UNIVERSITY OF MELBOURNE

METEOROLOGY DEPARTMENT

Project TOPCAT

Meteorological Reports

MAY 1964

PROJECT TOPCAT - METEOROLOGICAL ASPECTS

Preface

by U. Radok
Reader in Meteorology
University of Melbourne

In the period between July 21 and October 3, 1963, 41 research flights were carried out by an instrumented Canberra aircraft of the Royal Aircraft Establishment (R.A.E.), Farnborough, England. The flights were made over southern Australia with the purpose of obtaining gust velocity and acceleration records of moderate to severe clear air turbulence (CAT) which could serve for a detailed power spectrum analysis. It was hoped also to find indications of the physical nature of CAT.

The research project quickly acquired the code name "TOPCAT". Apart from the R.A.E. the following agencies took part in the project: the Weapons Research Establishment and Aeronautical Research Laboratories of the Australian Department of Supply, the Australian Bureau of Meteorology, the Divisions of Meteorological and Radio Physics of the Commonwealth Scientific and Industrial Research Organisation, and the Meteorology Department of the University of Melbourne. The flight operations were led by Mrs. Anne Burns of the R.A.E. who during the most crucial stages of the project acted in close co-operation with Dr. E. R. Reiter of the Colorado State University, Fort Collins, U.S.A., (brought to Australia with the help of a grant from the Department of Supply to the University of Melbourne).

The initial stage of Project TOPCAT dates from preliminary discussions between Mrs. Burns and the writer at Farnborough in February 1961 and was taken up by preparations. While the general development of flight instrumentation and techniques proceeded at the R.A.E. with the assistance of an observer from the A.R.L., Mr. C. K. Rider, all available past information on clear air turbulence was assembled in Australia.

Shortly before the start of flight operations Mr. K. T. Spillane, then acting Head of the Bureau of Meteorology's Research Section, organised the meteorological support for the trials and prepared a study of the jet stream and of CAT models which determined both the forecast methods and to some extent the flight routines to be adopted. This study forms the first paper of the report.

The first phase of the actual trials lasted from July 21 until September 2. During this period the meteorological direction came from the Bureau of Meteorology's Divisional Office in Adelaide and was in the hands of Mr. E. Mizon who had the assistance of Mr. L. Mitchell in Adelaide and of Mr. Spillane's group (Mr. G. H. Sabin and Miss L. J. Armstrong) at the Research Section in Melbourne. The forecasts and flight appraisals for this period are discussed by Mr. Mizon in the second paper.

The final phase of the TOPCAT trials started on September 3 when Dr. E. R. Reiter of the Department of Atmospheric Science in the Colorado State University took over the meteorological direction of the trials following Mr. Mizon's transfer to Sydney. Working in constant close contact with both Mr. Mitchell at the Adelaide Divisional Office and with the R.A.E. flight team led by Mrs. Burns, Dr. Reiter introduced new forecast techniques which proved outstandingly successful. This stage of the trials is surveyed by Dr. Reiter himself in the last paper.

The three papers are presented as preliminary contributions to the full report on operation TOPCAT, to be published probably by the R.A.E. They are intended primarily for the use of participants while preparing their own reports, and no attempt has been made to reconcile such differences of opinion as emerged during or since the trials concerning the most suitable methods of forecasting CAT. Such a reconciliation is expected to come about with the detailed analysis of the TOPCAT data which in general hold out promise of a substantial advance in our understanding of clear air turbulence.

PAPER III

CLEAR AIR TURBULENCE MODELS AND FORECASTING FOR PROJECT TOPCAT, SECOND PHASE, SEPTEMBER 1 - 30, 1963.

by

Elmar R. Reiter

Colorado State University
Fort Collins, Colorado.

ABSTRACT

A short account is given of clear-air turbulence (CAT) forecasting models and procedures used in "Project TOPCAT", from September 1 through October 3, 1963. Some preliminary results from the project are communicated.

CLEAR AIR TURBULENCE MODELS AND FORECASTING FOR PROJECT TOPCAT, SECOND PHASE, SEPTEMBER 1 - 30, 1963.

by
Elmar R. Reiter.

(1) Introduction

During the period July 21 through October 3, 1963, special research flights known as "Project TOPCAT" were carried out by a Canberra jet aircraft of the Royal Aircraft Establishment, Farnborough. The purpose of these flights, which were conducted over South Australia, Victoria and New South Wales, was to detect clear air turbulence (CAT) and to obtain records on gust intensities and gust frequencies.

Since CAT usually occurs in small and shallow patches, thus constituting a microstructural phenomenon of atmospheric flow, its forecasting from the macro-meteorological measurements of the general rawinsonde system presents a number of difficulties. These difficulties were increased by the requirement, that moderate and severe CAT should be present in order to produce useable records for power-spectrum analysis, and by the lack of upper-air information over the vast regions of the Indian and the Southern Oceans, from which the jet-stream systems were approaching the area under aircraft surveillance.

In view of these problems, the CAT forecasts had to rely heavily upon turbulence "models" obtained from the northern hemisphere, especially from the Continental United States. The following preliminary report shall give a short summary of these models employed in routine CAT forecasting during the period mentioned above, of their relative advantages and drawbacks, especially under the conditions prevailing over Australia.

(2) Turbulence Expectancy

A number of statistical investigations of CAT from the Northern Hemisphere (for literature see Reiter 1960, 1961, 1962a, 1963a,b) indicate a sharp decrease of frequency of occurrence with increasing gust velocity. The following table summarizes some of these findings.

Table 1: CAT Expectancy

Source of Information	Altitude Range	CAT Intensity	Frequency of Occurrence
Clem (1957)	25,000-45,000 ft	light CAT moderate severe	19 % of all flights 12 % " " " 2 % " " "
Estoque (1958)	Maximum frequency at 250 mb	2 ft/sec 5 ft/sec 10 ft/sec	15 % of km flown 1.2% of km flown 0.15% of km flown
Hislop (1951)	25,000 ft	4 ft/sec 8 ft/sec 12 ft/sec	1 gust per 13 km 1 gust per 97 km 1 gust per 650 km
Hyde (1954)	to 49,000 ft	light to moderate	28 % of all flights
	to 36,000 ft	moderately severe	7 % " " "
	22,000 to 28,000 ft	very severe	0.2 % of all flights
Murray (1953)	400 to 200 mb	$\geq$ 0.1 g $\geq$ 0.2 " $\geq$ 0.3	37.4 % of all flights 4.9 % " " " 0.2 % " " "

Conditions over Australia offhand would let us anticipate lower frequencies of CAT than indicated in Table 1, due to the lack of appreciable orographic sources, which certainly contribute to CAT frequencies encountered for instance over the United States, especially over the Rocky Mountains and the Alleghenies, and due to the more zonal conditions of flow in the Southern Hemisphere which are only infrequently interrupted by the formation of deep troughs - also known to stimulate CAT formation (Colson 1962, Reiter 1962b). Large air mass contrasts which result in the formation of stable layers and of large vertical wind shears also seem to occur less frequently and to a lesser degree of intensity over Australia than over the United States, thus providing less chance for the formation of shearing gravity waves as a possible source of CAT.

On the other hand, it will have to be borne in mind, that most of the data compiled in Table 1 were obtained either from routine commercial flights, or from flights exploring the

nature and structure of jet streams, rather than of CAT,
while the present research flights were scheduled to search for CAT and therefore were dispatched into regions of anticipated CAT formation. It was hoped that this procedure would at least in part offset any effects of the peculiarities of the jet-stream over Australia upon CAT frequency of occurrence. This apparently was the case because out of 15 special flights 6 produced usable records of moderate turbulence. During the flight of the morning of September 24 one moderate to severe gust was encountered which unfortunately remained unrecorded (see Table 2).

Table 2: CAT encounter during TOPCAT flights

Date	Forecast of CAT	Aircraft flight Yes	Aircraft flight No	CAT debriefing
4 Sept. 63	Yes	Yes		Moderate to strong
5	No	Yes		No
6	Yes	Yes		Light
10	Not specified		No	------
11	Yes	Yes		Light
12	Yes	Yes		Moderate
13	Yes	Yes		Very light
14	No	Yes		No
16	Yes	Yes		Perceptible to slight
17	No	Yes		Slight
18	No	Yes		Very slight
23	Yes	Yes		Light
24 morning	Yes	Yes		Light
24 afternoon	Yes	Yes		Light
25	Yes	Yes		Slight
26	Yes	Yes		No
27	No	Yes		No
30 morning	Yes	Yes		Light to moderate
30 afternoon	Yes	Yes		Moderate to severe
1 October 63	No	Yes		No
3 morning	Yes	Yes		Light to moderate
3 afternoon	Yes	Yes		Light to moderate

The application of CAT models to forecasting therefore increased the odds of encountering moderate CAT to about 40% of all flights as compared to approximately 10 to 12 % according to Clem (1957) and Hyde (1954), and approximately 5% according to Murray (1953). Although the number of research flights should not be considered sufficient to warrant a valid statistical statement of this kind, the odds would increase even higher if one eliminated those four flights from consideration, in which CAT was not anticipated in the forecast, and not found either.

From the foregoing we may draw the following conclusions:

(i) Some of the CAT models applied in arriving at CAT forecasts were able to increase the odds of encountering turbulence significantly above the expectancy for random flights.

(ii) A certain relationship between macro-meteorological flow patterns in the jet stream region and micro-scale disturbances, as evident from the occurrence of CAT, which has been assumed in arriving at these forecasting models, evidently is present in the atmosphere, but does not suffice to pinpoint areas of CAT precisely in advance.

An attempt to compare the percentage in miles flown in CAT with Estoque's or Hislop's findings presented in Table 1 has not been made, because of the peculiar search pattern which was flown once a CAT patch has been found and marked by smoke, penetrating the same CAT area again and again. This search pattern evidently biased the data in fovour of too much CAT when compared with the data presented in Table 1.

(3) Clear-air Turbulence Models

(a) CAT - Forecasting from Horizontal and Vertical Shear Parameters

A technique of forecasting CAT, which has been developed by George (1961) was used during the trial period July 21 through August 31. This technique in essence looks for areas in which the horizontal wind shear exceeds 50 knots per 150 nautical miles and in which the vertical shear simultaneously reaches values in excess of 6 knots/1,000 ft. Furthermore, wind speeds should be greater than 60 knots if CAT was to be expected in these areas. It was assumed that CAT may occur in a layer which extends from 3,000 ft below to 7,000 ft above the layer in which the shear requirements mentioned above are met.

In searching for moderate to severe CAT, this forecasting technique did not prove to be very successful. While it certainly may merit success in avoiding certain regions of possible CAT, it does not produce sharply enough defined regions within which an aircraft of limited range might successfully explore the presence of turbulent patches. The reason for this failure may be sought in several causes:

(i) The vertical extent of the layer in which CAT might occur according to the predictions given by this technique is too deep to offer more than a mere-chance encounter by an aircraft searching for turbulemce. Conversely, one might question the practical value of avoiding CAT by closing down an excessively deep airspace, when observations seem to indicate that turbulence actually occupies relatively thin layers.

(ii) It is difficult to see, how horizontal shear which usually is at least two orders of magnitude smaller than vertical shear, could provide an immediate physical input into turbulence generation other than in a few special cases (Clodman, Morgan and Ball, 1961). Instead of this, the presence of relatively strong horizontal shears should be taken as an indicator of a stable baroclinic zone, in which strong wind shears tend to be concentrated, intersecting the constant-pressure level under investigation. A direct search for such stable layers with vertical wind shears concentrated in them would therefore appear more fruitful.

(b) CAT in Stable, Shearing Layers

Under the assumption, that CAT may be caused by the presence of gravitational shearing waves along a stable "interface" or transition layer, several flights were dispatched into regions where such wave formation might meet favourable conditions (see Appendix).

If stable layers were reported in the upper troposphere of the Woomera or Adelaide soundings taken prior to flight time, the shears computed from the wind reports at the standard levels on either side of such stable layers were assumed to be largely concentrated within these stable layers rather than to be spread out uniformly over the depth between the two reporting standard levels.

Using the equation for gravity waves with critical wave length L_c, with vertical density discontinuity and vertical shear

$$L_c = \frac{\pi}{g} \frac{(\Delta u)^2 . T_o . T_1}{\Delta T . \bar{T}} \qquad (1)$$

missions. Δu and ΔT in equation (1) and Table 3 give the vertical shear and vertical temperature discontinuity assumed to exist across the interface. The subscripts o and 1 refer to the lower and upper layer respectively. $\bar{T}$ is the mean temperature of the two adjacent layers.

Table 3:
Vertical wind shear Δu (m/sec) for different temperature discontinuities and critical wave lengths at an interface.

ΔT	L_c = 200 m	L_c = 100 m	L_c = 50 m
2°	2.3 m/sec	1.6 m/sec	1.2 m/sec
4°	3.3	2.3	1.6
6°	4.0	2.9	2.0
8°	4.7	3.3	2.3
10°	5.2	3.7	2.6

The fact that microstructural details seemingly responsible for waves of "CAT lengths canot be assessed directly from the available soundings, thus, introduces a large factor of chance into the actual observation of CAT within microstructural stable and shearing layers.

If no such layers were evident in the upper troposphere, exploratory flights were scheduled in the vicinity of the tropopause level which in first approximation was considered as a discontinuity of essentially the same qualities as described by equation (1).

From evidence obtained over the United States (Reiter,1962c, 1963c; Reiter and Nania,1963)the significance of vertical vector shear, produced by a sharp turning of wind with height, in the generation of CAT with wind speeds much less than 60 knots was realized. These areas would not normally be considered in forecasts based on George's method, mainly because of the weak winds.

Such regions of relatively large vertical vector shear occur frequently in the entrance region of a well developed jet maximum, where two jet fingers - one coming from the north-west, one from the south-west - are merging. CAT was found to occur along the convergence line between these two jet fingers in a region of light winds, and within a stable layer showing a sharp turning of wind with height (see Appendix). The fact, that a turning of wind in CAT regions is associated with differential temperature advection has been pointed out by Schwerdtfeger and Radok (1959). From detailed CAT case studies over the United States it appears that the region in which turbulence is observed shows a tendency towards stabilization, with cold air sliding in underneath warm air.

Again, equation (1) and Table 3 may serve in establishing a "model" for CAT occurrence in the vicinity of these convergence lines. The atmosphere in the stable layers associated with these convergence lines is apt to show many more small-scale details than would appear from the teletype transmissions. Danielsen (1959) has commented on such detailed structure, which also became evident from the research-flight data of Project Jet Stream (Reiter, 1962a).

Such details in the vertical temperature structure might be explained by large-scale mixing processes between adjacent air masses, occurring under quasi-adiabatic conditions of flow, thus resulting in a "sandwiched" sequence of shallow stable and nearly adiabatic layers in this transition zone, rather than in a smooth and uniform lapse rate as it might appear from the teletype reports. Detailed wind measurements as have been taken over the United States with the FPS - 16 radar indicate the presence of small-scale vertical shearing layers at the same levels where shallow stable layers are indicated from radiosonde measurements (Reiter 1963d).

Wind measurements taken by the Canberra aircraft during Project TOPCAT seem to indicate, that the rapid turning of wind with height encountered in the vicinity of the CAT-bearing convergence lines takes place in relatively shallow layers. The appearance of some of the smoke trails released for the purpose of identifying turbulence patches corroborates this conclusion: some of the smoke puffs retained an almost spherical cross-section while others were distorted into quasi-horizontal drawn-out "sheets", (see Appendix, Flight of 3 Octover, afternoon).

Evidence from Project Jet Stream flight analyses (Reiter, 1962a; Reiter, Lang, et al.,1961) as well as from serial balloon ascents tracked by FPS-16 radar (Reiter 1963d) indicates that meso-structural details in the wind and temperature fields may retain their identity for hours and over hundreds of miles along the path of advection. Assuming that the small-scale phenomenon of CAT draws its perturbation energy in essence from meso-scale disturbances, it would not surprise that some of the turbulent patches encountered during Project TOPCAT seemed to be rather long-lived. The flight of September 12 (see Appendix) presented the most interesting data with this respect: near Lake Dutton, S.A., the aircraft encountered a small patch of moderate CAT, approximately 15 miles in diameter, embedded in nearly laminar surrounding flow. The patch was marked by a smoke trail and was then penetrated again and again from different directions. After following the patch for approximately 45 minutes, while it travelled in the prevailing upper current over almost 100 miles, preserving its identity as well as its general level of turbulence intensity, the measurements had to be discontinued for lack of fuel. On this occasion, the observation of the smoke trails seemed to indicate a wave pattern with wave lengths estimated to approximately 50 to 100 yards in turbulent flow. There also seemed to be a marked difference in smoke trail appearance between turbulent and laminar flow (see Appendix).

It is doubtful, whether or not the measurements taken during this flight will resolve the question as to the efficiency of frictional dissipation of turbulent kinetic energy in the free atmosphere. The final interpretation of data will have to consider, however, that CAT encountered in this and similar, but less striking, other cases, was surprisingly long-lived, thus suggesting either a continuous transfer of perturbation energy from meso-structure through CAT to frictional dissipation, or else a CAT mechanism which consumes only very small amounts of perturbation energy, thus being able to maintain itself without drawing a large amount of energy from mesostructural disturbances. This would be the case if "undulance" in the form of gravity-type wave disturbances along internal density discontinuities rather than "turbulence" were the main cause for the bumpiness observed by the aircraft.

(c) Orographic Effects on CAT Occurrence

Most of the research flights of Project TOPCAT were staged from the Royal Australian Air Force Base at Edinburgh near Adelaide, because it was felt that the Mount Lofty and Flinders Ranges extending in a north-south direction approximately along 139°E might contribute favorably towards higher

CAT frequencies in this region (Clodman et al., 1961). Further examination of the flight data will be necessary before an estimate of the actual significance of these mountain ranges in CAT generation can be made.

From cloud studies to the lee of the North-American Rocky Mountains it was found that small-scale wave perturbations at cirrus level with wave lengths of approximately 100 m as one would expect them in CAT are at times generated simultaneously with larger-scale lee waves as described by Scorer's (1949) theory. One might expect, therefore, that weather situations conducive to lee wave formation might also harbor a certain amount of CAT.

Corby and Wallington (1956) have studied the effect of size and shape of a mountain range upon lee-wave formation. The vertical displacement ξ_z of air flowing through a lee-wave pattern is given by

$$\xi_z = 2\pi h\, b\, e^{-k\, b} \left(\frac{U_1}{U_z}\right) \Psi_{z,k} \left(\frac{\partial \Psi_{1,k}}{\partial k}\right)^{-1} \sin k\, x \qquad (2)$$

where k is the lee-wave number, U is the horizontal wind speed, Ψ is the stream function satisfying the equation

$$\frac{\partial^2 \Psi}{\partial z^2} + \left(\ell^2 - k^2\right)\Psi = 0 \qquad (3)$$

The Scorer Parameter ℓ^2 is given by

$$\ell^2 = \frac{g\,\beta}{U^2} - \frac{1}{U}\,\frac{\partial^2 U}{\partial z^2} \qquad (4)$$

g stands for the acceleration of gravity, $\beta = \frac{1}{\theta}\frac{\partial \theta}{\partial z}$ indicates vertical stability, with θ symbolizing potential temperature, h is the height of the mountain ridge, and b its "half width". The shape of the ridge is assumed to be

$$\xi = \frac{h\, b^2}{b^2 + x^2} \qquad (5)$$

where x is the horizontal distance from the crest.

As is evident from equation (2) the effectiveness of a mountain range in generating lee waves depends to a certain extent upon its shape. In the case of the Mount Lofty ranges, which rise out of the ocean, the frictional differences between land and sea will amplify their orographic influence especially with southwesterly winds blowing from the Bight. Such winds will have to be expected with the passage of a well-developed trough over Adelaide associated with a surface front.

Postfrontal conditions also are likely to yield a decrease of Scorer's parameter (equation (4)) with height up to tropopause level, a condition which is required for lee-wave formation.

The weather situation of September 4 (see Appendix) constituted an ideal case meeting both conditions outlined above. The flight which was scheduled along the tropopause level encountered moderate to strong turbulence near Stonefield. Unfortunately, there was not enough fuel left to explore the full extent of the turbulent area, especially whether or not it continued upstream from the mountain range.

Since most of the CAT search flights were carried out in the general vicinity of the Flinders and Mount Lofty ranges, the possibility of terrain effects cannot be ruled out except for the case encountered over Lake Dutton described earlier. The turbulent region in this instance was encountered well upstream of the mountain range over flat terrain. Its drifting with the wind during such an extended period of time also suggests a non-orographic nature of this turbulence patch.

(4) <u>Conclusions and Recommendations for Further Research</u>

(a) <u>Evaluation of Forecasting Techniques</u>

From the foregoing it appears that the concept of CAT being a phenomenon essentially associated with vertical stability and vector-wind shear is quite valid. This would suggest a generating mechanism for CAT similar to the formation of travelling gravity waves. Forecasting in order to <u>encounter</u> rather than to <u>avoid</u> CAT apparently demands a more specific concept of the physical nature of CAT than is generally available from correlation of turbulence reports with large-scale weather patterns. It seems, however, that only flight programs as the ones carried out during Project TOPCAT are able to put to a test the "skill" of any CAT forecasting technique. In the end, a technique should only be considered satisfactory if it indicates the areas of possible CAT and excludes those which will not contain turbulence. This becomes essential in crowded air spaces, as for instance in some regions of the United States or Europe, where certain areas cannot be avoided by air traffic, but a choice of a suitable flight level may at least alleviate the hazard of encountering strong CAT.

Furthermore, the stability and shear conditions as observed in the upper troposphere and lower stratosphere during Project TOPCAT leading to certain CAT perturbations of atmospheric flow which yet will have to be evaluated from the aircraft records, may easily be compared with conditions of flow at higher levels of the stratosphere, where supersonic transport aircraft will be operating. It appears to be of importance, therefore, that the CAT forecasts made for Project TOPCAT and described above could be verified reasonably well, thus validating the physical model upon which they were based. This model now may be adjusted easily to higher levels of the atmosphere.

(b) Smoke Trail Technique

Originally it has been suggested to use smoke trails as indicators of the atmospheric disturbances causing CAT. Some visual observations of these trails revealed a marked difference in smoke trail appearance between laminar and turbulent flow. Several of the severer "bumps" seemed to manifest themselves in a steplike discontinuity along the smoke trail. On at least one occasion the formation of rather short (50-100 yards) waves along the extent of the whole trail has been reported (see Appendix).

As a whole, however, the photographical techniques did not prove to be very satisfactory. A 34 mm cine camera with black and white film was used for smoke trail photography. Due to the rather strong haze which was frequently observed in the upper troposphere, the smoke puffs did not provide sufficient contrast to give useable photographs. It is suggested, therefore, that experiments be carried out under varying sky and visibility conditions, with differently coloured smoke and with colour film. A camera somewhat lighter and easier to handle than the rather bulky cinema camera might be of advantage.

While the smoke trails left something to be desired in revealing the kind of perturbations responsible for CAT, they proved to be invaluable for marking turbulent patches and identifying them on subsequent traverses. Only in this fashion could the long-lived nature of some of the turbulent areas be established with certainty.

(c) Suggested Avenues of Future Research

While it will be possible to gain some idea of the dimensions of turbulent patches, and follow their drift, from the data obtained during Project TOPCAT, the question of the large scale extent of turbulent regions is still left open. As soon as the research aircraft spotted CAT worth while to investigate it commenced to fly additional traverses through the same turbulent patch, in accordance of the objectives of this measurement program. In addition to knowing the structure of individual patches it would be of interest, however, to measure the overall extent of turbulent zones and their location and orientation in space. It is recommended, therefore, that serious consideration should be given to a simultaneous two-aircraft survey of CAT regions. One aircraft with essentially the same instrumentation as Project TOPCAT's Canberra would carry out measurement flights through individual CAT patches in order to assess their physical nature. A second aircraft, preferably equipped with automatic wind calculating and recording equipment, would simultaneously explore the atmospheric layers in and adjacent to the CAT layers along relatively long and straight flight legs. This second aircraft should also keep an accurate log on position and intensity of encountered CAT. It would not necessarily have to be equipped with expensive gust recording equipment however. A combination of both sets of data should yield an even deeper insight into the physical nature of CAT than is possible so far.

REFERENCES

Clem, LeRoy, H. 1957 Clear-air turbulence from 25,000 to 45,000 feet over the United States. Air Weather Service, Tech, Rept. No. 105-147.

Clodman, J., G.M.Morgan, Jr., & Ball, J.T. 1961 High-level turbulence. Air Weather Service Tech.Rept. 158

Colson, DeVer, 1962 Analysis of special clear-air turbulence program for March 1962. Paper given at 4th Conference on Applied Meteorology. Hampton, Va., Sept. 10-14, 1962.

Corby, G.A. & C.E.Wallington, 1956 Airflow over mountains: the lee-wave amplitude. Quart.Journ.Roy.Meteor.Soc., 82: 266-274.

Danielsen, E.F. 1959 The laminar structure of the atmosphere and its relation to the concept of a tropopause. Archiv Meteor.Geophys., Bioklim., Ser.A, 11(3): 293-332.

Estoque, M.A. 1958 Some characteristics of turbulence at high altitudes. Geophys.Research Directorate, Air Force Cambridge Res. Lab., Res. Note No. 4.

George, J.J. 1961 Prediction of clear-air turbulence. Shell Aviation News, No. 273, March 1961.

Hislop, G.S. 1951 Clear-air turbulence over Europe. J.Roy. Aeronaut. Soc., 55:185-225.

Hyde, E.A. 1954 High altitude air turbulence. Flight, 65: 492-493.

Murray, R. 1953 The upper troposphere and lower stratosphere near jet streams: an examination of observations made by the Meteorological Research Flight, Farnborough. Meteor.Res. Paper No. 813.

Reiter, E.R. 1960 Turbulenz im wolkenfreien Raum (Clear-Air Turbulence). Berichte d.Deutsch.Wetterdienstes, No. 61, 42 pp.

———— 1961 Meteorologie der Stahlströme (Jet Streams). Springer Vienna, 473 pp.

———— 1962a Die vertikale Struktur des Strahlstromkernes aus Forschungsflügen des Project Jet Stream. Berichte d.Deutsch.Wetterdienstes, No.80, 30pp.

———— 1962b The atmospheric microstructure and its bearing on clear-air turbulence. A preliminary report. Colorado State University Atmospheric Science Tech.Paper No. 39.

Reiter, E.R. 1962c A case study of severe clear-air turbulence. Colorado State University, Atmospheric Science Tech.Paper No. 30.

---------- 1963a Jet-Stream Meteorology, University of Chicago Press, 515 pp.

---------- 1963b Nature and observation of high-level turbulence, especially in clear air. Colorado State University, Atmospheric Science Tech.Paper No. 41.

---------- 1963c Occurrence and causes of high-level turbulence. Final Report. Colorado State University, Atmospheric Science, Tech.Paper No. 45.

---------- 1963d Exploratory study on the physical nature of certain mesostructural details in vertical wind profiles. Colorado State University, Atmospheric Science, Tech.Paper No.47, 17 pp.

----------, H.Lang, R.Mook, G.Wendler 1961 Analyse dreier Forschungsflüge des Project Jet Stream. Archiv Meteor.Geophys., Bioklim., Ser.A, 12:183-224.

----------, & A.Nania 1963 Jet-stream structure and clear-air turbulence. To be published.

Schwerdtfeger, W. & U.Radok 1959 Hodograph analysis as applied to the occurrence of clear-air turbulence. J. Meteorol., 16: 588-592.

Scorer, R.S. 1949 Theory of waves in the lee of mountains. Quart.Journ.Roy.Meteor.Soc., 75:41-56.

PROJECT TOPCAT

Australia 1963

FORECASTING AND DEBRIEFING LOG

by E. R. Reiter.

Wednesday, 4th September, 1963:

Return flight Sydney - Adelaide - Woomera.

Scheduled for flight level 27,000 feet along sharply defined tropopause over and to lee of Flinders Range.

Passage of cold front preceded flight by short time period.

Debriefing

Moderate to strong CAT was actually encountered along range. Smoke trail was released and flown through again. CAT was encountered at same spot in Lagrangian system.

Very good recorder trace obtained from this flight.

Thursday, 5th September, 1963:

Flight scheduled at tropopause (28,000 feet) along Flinders Range. Strong cyclonic shear indicated from map south of Adelaide. Not much CAT expected, since lower levels are rather stable.

Debriefing

No CAT encountered.

Friday, 6th September, 1963:

Flight scheduled along tropopause and along 140 degrees between coast and Woomera. Zone of two merging jet fingers south of Woomera might give some CAT.

Debriefing

Very light CAT encountered. A few cloud photos taken.

Monday, 9th September, 1963:

No flight scheduled, because of poor WX situation. Ridge between two jet maxima over area.

Tuesday, 10th September, 1963:

WX situation indicates strong jet moving into area (Adelaide 31,000 feet, 128 kts; 36,000 feet, 156 kts). Jet seems to split between coast and Woomera in a pronounced delta situation.

Woomera sounding shows stable layer 27-31,000 feet. Adelaide shows rather stable conditions throughout troposphere. Dry layer on top of moist layer commences at 24,000 feet. Stable conditions within the dry layer may be indicative of strong sinking motion.

Fairly sizeable vertical shears over Adelaide in stable layer, also horizontal cyclonic shears south of Adelaide.

Flight Plan

Adelaide - Mount Gambier 24,000 feet.

Mount Gambier - 140 degrees E - Woomera 27-31,000 feet.

Woomera - Adelaide 41,000 feet on top of an adiabatic layer.

Debriefing

No flight. Engine trouble.

Wednesday, 11th September, 1963:

WX situation: large jet with strongest winds at about 36,000 ft (160 kts). Jet shows strongly pronounced splittings tendency over Adelaide.

Woomera sounding 2000Z shows many stable layers below 300 mb, tropopause at 200. Not too favourable for orographic turbulence.

Adelaide sounding 2300Z shows stability, too, but less than Woomera. Tropopause at 308 mb. Strongest shear (vertical) actually above tropopause.

Flight Plan

Take off 11.15 for Woomera, for Jindivik exercise. Flight level forecast 26-31,000 feet would lead into tropopause region. However, not much shear.

Return flight 3.00 p.m. - Woomera - Mount Gamb
140 degrees E fl

was not pursued, however, due to scheduled Jindivik exercises. Smoke was released in light CAT region near Adelaide on a northerly heading. Plane made 360 degree circle. No CAT on second pass. Pilot (Flt. Lieutenant Morrison) noted, however, that smoke had spread out in a rather thin sheet sloping upward to the east at an angle of approximately 15 degrees. No further exploration due to Jindivik exercise.

Thursday, 12th September, 1963:

Strong jet core (approx. 225 kts) in Adelaide region. Stable layers underneath core. Strong vertical and horizontal shears indicated south of Adelaide. Plane is to explore possible CAT in these stable layers at 24 and 28,000 feet. On return from Woomera flight is scheduled near jet core level. Stable layers are expected to slope upward towards south. Pilot is instructed, therefore, to keep altitude during first leg flexible towards higher levels.

Flight Plan

Adelaide - Mount Gambier	24,000 feet + 2,000
Mount Gambier - Adelaide	28,000 feet + 2,000
Adelaide - Woomera along 140°	28,000 feet
Woomera - Adelaide	34,000 feet

Explore CAT whenever encountered. Else explore strongly developed jet max.

Debriefing

Highest speeds 31 degrees 48 S, 137 degrees 02 E, 282°/133 kts at 31,000 feet.

At this point moderate CAT encountered in small patch, 3' 20" duration of longest record. Patch was approximately 14 miles across and long. This patch was marked by smoke and photographed (slight waves seemed present. Questionable, however, whether these were produced by aircraft). Aircraft followed this patch downstream 80-100 miles - 45 minutes). CAT stayed at pretty much the same magnitude all the while.

Lt. Morrison: Smoke went into sinusoidal waves. Wave lengths were too large to be aircraft-produced. Waves were largest where CAT was severest. One run 1,000 feet above, one 2,000 feet below 32,000 (main level) also showed CAT but less; much less on lower level, slightly less on higher level. CAT patch moved across mountains. CAT was still there when mission was abandoned due to lack of time and fuel.

On way up (level 28,000 feet) thin cirrus was observed below flight level (presumably on base of stable layer evident from Adelaide sounding).

Aircraft winds were much lighter in general than balloon winds. Smoke trails seem to give wave pattern even after 3 minutes. Some of them broke up. Even one step was observed. Wave length of smoke waves approximately 50-100 yards.

Post Analysis

Shows that aircraft winds were nearly correct. Merging - zone of two jet fingers apparently was moving in over area, with rapidly weakening winds.

Radiosonde winds seem to be too high on the average, which suggests application of curvature of earth correction would have been desirable.

Friday, 13th September, 1963:

Jet maximum rapidly drifting eastward. Well pronounced mergin zone between two jets seems present over east coast between Sydney and Brisbane. Surface chart shows two cold fronts in area, similar to setup encountered over U.S.A. If situation does not deteriorate too rapidly, CAT should be encountered in this region.

Williamtown (Sydney) shows 40 degree turning of wind with height near tropopause or stable layer at 250 mb (34,000 ft).

Cobar shows tropopause at 36,000 ft. - not much turning of wind with height.

American B707 reports severe CAT over Avalon near Melbourne between 20 and 30,000 feet, 0900 EST, outside of shear area according to George, but in general vicinity of convergence line between two merging jets,

Flight Plan

Adelaide to Williamtown. Explore 31-37,000 feet region. Follow a line Adelaide - Mildura - Cobar - between Coff's Harbour and Williamtown. Deviate approximately 60-100 miles on either side of this line, going up and down at same time.

2nd part: Williamtown - Brisbane 31-37,000 feet. Stay over or east of mountains and explore convergence zone between two merging jet fingers.

Both parts of the mission will be done without refuelings, in one stretch.

Take off 1:45 S.A. time.

Debriefing

Convergence line was not found. Winds were very light. Only very light CAT over coastal portions of flight.

WX map of 6 hours later shows rapid decay of situation. Convergence line moved towards east very rapidly, diminishing in intensity.

Saturday, 14th September, 1963:

140 kts jet shown rather far to north of proposed flight. Constitutes tail end of strong max which moved into area only yesterday.

Flight Plan

Richmond (Sydney) to 35S/148E to 32S/145E to Adelaide. Flight should lead along anticyclonic side of subtropical jet. Levels: 33-39,000 feet. No turbulence expected.

Debriefing

Winds stronger than forecast. 155 knots, at 38,000 feet, 32S, 141 degrees 28E. Haze at 38,5-39,000 feet. No CAT.

Monday, 16th September, 1963:

WX situation shows jet stream picking up slightly in speed, probably due to low moving into vicinity of Tasmania and probably cold surge behind it. Cold front has moved through Adelaide area in early morning hours (approximately 5 a.m.).

Adelaide 2300Z sounding shows same upper tropospheric characteristics as Woomera at 2000Z. Jet system, therefore, has shifted south, characteristic of post-trough conditions.

Adelaide shows strong vertical shear in stable layer near 20,000 feet.

Flight Plan

Climb out: Adelaide - 35S, 140E, 20,000 feet - Mount Gambier between 19-23,000 feet.

Mount Gambier - 32 degrees S, 140E at 33,000 feet + 2000 feet. Some CAT (orographic) possible at both levels. If lower level shows clouds, proceed to higher level. If CAT is found, explore.

Debriefing

Perceptible to slight CAT at 19-21,000 in slight haze layer. Another haze layer at 31 deg. 30S, 139E, approx. 33-35,000 feet. CAT continuously on way down to Mount Gambier.

One slight patch of CAT was found over Stonefield. Smoke trail showed slight dip, but no sine wave as on previous occasion of moderate CAT. In flying back, patch could not be found.

Tuesday, 17th September, 1963:

Tail end of jet stream over Melbourne, from a south-westerly direction as of 16th September 1730 maps.

Flight Plan

Mount Gambier, Laverton, at 30-33,000 feet. Not much CAT expected. Flight should be mainly on anticyclonic side of jet.

Take off approx. 1000 hours C.S.T.

Return in afternoon along same flight pattern.

Debriefing

Slight CAT approx. 33,000 feet 80 miles SE of Edinburgh to Nhill.

Wednesday, 18th September, 1963:

Region of S.A., Vic. and N.S.W. down to Tasmania covered by blocking high. Jet stream moves in aloft, however. According to aireps it seems to have strong anticyclonic bend southeast of Forrest over the Bight.

Flight Plan

Take off approx. 1000 hours C.S.T. on routine exploratory mission Adelaide - Mount Gambier - Laverton - Mount Gambier - Adelaide.

Not much in way of CAT expected. Watch for strong horizontal and vertical shears in Laverton region, also for decrease in temperature. Flight level 36K $\pm$ 2,000 feet.

Debriefing

Very strong vertical and horizontal shears encountered between Mount Gambier and Laverton.

0130Z		0213Z	
Mount Gambier			
38,000 feet	261/125	32,000 ft.	353/35
37,000 "	258/90		
36,000 "	246/85		

0144Z	
Laverton	
35,000 feet	245/75
34,000 "	228/42
33,000 "	239/38
32,000 "	211/25
31,000 "	218/30
32,000 "	235/22

Very slight CAT at 32,000 feet halfway between Laverton and Mount Gambier. A very shallow but intense branch of the jet stream thus seems to be crossing the blocking high pressure ridge, while the main jet seems to be holding further to the NE (region of 30S 130E).

Thursday, 19th September, 1963:

Blocking situation still continues with no signs of imminent change. It was decided, therefore, to have the two-day inspection of the aircraft now, if possible, rather than Thursday and Friday of next week when flying conditions again might be more promising.

Friday, 20th September, 1963:

Blocking situtation still prevails, however, with indications of weakening upper winds in this region. Very light winds, max approximately 50-30 kts. No CAT indication from forecast according to Melbourne, which justifies decision of yesterday to have airplane overhauled.

Monday, 23rd September, 1963:

Blocking situation still prevailing. High on surface has however, shifted to NE.

36,000 ft winds show interesting merging pattern of two jet fingers.

2300Z, 22nd September, 1963.

Adelaide	298/69
Woomera	268/55
Maralinga	288/16
Oodnadatta	278/105

Strong horizontal and vertical shears indicated south of Oodnadatta. CAT expected in merging zone, if it can actually be found.

Flight Plan

Adelaide - Woomera - Oodnadatta - zero drift to 139E - Adelaide.

Level 35-40K, winds of 36K should be compared with our chart. Else concentrate on 36-40K.

Debriefing

Horizontal shear has been found all right. Minimum winds 42 kts. Max. winds 120 kts 27 deg. 37S, 135°55E at 36,000 feet.

Very slight CAT ar 20K, 28K, 32K and 38 during climb out. Light CAT over Oodnadatta at 38,000 feet. CAT occurred with zero drift. In fact, slight CAT occurred so continuously that attempts to take a smooth-air data sample for comparison failed.

Tuesday, 24th September, 1963. Morning:

Strong confluent region SE of Alice Springs still maintains itself. Possibility of CAT with trailing end of strong trough passing aloft over N.S.W. Max. winds near 36,000 feet, max. vertical shears seem to be slightly lower than yesterday (< 31,000).

Flight Plan

Take off approx. 9:30 Level 36,000 feet ± 2,000. northward along 140 degrees E to approx. 27 deg.S. Watch for shift in wind direction and increase in wind speed near 26 to 27 deg. S. In case CAT is encountered, explore the CAT bearing layer horizontally in M shaped flight pattern. Look for stronger patches. In this case continue to 24 deg.S then re-fuel in Alice Springs.

Debriefing

Winds confirmed. Max. wind on return 120 kts, 34,000 ft. near 27 N. 20 kts over Adelaide. Zero knots over Stonefield at 37,000 feet. Small patch of light CAT 70 miles NE of Broken Hill, 31.54S, 139.45E, 32,300 feet showed detailed structure of a number of very small patches. Patches all about 50 sec. duration. One was measured, was still there on return, nothing upstream (10 miles) and below (500 feet). Also a few patches at 34,500, very slight, however.

Winds in turbulent region only approx.30kts.

Tuesday, 24th September, 1963. Afternoon:

Shear line still prevailing NE of Adelaide and Mildura with SE jet over Mount Gambier.

Flight Plan

Adelaide - Mount Gambier - 30 deg.S, 147 E - Adelaide at 28,000 to 34,000 ft. Search again for convergence line and possible CAT at tropopause level (according to Woomera soundings at approx. 29,000 ft.).

Debriefing

Max. wind 65 kts, 129^{0}, 34 deg. 26 S, 141 deg. 28 E, 28,000 feet. Convergence line still established, but did not fly into northern shear area.

Light CAT at 28,200 ft., measured contrail was smooth in smooth area, turbulent in CAT (near Broken Hill). (Change was evident very abruptly in contrail appearance). Light CAT also observed 32.3K. 31.2K over Mount Gambier down to 27.3K.

28K and 32K were the main levels of light CAT. Flying through smoke trail, no CAT in trail, but light CAT further to east than original patch. All the time winds changed direction rapidly with height (e.g. by 38 deg. in

2,000 ft). CAT was found with winds 054 deg. 34 kts.

Photos taken of smooth and turbulent patch of CAT.

Wednesday, 25th September, 1963:

Convergence line has shifted slightly to the north, with upper level easterlies over Victoria. 130 knots, 280 deg. at 31,000 feet over Brisbane indicates strong subtropical jet stream in this region.

Flight Plan

Adelaide - 30 deg.S, 145E - Brisbane
Region to south of Brisbane cannot be explored as originally planned, because of 2-day air defence excercises scheduled out of Sydney. Area closed to air traffic. Flight levels: 26-31 K a nd 40-42 K. Exploration of two stable layers, especially the lower one associated with strong vertical shears and possibility of CAT, especially near convergence line.

Debriefing (from Telegram)

Easterly winds veered westerly between 143 and 144 east, remained westerly, speed increasing with decreasing southerly latitude, to max of 140 kts at 27 S. Slight turbulence 50 N M southeast Broken Hill, not recorded. Winds found Brisbance area agree with 242300 chart. CAT near 28 K. Shear line further to west than anticipated. Large CU in Brisbane area, no CAT.

Thursday, 26th September, 1963:

Shear line seems to hold steady as on previous day. New jet branch appears SW of Woomera, with substantial vertical shears, and with turning of wind from 190 to 250 degrees through a very deep stable layer (24 to 33K).

Flight Plan

Sydney area still closed. Brisbane - 28 S - 28 S,138 E - Adelaide. Flight level 33 K to 24 K. Watch for CAT near 143 E (trough line) and south of turning point (138 E), especially at 24 K level.

Debriefing

Very strong vertical shear over Brisbane. 210deg/100 kts at 30,000 feet, 305 deg/70 kts at 32,000 feet. No CAT along whole flight. Northwesterly winds are not evident from maps but were encountered during southbound leg of flight.

At 145 E trough was evident from sharp line of Cu up to 26,000 ft. Line of Cu and Cb also over Brisbane (26,000) with strongly shearing anvil on top. Aligned along direction 160 degrees. No CAT downwind and over top of these Cu, even at 27 K flight level.

Friday, 27th September, 1963:

Weather situation does not indicate any CAT. Winds of yesterday's flight proved to be correct, with light trough having moved through region.

Flight Plan

Crew wants to visit with B-57 pilots in Melbourne. Flight level at 31K+2K should lead into vicinity of tropopause. No CAT anticipated.

Debriefing

NO CAT found as expected.

Monday, 30th September, 1963. Morning:

Well-developed subtropical jet stream over Oodnadatta region, with pronounced confluence line over Woomera.

Flight Plan

Adelaide - Woomera - Oodnadatta - Woomera. Levels 27 K to 33 K. Light CAT possible in region of shear line slightly north of Woomera outbound, near 30 to 31 K inbound in region of max turning of winds with height. If any CAT patches are found they are expected to move with the wind, since there would hardly be any orographic or frontal perturbation energy input from below. Take off 11.05.

Debriefing

Light to moderate CAT in very small patches (could not be identified properly on return runs, therefore, conclusion "small"). One severe bump (isolated, estimated 1g) in small isolated patch at 28,300 ft at 29 deg. 11S, 140 deg. 31E. Patches seemed to be shallow. One contrail photographed, with sharp vertical drop in trail, coinciding with spot where bump occurred. Also marked difference observed in contrail appearance between laminar and turbulent flow.

Monday, 30th September, 1963. Afternoon

Jet max seems to move eastward rather rapdily, while confluence line still occupies approx same regions earlier this morning.

Flight Plan

Woomera - 26S, 142E - Adelaide. Concentrate on layer 29-31K. CAT again expected in region of strong turning of wind with height.

Debriefing

Better CAT patches found than in morning. 29 deg. 55 S, 141 deg. 07 E. First patch found at 27.200 ft 1000 ft below - still good CAT; 500 ft above, not much CAT there. Smoke trails laid 3 miles upwind gave about same turbulence. There seemed to be larger CAT layer. Small CAT patch also found during turn. One moderate to severe bump found in one small patch. Temperature seemed rather uniform. "Green Satin" did not seem to work properly.

Winds in CAT region	262 deg	12 Kts	26,000
	270 "	25 "	27,000
	289 "	33 "	28,000

position: 30 deg 39S, 141 deg 02E to 30 deg 12S, 141 deg 15E.

Tuesday, 1st October, 1963:

Convergence line aloft seems to move eastward at a rate of approx. 4-5 degrees long. per 6 hours. CAT regions, therefore, deteriorating rapidly. Also vertical turning of wind seems to have increased.

Flight Plan

Aircraft due for comparison flight with DC3 at Wagga - Wagga. Adelaide - Wagga at 27-31 K. Convergence line expected over Wagga. Try to fly search pattern there if time permits. Not much CAT expected.

Debriefing

Aircraft did not catch up with convergence line. No CAT.

Thursday, 3rd October, 1963. Morning:

Marked confluence line in region of Woomera and Cobar, between subtropical jet with strong horizontal shear and southwesterly jet stream branch. Possibility of CAT along this shear line, mainly in layer 26K to 31K of rapid turning of wind with height (196 deg - 260 deg). Secondary layer with strong scalar wind shear between 32-32K (60 - 99 knots) according to Woomera sounding.

Flight Briefing

Northward along 140 degrees, till area of veering of wind is reached at approximately 31 degrees S - then course 070 degrees as far as possible. Fly search pattern along this leg. Levels: 26-31 K, and 32-34K with preference to lower layer.

Debriefing

Lots of CAT, light to moderate, 31 degrees S, 140 degrees E, 28-29,000 ft. Aircraft did not follow leg at course 070 degrees, because CAT was quite good in convergence area where predicted.

Thursday, 3rd October, 1963. Afternoon: (III-26)

Confluence condition still holding up. Appears to be moving toward SE.

Flight Plan

Explore area of previous turbulence, which possibly may be further south now. Same flight levels as during morning flight.

Debriefing

Light to moderate CAT again at 140 degrees E, 32 deg. S, 28-29K ft. Downward bumps seemed to be stronger than upward bumps. Light CAT almost continuously. Wind veering sharply near 32 degrees S between 26K and 30K. Most of the turbulence found immediately north of convergence line in (slight) westerly winds.

Two haze horizons observed, one approximately at flight level of turbulence, the other slightly higher, probably around 34 K. Smoke puffs: some stayed well rounded, some seemed to spread out into thin horizontal sheets, probably depending on meso- or microscale vertical shear systems.

Due to strong haze, smoke puffs were lost quickly. Could not be photographed. One probably would have to use coloured smoke and colour film.