was regained at an altitude of around A100 (approximately 3000 m) where the aircraft emerged from the cloud. The aircraft and the 56 people on board then made a successful emergency landing at Meekatharra.

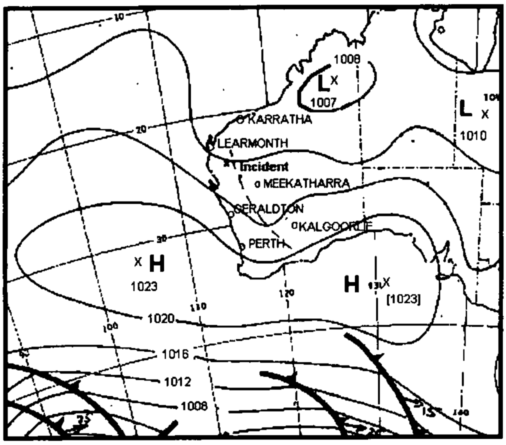
Corresponding author address: Mr G. Foley, Bureau of Meteorology, PO Box 1370, West Perth, WA 6872, Australia.

* Due to the relevance of the information to aviation interests International Civil Aviation Organisation (ICAO) units of Flight Level (FL), Altitude Level (A), height (feet) and distance (nautical miles or nm) are included.

† TAT is defined as the temperature of air that is stopped from its motion and is the sum of the static temperature of the air and the temperature caused by the ram effect as the air is stopped.

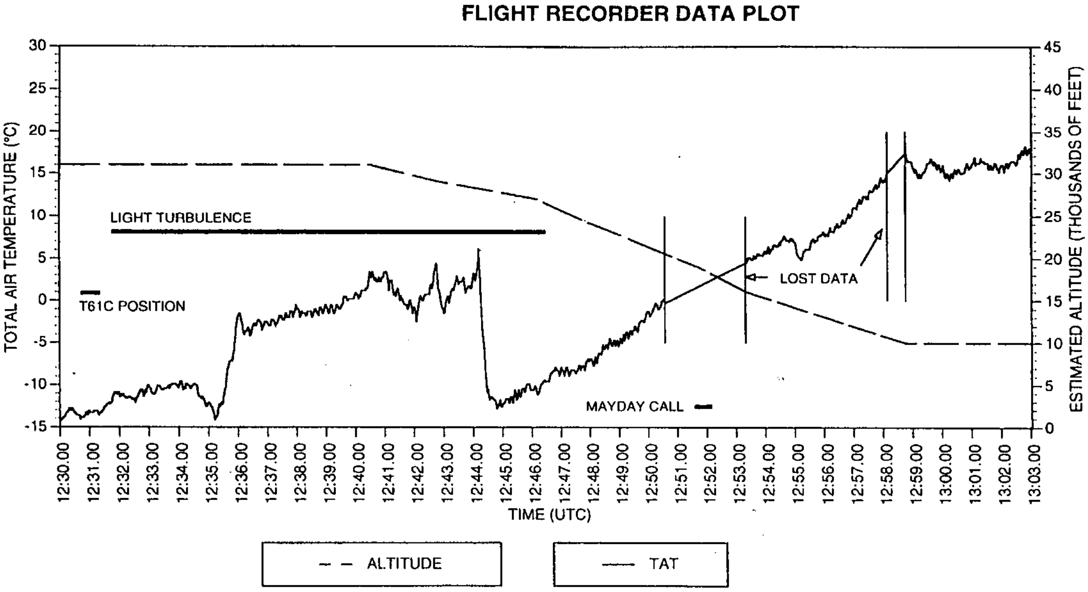
Downward vertical motion in the upper levels of the troposphere adjacent to thunderstorms (and attendant subsidence warming) has been recognised to occur as a compensating flow for the mesoscale upward transport associated with the convective process (see Fritsch 1975; Hoxit et al. 1976; and Kessler 1985). The magnitude of warming experienced in this incident has not been reported very often however. One notable observation of significant warming was described in Hoxit et al. (1976), where the approach of a severe squall line was monitored at North Omaha, Nebraska, USA in 1957 using serial rawinsonde ascents approximately every 90 minutes. The study found the temperature change prior to the arrival of the squall line was most pronounced in the upper troposphere, where an increase in temperature at 200 hPa of around 13°C was observed.

Fig. 1 **MSLP analysis for 1200 UTC 22 March 1992. Place names used in the text are denoted here.**



A similar event was reported on the western periphery of tropical cyclone *Kerry* in 1979 when a Boeing 747 enroute from Port Moresby to Brisbane encountered an 18°C temperature rise in 60 km (32 nm) when diverting to avoid a strong convective area (Holland et al. 1984). The aircraft was flying at FL370 (11300 m) and lost considerable power when it flew into this mass of warmer air. The incident occurred when the aircraft was about 75 km (40 nm) from the western flank of the main area of convection. A conceptual model was proposed that the effect arose from dynamically forced subsidence along a confluence between the environmental flow and outflow from a major convective complex.

Fig. 2 **Time-section from aircraft flight recorder at around the time of the incident showing the variation in Total Air Temperature (TAT), aircraft altitude and turbulence indicator (source: BASI).**



Note: The Altitude values used in this chart are estimates based on pilots reports recorded on the AVR tape. Intermediate values have been interpolated to provide straight lines between the reported altitudes.

Data

Chart analyses from the Perth Regional Office and the National Meteorological Operations Centre (NMOC) in Melbourne were used in this study. Infrared satellite imagery from the Japanese GMS-4 geostationary meteorological satellite was examined to identify cloud features and to analyse cloud-top temperatures. Upper wind and temperature information was collected from Bureau of Meteorology field station observations and supplemented by in-flight aircraft reports (AIREP). Measurements of the OAT and TAT from the aircraft were obtained from its flight recorder data system, and supplied by the Australian Government's Bureau of Air Safety Investigations (BASI).

Meteorological conditions at the time of the incident

From a forecaster's viewpoint the general synoptic situation was not a particularly unusual one. At 1200 UTC 22 March 1992, the mean sea-level pressure chart (Fig. 1) showed a high pressure ridge lying with its axis to the south of the continent. A low pressure area of 1007 hPa was located over the north of Western Australia. Between these two features was a broad easterly airflow and embedded in this was a trough line running approximately north/south. The thunderstorm activity was apparently initiated by convergence of moist (surface dew-point temperatures were of the order of 17°C) unstable air in the vicinity of the trough.

The closest Bureau of Meteorology upper wind station to the incident was Meekatharra (Fig. 1) and the last ascent performed prior to the incident occurred at 0500 UTC 22 March 1992. The vertical wind profile (see Fig. 3) showed northeast to northerly winds from the surface to around 2000 m flowing into the trough. Above 2000 m there was an abrupt change to a westerly flow, that shifted northwesterly with height.

Enhanced infrared satellite imagery for 1200 UTC 22 March 1992 (Fig. 4) indicated the approximate cloud-top temperatures at the time of the incident. The position of the aircraft at the time of the incident is shown. The black area to the east of the aircraft represents the coldest cloud tops with temperatures between minus 63°C and minus 68°C, and hence the strongest convective activity within the cloud system. Cloud-top temperatures in the vicinity of the aircraft were around minus 57°C. Observations by the flight crew indicated the aircraft was flying in clear air at FL310 (9500 m) with an OAT of minus 39°C, prior to the incident, suggesting a veil of cirrus was located above the aircraft.

The satellite imagery also suggests that the cloud tops were being blown off towards the southeast, consistent with the observed northwesterly environmental wind shear. The cloud pattern is asymmetrical, with the black (coldest) area displaced to the east of the main cloud mass. This may have been the result of earlier convection to the west that was in the process of dissipating at the time of the imagery. The pilot (personal communication) mentioned that there appeared to be decaying cells in the area. The aircraft flew in clear air until its descent into stratiform cloud at FL190 (approximately 5800 m).

Fig. 3 **Modified temperature profile based on 2300 UTC 21 March 1992 radiosonde ascent from Learmonth Observing Office. Wind profile at right is for Meekatharra at 0500 UTC 22 March 1992. Full wind barbs represent 5 m/s, half barbs 2.5 m/s and flags 25 m/s.**

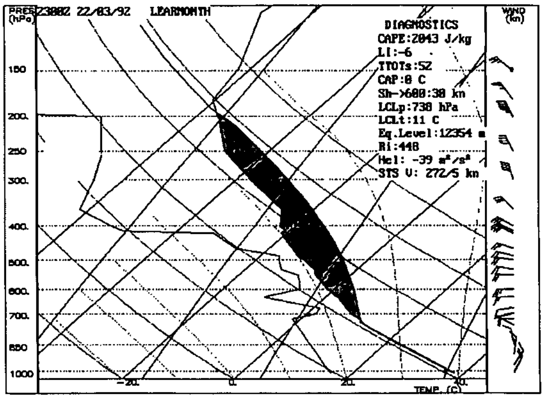
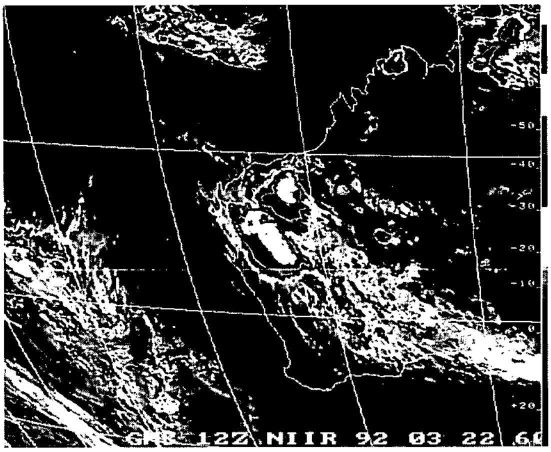


Fig. 4 **Enhanced infrared satellite imagery (Japanese GMS-4) for Western Australia for 1200 UTC 22 March 1992. Approximate location of incident denoted by (x).**



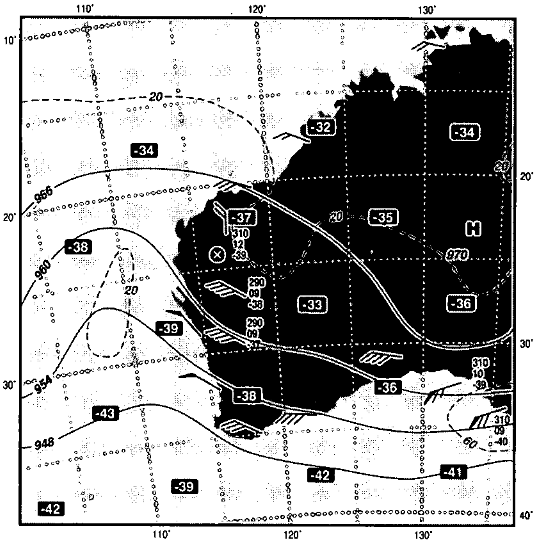
The nearest Bureau of Meteorology radiosonde station that could be considered to be reasonably representative of the atmosphere near the incident was at Learmonth, approximately 400 kilometres to the northwest. The morning ascent was conducted at 2300 UTC 21 March; 13 hours before the aircraft encountered the anomaly. The temperature profile at Learmonth is shown in Fig. 3 with the lower levels modified to reflect the surface dry bulb and dew-point temperatures in the Meekatharra area at the time of maximum heating.

The tropopause at Learmonth occurred at a pressure level of 180 hPa which corresponded to a height of around 12800 m (42000 ft). Interpolation between the tropopause heights at Learmonth, Geraldton and Kalgoorlie suggested that the tropopause at Meekatharra would have been at around 12500 m (41000 ft). Similarly the freezing level in the area of the incident was estimated to be near 4200 m (13800 feet).

A parcel of air lifted from the surface is shown to ascend to a temperature of minus 58°C, very near to the tropopause, giving a substantial Convective Available Potential Energy (CAPE) value of 2043 J kg^{-1}. It is suggested that an increase in vertical motion due to the presence of the trough could have enabled air to penetrate the tropopause and enter the stratosphere. Organisation of the storm cells by the vertical wind shear may also have increased the strength of the updraughts closer to the trough. This is supported by measurement of the storm's cloud-top temperatures from satellite imagery.

The 300 hPa contour analysis for 1200 UTC 22 March 1992 issued by the National Meteorological Operations Centre (NMOC) Melbourne is shown in Fig. 5. The incident occurred on the eastern flank of a slow-moving upper trough. Superimposed on Fig. 5 are wind and temperature observations at or close to the 300 hPa level near the time of the incident, including reports from aircraft (both the aircraft involved in the incident and another similar aircraft on the same route that night). Winds along the track were generally northwesterly at 15 to 20 m/s (30 to 40 knots), however an anomalous northerly wind of 10 m/s (20 knots) was reported by the aircraft just prior to the incident.

Fig 5 **300hPa contour height analysis for 1200 UTC 22 March 1992 from NMOC and plots of upper winds and AIREPS at and near the 300 hPa level between 0800 UTC and 1200 UTC 22 March 1992. Figures associated with AIREP denote the Flight Level of the aircraft, the time of the report (to the nearest UTC hour) and the OAT. Wind barb nomenclature same as Fig. 3.**



Discussion

The temperature anomaly was reported on the western side of, and, in close proximity to, the area of strongest convection within the cloud system. Consistent with the conceptual model proposed by Holland et al. (1984) air flowing out of the thunderhead appears to have encountered environmental northwesterly winds on the upstream side of the storm. The confluence of air of differing origins and physical characteristics could have caused the outflowing air on the western flank of the thunderhead to return from the stratosphere to the troposphere and, in descending, to warm. Dry adiabatic warming of a parcel from above the tropopause based on the data from the radiosonde ascent at Learmonth (temperature of around minus 62°C) to the flight level of the aircraft, FL310 (9500 m) would produce a temperature near to minus 28°C. This result is in reasonable agreement with the reported OAT measurement from the aircraft.

There are however some notable differences here in the scale of the phenomenon producing this effect. While in Holland et al. (1984) and in Hoxit et al. (1976) the anomalous warming was associated with major mesoscale organised features (one a tropical cyclone and the other a squall line disturbance), this event suggests that single cumulonimbus may be capable of inducing such significant temperature anomalies, given the right circumstances.

If the phenomenon is the result of folding of stratospheric air back into the troposphere with attendant warming as it descends, and the most likely mechanism is strong convection interacting with the environmental flow, then it is reasonable to assume that, where there is strong thunderstorm activity there is a likelihood that an area of anomalous warming may be present somewhere around the storm cell, at some time within its life cycle, given a favourable ambient flow. In this case the aircraft encountered the phenomenon on the upwind side and approximately 55 km (30 nm) from the active convective cell in an environmental flow of around 20 m/s (40 knots).

The anomalous zone may exist away from the main convective area and be transitory in nature. However the exact area of horizontal and vertical extent is undetermined from these data. All that is known is that the aircraft encountered significant warming for approximately 8 minutes of flight time and between FL310 and FL280 (Fig. 2), approximately 55 km (30 nm) from a convective cell. The duration and vertical depth of the anomaly would also depend on the rate of entrainment of the surrounding air.

It is appropriate to relate some of the pilot's comments here. His normal practice (and it is understood that this is standard practice for that airline) when diverting around strong radar echoes was to ensure a buffer of 20 km (10 nm) between the radar echo and the aircraft. As an extra safety margin on this occasion he diverted 55 km (30 nm) from the strongest echo.

The pilot also commented that he had been flying in an area of innocuous radar returns - visible as a 'green fuzz' on his radar screen rather than a definite echo indicating precipitation. He noticed that the warming commenced as they flew along the boundary between these weak returns and the clear air. It is suggested that this boundary may have delineated air masses of differing characteristics.

Another interesting comment was that prior to the incident there had been an 'incredible' display of St Elmo's Fire, the 'best that he had ever seen'. Whether this was a precursor to this type of event or merely coincidence is conjectural at this stage.

Other evidence of anomalous warming events

Following the event a survey was initiated in September 1992 asking QANTAS Airlines pilots if they had ever encountered similar temperature rises. The result was that over sixty pilots made contact to say they had previously experienced this type of event, particularly in tropical areas. A sample of responses indicating the degree of warming, the altitude and location where the phenomenon was experienced is shown in Table 1. Although anecdotal, unsubstantiated and incomplete, the information serves as persuasive evidence that this phenomenon is at least known to pilots. One particular event related by a pilot of 30 years experience illustrates the comparative infrequency of encounters with this phenomenon. While flying on the southern side of the ITCZ on 21 January 1995 (personal communication), he was 'very surprised' to observe a rapid temperature rise from minus 53°C to minus 28°C at FL430 (approximately 13,100 m) in the middle of the Pacific Ocean to the north of Fiji. He claimed that he had never encountered such an effect before, despite his lengthy flying experience. Similarly, although some pilots reported several encounters, other very experienced pilots had encountered the phenomenon rarely.

Subsiding air from the stratosphere should be dry and cloud-free and yet several pilots in Table 1 reported flying in cloud at the time of encountering rapid temperature rises. This may be related to human limitations in determining horizons and boundaries in such conditions or to the mixing of stratospheric air with moist air from the thunderstorm updraft or the surrounding environment. The available evidence is insufficient to definitely support either proposition.

No definite evidence can be gained from the survey on the actual size or extent of these anomalous zones, however it appears that the area of anomalous warming is a small-scale phenomenon with a limited lifetime linked to the life cycle of a 'host' convective system.

Summary and conclusions

A passenger aircraft enroute from Karratha to Perth experienced a marked warming of up to 18°C above the environmental temperature for approximately eight minutes, in close proximity to thunderstorm activity. The incident took place in a data-sparse region which hampered close meteorological examination; however estimation of the extent of warming resulting from adiabatic descent of an air parcel gave close agreement to the OAT recorded by the aircraft.

This apparently localised area of marked warming is probably present in association with the life cycle of thunderstorms that are energetic enough to penetrate the stratosphere, as long as the environment is conducive to the set-up of a perturbation at or near the tropopause that would allow the downward transport of stratospheric air.

The true vertical extent of the temperature anomaly is unknown generally, but in this instance it extended down to at least around 8500 m (28000 feet), where the anomaly ceased to be observed by the aircraft.

The anomalous temperature zone appears to exist away from the main convective area and may be transitory in nature, dependent on the extent of the storm's outflow to the stratosphere, its interaction with the environment, and the rate of subsequent entrainment by the atmosphere. As this effect occurs at typical cruise altitudes for commercial jet aircraft and can affect their engine performance to varying degrees, it is worthy of wider recognition in the aviation and meteorological community than is presently the case. Further observation and study of this phenomenon is warranted, particularly with regard to pilot reports of the presence of cloud in some warming episodes.

Table 1. **Anecdotal evidence provided by QANTAS pilots on encounters with marked temperature warming at cruise altitudes. N/A denotes information not available.**

Altitude	Degree of warming Encountered	Cloud estimate	Vicinity Thunderstorm?	Area Encountered
N/A	10-12°C	N/A	yes	Pacific Ocean
N/A	10°C in 2 to 3 mins	N/A	yes	New Guinea
FL370	17°C in a few mins	N/A	yes - tropical cyclone *Kerry*	off Townsville Australia
FL390	24°C in 3 mins	'apparent' stratiform	yes - 20 nm from storm	North of New Guinea
FL370	25°C in 30 secs	N/A	yes	Ambon
N/A	10-15°C	N/A	yes	Bay of Bengal
N/A	'dramatic'	high level cloud	'significant' vertical development	Ambon
FL410	10°C	N/A	yes – 10 to 15 nm from storm	Fiji area
FL370	18°C over 70 nm	in cloud	forming typhoon	ENE of Taiwan
FL350	10°C in 5 min	in cloud	yes - cells 25 nm away	10°S 173°W approx.
FL350	10°C in 5 secs	in cloud	yes	3°S 133°E
FL390	29°C	clear air	yes	west of Philippines
FL370	26°C	in cloud	no apparent Cb	Indonesia
FL390	20°C in 15 secs	high level cloud	large return yes - 15/20 nm away	Vietnam
FL350	17°C	N/A	yes - 15/20 nm from large Cb	on Equator, enroute Nerita to Perth

Acknowledgments

Mr Barry Hanstrum and Mr Alan Scott of the Western Australian Regional Office offered valuable advice and assistance with the manuscript. Dr Greg Holland of the Bureau of Meteorology Research Centre and Mr Bryan Stott of the Bureau of Air Safety Investigation provided enthusiasm for and encouragement with this study. The comments of two anonymous reviewers contributed significantly to the final version of this paper.

References

Fritsch, J.M. 1975. Cumulus dynamics. Local compensating subsidence and its implications for cumulus parametrisation. *Pure Appl. Geophys.*, *113*, 851-67.

Holland, G.J., Keenan T.D., and Crane G.D. 1984. Observations of a phenomenal temperature perturbation in tropical cyclone Kerry (1979). *Mon. Weath. Rev.*, *112*, 1074-82.

Hoxit, L.R., Chappell, C.F. and Fritsch, J.M. 1976. Formulation of mesolows or pressure troughs in advance of cumulonimbus clouds. *Mon. Weath. Rev.*, *104*, 1419-28.

Kessler, E. 1985. *Thunderstorm Morphology and Dynamics.* University of Oklahoma Press, Norman and London, 411 pp.