OBJECTIVE DETECTION AND FORECASTING OF CAT: A STATUS REPORT

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Accidents involving encounters with clear-air turbulence (CAT) have shown some increase over the last five years. Reasons include reduced staffing of airline meteorology departments, and the decreasing volume of pilot reports (PIREPs) passed through air traffic control (ATC) centers. Hence, CAT has become the largest single cause of weather-related injuries occurring in commercial carriers at cruising altitudes.

A technique for objective operational CAT detection (the SCATR index) has been formulated. Its physical basis ties CAT to total energy dissipation as a response to meso- and synoptic-scale dynamical processes associated with upper-level jet stream/frontal zones. Early case studies using properly analyzed routine RAOB rawinsonde sounding data (provided by the PROFS/Central Weather Processor (CWP) group have shown promise.

Introduction

Clear-air turbulence (CAT) continues to be a significant problem for commercial flight operations above about 500 mb. Upper-level SIGWXs (significant weather advisories), which rely heavily on PIREPs, seem to be the only reliable means of monitoring CAT. The currently available SIGWX forecasts are highly subjective and generally considered unreliable. A technique has been developed for CAT detection which is objective and is based on sound physical principles: the Specific CAT Risk (SCATR) index formulation [Keller, 1984, 1985].

The SCATR index technique, originally formulated by Roach (1970), uses objectively analyzed grid point data from RAOBs consisting of horizontal wind components, temperature and heights to diagnostically calculate a quantitative measure of the total energy dissipation rate due to CAT which results from meso- and synoptic-scale deformation processes. That RAOB data can be used to resolve mesoscale features has been suggested by Keller (1981) and Kennedy and Shapiro (1980). Further studies into the role of CAT as a diabatic heat source, done as part of the previous research effort for NASA and PROFS into the physical basis of the SCATR formulation, seem to show that both the structure and intensity of CAT as predicted by the SCATR formulation are consistent with observational measurements of CAT by experimental aircraft (e.g., Shapiro 1976; Kennedy and Shapiro 1975, 1980).

Background

The basis of this technique is a deterministic formulation for calculating the rate of total energy dissipation in the free atmosphere. This formulation is an extension of that originally published by Roach (1970). The formulation has been extended in part by applying it to an idealized model based on aircraft measurements of turbulence made subsequent to Roach's work (Kennedy and Shapiro, 1975, 1980). An analysis of this case has shown that the SCATR index formulation predicts CAT of an intensity and structure consistent with turbulence observed by experimental aircraft in frontal shear zones in this study.

In this formulation, CAT is viewed as a manifestation of internal, frictional dissipation of total energy within a volume of air of unit area and of potential temperature thickness, $\Delta\Theta$. The rate of total energy dissipation, vertically integrated through $\Delta\Theta$ can be shown (Roach, 1970) to be

$$\bar{E}_L = \left\{ \begin{array}{c} \frac{(\Delta V)^2}{24} \, \Phi_L, \Phi_L > 0 \\ \hline 0, \ \Phi_L \leq 0 \end{array} \right)$$

where in isentropic coordinates

$$\Phi = \left(-2 \mid \frac{\partial \vec{V}}{\partial \theta} \mid^2 \cdot \left[\frac{\partial \vec{V}}{\partial \theta} \cdot \left(\frac{\partial \vec{V}}{\partial \theta} \cdot \nabla \right) \vec{V} + \frac{c_p}{\theta} \frac{\partial \vec{V}}{\partial \theta} \cdot \nabla T \right] + \nabla \cdot \vec{V} \right)$$

ΔV is the magnitude of the horizontal vector wind difference through $\Delta\Theta$, and

$$\Big(\Big)_L = \frac{1}{\Delta\Theta} \int_{-\Delta\Theta/2}^{\Delta\Theta/2} (\,) d\Theta$$

The mathematical development of this formulation is given in isentropic coordinates which yield somewhat cleaner derivations than the pressure coordinates used by Roach in his development (Keller, 1986). The use of isentropic coordinates has other benefits, in particular with respect to resolving internal fronts.

The quantity, Φ_L, represents the grid scale forcing by larger-scale dynamical processes which are attempting to change the local gradient Richardson number,

$$Ri_L = \left(\frac{g}{\theta_o} \right) \frac{\Delta\Theta \Delta Z}{(\Delta V)^2}$$

within a given layer. Roach's fundamental assumption is that turbulence occurs within the layer as a response to these forces when they are acting to decrease Ri_L too rapidly within the layer. The role of turbulence is to work against these forces in an attempt to maintain Ri_L at a small but nearly constant value. At least one observational study (e.g., Kennedy and Shapiro, 1975) has shown that the rate of energy dissipation is nearly equal to the rate at which the larger-scale deformation field, associated with the three-dimensional meso- and synoptic-scale dynamics of the jet stream/frontal layers, is acting to increase the vertical shear within the layer. Since Ri_L is highly dependent on the vertical shear, this suggests that the basic assumption is not unreasonable. No such relationship is assumed to be relevant to layers where these large-scale processes are attempting to increase Ri_L.

Some Results

The tasks under the effort with the PROFS/CWP application have included verification of the formulation and resulting algorithms being used, calculation of a specific CAT risk (SCATR) index, and validation of expected regions of CAT against PIREPs. In those cases studied thus far the performance of the SCATR index, calculated using objectively analyzed rawinsonde data, has been quite encouraging. Since the formulation being applied is sensitive to the input data, it is anticipated that the performance of this index will improve as both data systems and analysis techniques evolve at PROFS.

Estimates of turbulent energy dissipation rates have been calculated for several cases of documented CAT. The grid data used for this purpose were provided by objective analysis of standard raw RAOBs on isentropic surfaces. The values of energy dissipation rates were consistent with what is to be expected from moderate-to-severe turbulence, taking into account some known minor limitations in the current analysis and computer algorithms.

Figure 1 shows a cluster of reported encounters (the locations were provided by C. Knable, United Airlines personal communication) which occurred between 0200Z and 0400Z, 29 October 1983, over central Colorado between about 28,000 and 32,000 feet. Also shown are isolines of the SCATR index calculated using analyzed 0000Z, 29 October 1983, data for the 356 K isentropic surface or approximately 32,000 feet near the area of the encounters. The locations of the horizontal grid points are shown by the little '+'s.

Figure 2 shows the SCATR index field for the 352 K (or 35,000 feet) surface for 0000Z, 28 November 1984, over the Wisconsin/Illinois area. Although their exact coordinates are not shown, numerous reports of moderate to severe CAT were reported over southern Wisconsin and northern Illinois within several hours

356K

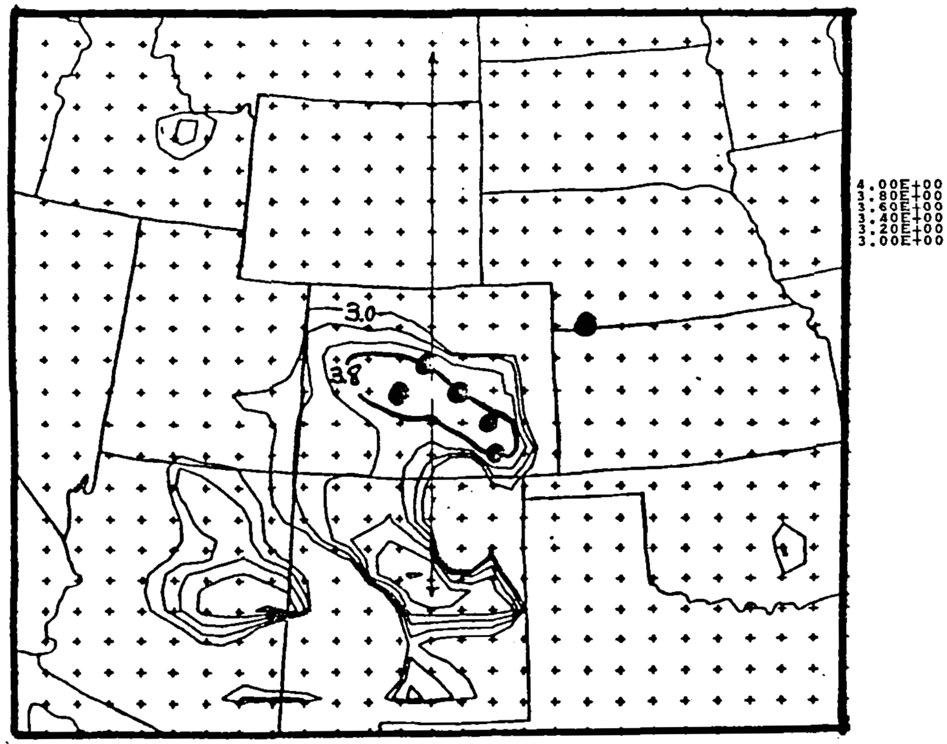

Figure 1. Cluster of CAT Encounters over Central Colorado between 28,000 ft. and 32,000 ft., 29 October 1983.

($= \log \overline{E}_L + 7$) 352K (~ 35,000 ft.)

$\overline{E}_L = \frac{(\Delta v)^2}{24} \Phi_L$ Calculated using RW data analyzed by NOAA/ERL/PROFS Central Weather Processor Project.

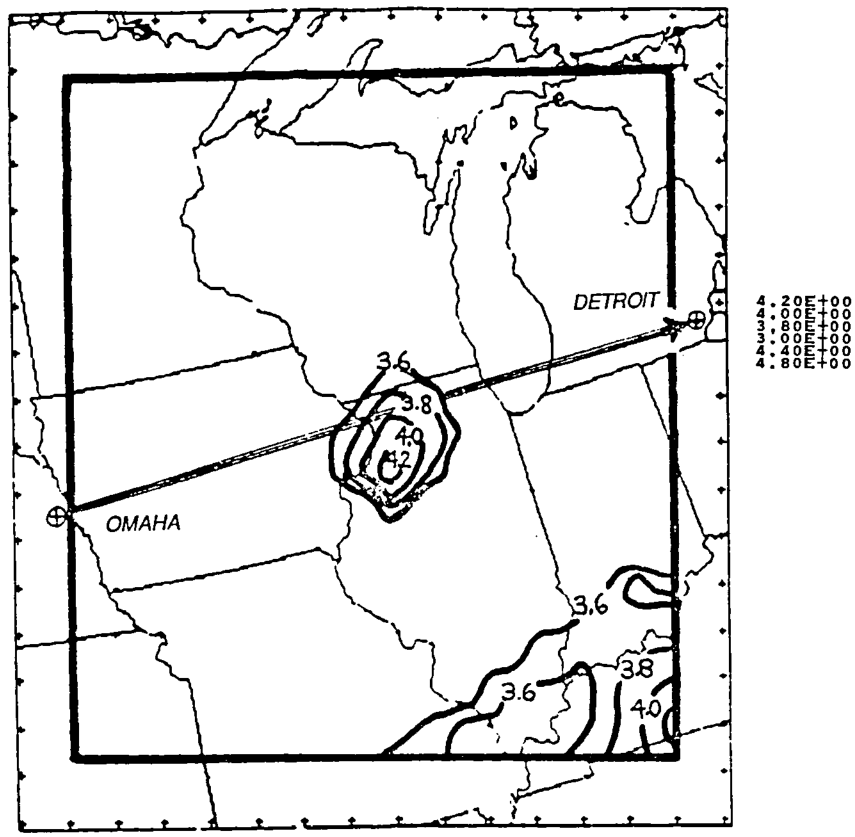

Figure 2. SCATR Index Field for 35,000 ft. on 28 November 1984, over Wisconsin/Illinois Area.

of this analysis time (J. Pappas, Western Airlines personal communication). A line is shown running diagonally from Omaha, Nebraska, to Detroit, Michigan. This is supposed to represent a hypothetical flight path between these two cities. Figure 3 shows the vertical cross section corresponding to this hypothetical flight path. This is a good illustration of the potential use of such an index. Provided with such a picture, an ATC meteorologist could suggest that flights along this path might use flight level 280 or 300 to minimize the possibility of encountering CAT.

Summary

The PROFS/CWP project has made a good start in applying a prototype algorithm of the SCATR index formulation into its software system. Several cases of documented commercial aircraft encounters with severe CAT have been examined. Consistent with its apparently sound physical basis, the performance of the SCATR index in these cases has been quite encouraging. Because of the important role of mesoscale deformation processes in CAT formation, the performance of the SCATR index should improve as the data base "enhancements", which increase the resolution in both space and time, are brought into the objective analyses. The SCATR index should also have applications in the forecasting of CAT potential using forecasted variables as input or by actually being built into the code of a short-term (3-12 hours) forecasting model.

While a great deal of progress has been made during the first nine months of the effort to provide a viable, objective CAT forecasting tool, considerable work remains before the SCATR index is ready to be used operationally in the ATC environment. At this time, all PIREPs of CAT are being archived along with RAOB data at PROFS/CWP in order to perform a statistical validation of the performance of the prototype SCATR index software system. Other tasks necessary in the development of the SCATR index technique to meet operational needs are planned; they include:

- Develop improved algorithm for optimum utilization of isentropically analyzed grid point data.

- Investigate forecasting applications of the SCATR formulation: CAT forecasting as well as its use in parameterizing short-term time dependent forecast models for CAT effects.

- Begin developing parameterizations for terrain (mountain wave) and organized convective systems for their role in exciting atmospheric gravity waves; thus increasing CAT intensity.

- Evaluate the performance of the SCATR index for effect of data "enhancements" once they become operational.

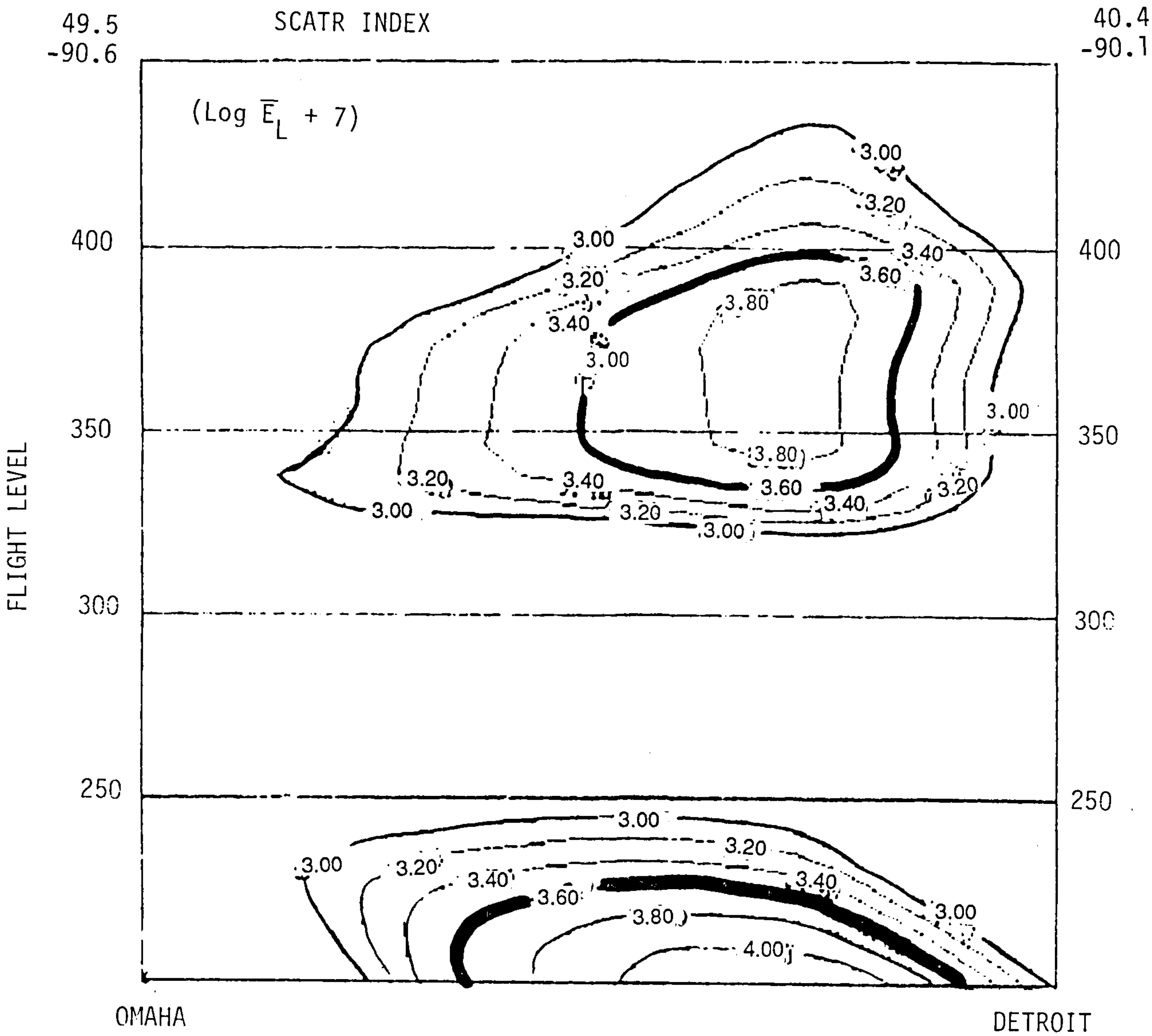

Figure 3. Vertical Cross-section Corresponding to a Hypothetical Flight Path between Omaha and Detroit.

- Compare residual and "direct" total energy dissipation within individual parcels. A statistical analysis will be used to correlate these two independent values. It is hoped that these calculations can be performed using data obtained during the GALE field study.

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