Progress in Clear-Air Turbulence Research and Forecasting

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#54

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ABSTRACT

A brief description and summary of prelimi-
nary findings of Project TOPCAT will be given.
This project consisted of clear-air turbulence
(CAT) measurement flights executed by a special-
ly instrumented Canberra aircraft over South-
east and Central Australia. The research pro-
gram was initiated in order to augment our know-
ledge on the detailed structure of the upper
troposphere and lower stratosphere in view of
the requirements for supersonic transport opera-
tions.

Since during this project the task was to
find rather than to avoid CAT, standard methods
of forecasting this phenomenon were put to a
critical test. Their inadequacy and possible
ways of improvement will be outlined in this
paper.

1. Project TOPCAT Research Flights

During the period July 21 to October 3,
1963, 41 research flights were carried out over
southeastern Australia by an instrumented
Canberra aircraft of the Royal Aircraft Estab-
lishment, (R.A.E.), Farnborough, England. The
purpose of these flight operations was to ob-
tain detailed spectrum distributions of atmos-
pheric gusts causing the phenomenon of clear-
air turbulence (CAT) in the upper troposphere
and the lower stratosphere. The gust recordings
obtained from these measurement flights are
still being evaluated at the RAE and at the
Aeronautical Research Laboratories of the Aus-
tralian Department of Supply. Results should
be forthcoming.

In support of these research flights, CAT
forecasts had to be made under the consideration,
that the aircraft should be dispatched into
regions of expected turbulence in order to ob-
tain gust records. As it turned out, this ob-

jective provided a possibility of stringently
testing present CAT forecasting methods, and of
implementing new forecasting procedures where
required.

2. Present Status of CAT Information

From past experience it has become a well
established fact, that CAT is not necessarily
tied to superadiabatic conditions and convective
vertical motions as they may exist in parts of
the troposphere. CAT is frequently encountered
at and above tropopause level (Fig. 1) and with-
in the "jet-stream front", a stable and baro-
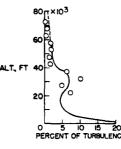clinic zone underneath the jet core (Fig. 2).

Fig. 1: Turbulence occurrence from U-2 data
(circles, Coleman and Steiner 1960),
and from data presented by Press and
Steiner (1958) (solid line), and by
Coleman and Stickle (1961) (dashed
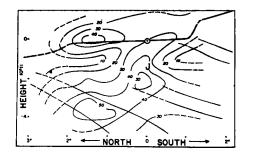line). (Rhyne and Steiner, 1962).

Fig. 2: Mean distribution of turbulent flying time (CAT) in per cent of total flying time for nine Project Jet Stream flights 1956-1957. T = position of jet core. Horizontal distance from jet core in degrees of latitude, vertical distance in 10^3 feet. Heavy line indicates tropopause. Stable layers are marked by sloping solid and dashed lines. (Sasaki 1958)

From close correlations between orographic features such as ranges of mountains or hills, coastlines, etc., with CAT occurrence in the upper troposphere and lower stratosphere (Clodman et. al. 1961) one was able to conclude that gravity-type wave disturbances are one of the causes leading to CAT in a stable environment (Reiter 1963a). Evidence of the existence of such wave disturbances of the required wave length (order of magnitude of 200 m for a conventional jet aircraft) could be gathered from photogrammetric studies of cirrus undulatus (Reiter, Hayman 1962; Reiter 1962, 1963 b, c; Reiter, Nania 1964).

Theoretical studies (Helmholtz, 1888, 1889, 1890; Haurwitz 1941; Sekera 1948; Sasaki 1958; Panofsky and McLean 1964), may actually provide us with a physical "model" of CAT formation: Helmholtz waves below a certain critical wave length, or above a critical wave number forming along a temperature discontinuity with vertical wind shear, will amplify exponentially with time, thus leading to turbulence. This becomes evident from an instability criterion similar to Richardson's derived from the perturbation equations:

$$R = \Delta \rho - \frac{K \bar{\rho}}{2 g} (\Delta V)^2 \begin{array}{c} < \\ > \end{array} 0 \begin{array}{l} \text{unstable} \\ \text{stable} \end{array} \quad (1)$$

where $\Delta \rho$ is the density discontinuity across

the interface, ρ is the mean density Δ u is the vertical wind shear between the 2 layers under consideration, K is the wave number, and g the acceleration of gravity. The critical wave number, according to above expression would be

$$K = \frac{2 \Delta \rho}{\bar{\rho}} \cdot \frac{g}{(\Delta V)^2} \quad (2)$$

Richardson's original criterion

$$Ri = \frac{K_T}{K_M} \frac{g}{\theta} \frac{\frac{\partial \theta}{\partial z}}{\left(\frac{\partial V}{\partial z} \right)^2} \quad (3)$$

formally - but not dimensionally - appears to be very similar to expression (2).

(K_T is the exchange coefficient of heat, K_M the exchange coefficient of momentum). The ratio of these two coefficient has been assumed by Richardson to be 1. According to Petterssen and Swinbank (1947) a value of 0.65 seems to be more likely.

Richardson's criterion has not given unambiguous correlations with CAT, mainly because critical values have been evaluated over too deep an atmospheric layer to be of significance for the meso-structural "sheets" in which CAT seems to occur.

This physical "model" of CAT may be extended to supersonic transport (SST) operations, considering the greater wave lengths of wave disturbances, to which this aircraft will respond. In addition to the input from alternating up and down drafts one should consider the effect of discontinuity surfaces in temperature which may be warped into a wave-like pattern. If a SST "skimmed" along such a discontinuity surface, a periodic change in Mach number may result in equivalent changes in the drag coefficient and consequently lead to CAT without a wind-generated cause (Reiter 1964a,b; Webb, 1963).

Statistical approaches in CAT research (Colson 1962, 1964) have tried to establish correlations between atmospheric flow parameters and patterns and the occurrence of turbulence. It has been found that combinations of jet streams and upper troughs, and regions of combined strong vertical and horizontal wind shears are prone to develop CAT (George, 1961). It has been mainly on the strength of statistical findings that routine forecasting techniques for CAT have been developed.

3. CAT Forecasting Techniques

A method developed by George (1961) has been accepted widely for CAT forecasting. It is based on the assumption that a combination of strong horizontal (> 50 kts /150 nautical miles) and vertical wind shears (6 kts/1000 ft.) is able to generate CAT. A wind speed of at least 60 knots should be present in the CAT region. This method usually produces satisfactory forecasts near the "jet-stream front" of a well developed jet stream, where strong shears are concentrated within a stable and baroclinic layer. So, for instance, of the CAT cases shown in Fig. 3., the ones over the Alleghenies would have been predicted all right. As may be seen from the cross sections of Fig. 4, 5 and 6, turbulence is encountered in the stable region underneath the jet core. Scalar wind shears, both horizontal as well as vertical, are appreciable in this region, while the wind direction stays rather uniform throughout the upper troposphere.

Fig. 4: Cross-section of potential temperature (degrees absolute) through the atmosphere from Sault Ste. Marie, Michigan (SSM), to Cape Hatteras, N. Carolina (HAT), 13 April 1962, 00 GCT. Stable layers and tropopause are marked by heavy lines. CAT in the vicinity of the cross-sectional plane: open inner circles -- light CAT; half-black inner circles -- moderate CAT; black inner circles -- severe CAT. The black portions of the outer rings indicate the time of CAT observation (plus or minus 6 hours from map time shown as black semi-circles to right or left of inner circle).
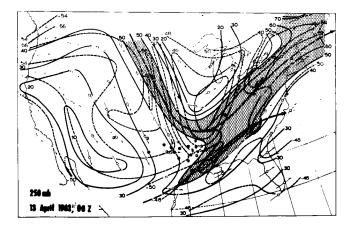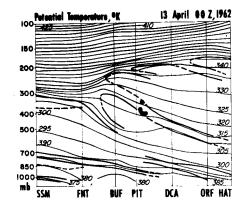

Fig. 3: Isotachs (solid lines, heavy numbers, mps) and isotherms (dashed lines, light numbers, centigrade) of the 250-mb surface for 13 April 1962, 00 GCT. Regions with speeds > 50 mps are shaded. Half-filled circles stand for reports of moderate CAT, heavy dots denote severe CAT. (Numerous reports of light CAT have been omitted). Wind directions at reporting station are indicated by arrows. Jet axes are shown by heavy dashed lines and arrows.
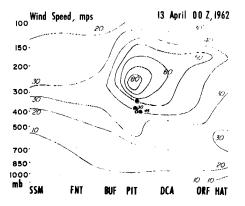

Fig. 5: Same as Fig. 4, except cross section of wind speeds (mps). Region with speeds > 60 mps are shaded.
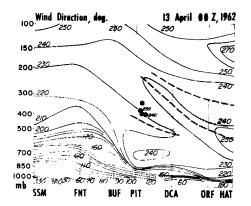
Fig. 6: Same as Fig. 4, except cross section of wind direction (degrees). Areas of backing and veering of wind with height in CAT region are indicated by different hatching.

There may be a slight disadvantage to this forecasting method as it is presently employed: It extends the air space for which CAT warnings a are issued, to 7000 ft. above and 3000 ft. below the layer in which critical shears are observed. Normally such deep air spaces cannot be avoided under the present Air Traffic Control (ATC) system.

4. Forecasting Techniques Employed During Project TOPCAT

During the first six weeks of Project TOP-CAT, when CAT forecasts were made following established routines (Spillane 1964) it became evident that the CAT criteria employed were not stringent enough. Apparently there is a difference in the skill score for forecasts made in order to avoid rather than to search for CAT. The two standards of measure could, of course, be combined into one, if CAT forecast but not encountered would be counted as failure, the same as CAT not predicted but encountered.

During the second half of the program, it was decided to place more emphasis on the meso-structure of the atmosphere in predicting CAT. The skill score improved accordingly by more than one order of magnitude (Reiter, 1964c).

The CAT forecasts were based upon the following considerations: Since horizontal wind shear hardly ever is of a magnitude to produce turbulence except for very special conditions (Clodman et.al., 1961) it was abandoned as a forecasting tool. Shallow stable and baroclinic layers were searched for instead, since they are the primary reason for the existence of hori-

zontal shears, and -- in combination with vertical shears -- would provide the physical setup for the formation of gravity waves. Such stable layers usually may be detected fairly easily from radiosonde records. Difficulties inherent in the rather sparse upper air network over Australia were in part overcome by careful analysis for time continuity. It should be mentioned at this point, that the smoothing of vertical temperature profiles, permissible under present coding regulations, obliterates some of the shallow stable layers which may be of importance, especially in the upper troposphere near jet streams.

Vertical vector wind shear across these stable regions was taken as a second criterion. This vector shear could be produced either by a scalar increase of wind with height (see Fig. 5) or by a sharp turning of wind through a shallow layer. The latter situation was encountered several times over Australia during the second half of Project TOPCAT. It unfailingly produced CAT, even with winds only of the order of 30 kts. The criterion of a minimum speed of 60 kts, therefore, was abandoned for those cases where vertical shear was produced by turning of wind with height rather than by a linear increase without directional changes. A classical case of this kind over the United States, although with stronger winds, is presented in Figs. 7, 8, and 9. The
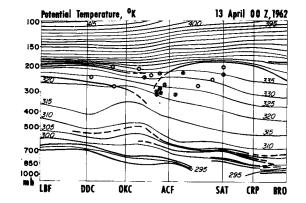

Fig. 7: Same as Fig. 4, except cross-sectional plane extending between North Platte, Nebraska (LBF), and Brownsville, Texas (BRO).
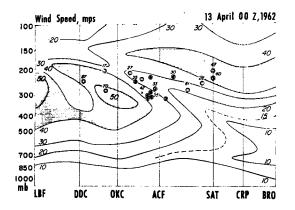
4

Wind Speed, mps   13 April 00 Z,1962

Wind Direction, deg.   13 April 00 Z,1962

Fig. 8: Same as Fig. 7, except cross-section of
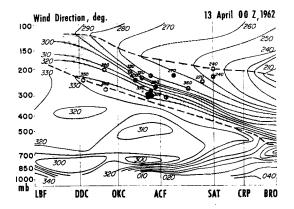wind speeds (mps). Regions with speeds
> 40 mps are shaded.

Fig. 9: Same as Fig. 7, except cross-section
of wind direction (degrees). Areas
of backing of wind with height in
CAT region are indicated by shading.

cases of CAT shown in these cross sections occur
in the region of merging between two jet branches
(Fig. 3). As may be inferred from this case
study, the northern jet branch actually "dips"
underneath the southern one. The rapid turning
of wind with height, therefore, becomes an in-
dicator of differential temperature advection
(Schwerdtfeger and Radok, 1959). This, appar-
ently, favors the formation of stable and baro-
clinic zones, which -- because of the existing
vector wind shear -- may become subject to
gravity-wave formation.

With the rather small number of research
flights available, no accurate lower limits can
be placed at this time on the vertical vector-
wind shear required to produce CAT. It appears,
however, the George's criterion for a scalar
shear of 6 knots/1000 ft. may apply to vector
shear as well.

5. Suggestions for Future Research

Our meteorological sounding system offers
considerably more information than is presently
used in routine analysis and forecasting oper-
ations. Since CAT seems to be a phenomenon
associated with mesostructural details of verti-
cal wind shear and temperature the vertical wind
and temperature profiles measured by our sound-
ing systems should be scanned for such details.
This could easily be done by electronic computers.

Efforts should be made to establish a closer
correlation between observed CAT occurrence and
atmospheric layers rather than broad-scale fea-
tures in flow patterns. Such correlations should

help to overcome the difficulty of predicting
CAT in too deep an air space and in too wide a
region. With the employment of electronic
computers it is hoped, that critical values of
shear, stability and baroclinicity may be estab-
lished, and indices of CAT expectancy, perhaps
simular to the ones proposed by Panofsky and
McLean (1964) could be tested.

Measurement programs of CAT still have to
be considered an important tool in exploring the
physical nature of CAT. A preliminary study
during Project TOPCAT, employing smoke trails
in marking CAT regions, proved to be rather
promising. In one particular instance, such a
turbulent patch could be followed for 45 minutes
while drifting downstream with the wind. So far,
with only very few exceptions, CAT usually has
been considered a by-product to atmospheric
research flights. More knowledge on this phe-
nomenon could be obtained at smaller cost if it
were given a higher priority level in measurement
programs. Especially the mesostructure of the
stratosphere and its possible effect on SST opera-
tions are still in the stage of guesswork. De-
tailed measurements in this region should be of
great interest to the aeronatutical engineering
community as well as to meteorologists.

Last, but not least, a simple but effective
in-flight CAT warning system is still lacking.
Various techniques of ground-based radar detection
of possible CAT - bearing layers may be tech-
nically feasible, but rather costly to put into
operation. The possible effect of CAT on fast-
flying aircraft should provide enough challenge
for research on detection devices.

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