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NEW ZEALAND METEOROLOGICAL SERVICE

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SURVEY OF CLEAR AIR TURBULENCE

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NEW ZEALAND METEOROLOGICAL SERVICE

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INTRODUCTION

Atmospheric turbulence has always created a problem for aviators. It was once thought that aircraft flying in the upper troposphere and stratosphere would escape turbulence but pressurised aircraft found CAT and at the present rate of progress of research and development, turbulence will remain a problem for sub-sonic jet aircraft and will be a problem when supersonic aircraft move into the stratosphere.

All turbulence may be regarded as potentially dangerous but clear air turbulence is a greater menace because it is invisible. If the airflow about the aircraft was visible it is possible that the correct counter action could be taken with the result that the aircraft involved would remain under control at all times. Unfortunately this is not so and while advances are being made in the detection and forecasting of CAT, it will be some time before the aviator can be given a completely certain warning service.

There have been several well documented cases of large jets going out of control as a result of turbulence, a notable one in 1963 being that of a Boeing 720 breaking apart in the ensuing dive and killing all on board.

"Coffin corner" is well known to jet operators as the state where the speed of low speed stall approaches the speed of high speed buffet. Most jet operations at altitude in the cold thin air take place near this region, and minor accelerations or decelerations in the wrong sense can quickly get a pilot into trouble.

CAT can cause such accelerations and even if the pilot manages to effect a recovery from a dive following loss of control during a turbulence encounter, such a recovery may subject the aircraft to serious overloading which can lead to structural failure. And, of course, the loss of height during such dives is considerable; there have been several catastrophies with the aircraft arriving at the ground without recovering from the dive.

The extent to which CAT affects air operations can be gauged from the results of a survey of incident reports received by U.S. Weather Bureau during the year 1964.

> 8,507 reports were received and of these
>
> 671 were reports of moderate or greater intensity and of these:
>
> 497 were reported to be moderate;
>
> 163 were reported to be severe;
>
> 11 were reported to be extreme.

Another survey conducted by the Flight Safety Foundation for N.A.S.A. in 1964 into the cost attributable to CAT resulted in a total of $18 million. The cost of diversions based on forecasts or reports amounted to $16 million. This total does not include time-on-the-ground costs due to inspections, nor the loss of earning power of those injured. However, it represents a considerable outlay and one which could be reduced if a greater understanding and more precise forecasting of the phenomenon were achievable.

More and more aircraft are moving into the higher altitudes - say from 20,000 to 40,000 ft and turbulence encounters must be expected. Apart from the economic point of view the safety and passenger comfort aspects must be considered, and it is essential that better forecasting techniques be developed.

As a result, this problem of Clear Air Turbulence has received considerable attention over the past 15 to 20 years, and greater efforts have been made during the past decade. The problem, more or less caught people unawares in the early days, and preparations are being made to meet the problem for supersonic transports in advance.

The power spectrum of turbulence is being investigated for the aeronautical engineers while the preferred locations in association with macroscale meteorological features, geographical and seasonal distributions are being investigated for the meteorologist and operator. In addition airborne and ground station detection techniques are being investigated.

Atmospheric Motions Causing Variations in the Motion of an Aircraft

Turbulence to the meteorologist or physicist is the chaotic motion of the atmosphere which gives rise to the diffusion or transfer of properties of the atmosphere, e.g. transfer of kinetic energy, temperature, momentum, etc. To the aviator it means a rough ride as a result of encountering certain atmospheric properties which cause bumpiness. CAT is characterised by its cobblestone effect. It is the co-ordinate system used to describe the atmospheric motions that accounts mainly for the different points of view.

The physicist uses one of two-co-ordinate systems to study the problem; the Lagrangian system which moves with the volume element of the atmosphere it is concerned with, or the Eulerian co-ordinate system which is fixed in space and the motion of the atmosphere is studied as it passes by this so-called reference. In diffusive turbulence the studies are made in terms of how the atmosphere particle motions vary with time, and about their mean motions.

Aircraft responses are measured with respect to a third co-ordinate system - the aircraft itself moving through the fluid atmosphere and its turbulence is the variation of the aircraft's motion about its mean value. It filters from the whole spectrum of atmospheric turbulence those frequencies to which it is most susceptible. These depend on its size, shape and speed. Unfortunately for the researchers, different aircraft respond to different frequencies and hence the question of deriving a universal model for CAT is complex.

From the structural point of view it is the small wavelength/high frequency disturbances which are important. They may set up vibrations in certain components thus affecting their fatigue life and endanger the aircraft structure. On the other hand, they have little or no effect on the bodily movement of the aircraft.

At the other end of the scale, the long wavelength disturbances move the aircraft bodily but smoothly and impose no strains on it.

Between these two extremes is a spectrum of wavelengths which causes an aircraft to pitch and roll, submits it to strains, makes it difficult to control, and thus affects the safety and comfort as well as the aircraft integrity.

This is the range of wavelengths that the meteorologist is concerned with.

Based on simplified theoretical considerations of the centre of gravity load factor response to vertical gusts, the lift coefficient of the aircraft, and assuming that the observed low level gust intensity occurs at higher levels, the wavelengths affecting different aircraft have been calculated and are shown in Table I.

TABLE I

		Altitude Ft.	Wavelength Ft.	
			Minimum	Maximum
Small Aircraft	take off	0-10,000	10-8	Several hundred
	cruise	0-20,000	25-18	
Conventional Transport		0-30,000	35-60	16,000
Sub-sonic Jets		20-40,000	80	16-18000
High Performance Supersonic Fighter		20-50,000	150-200	4-7,000

Supersonic Transports are considered to react to wavelengths between 10 and 100,000 ft in the lower atmosphere and from 800 to 60,000 ft at 100,000 ft.

The atmospheric motions which contribute to these wavelengths are the eddies of diffusive turbulence, but in addition the regularly varying motions of waves also contribute. The term undulance has been given very aptly to the non-diffusive atmospheric wave motions which give rise to bumpiness.

The different properties of Turbulence and Undulance are shown in Table II.

TABLE II

UNDULANCE	TURBULENCE
Wave Motion	Random Motion
Specifically Defined	Probabilistically Defined
Non-diffusive	Diffusive
Stable Layer Location	Neutral/Unstable Layer Location
Discrete Spectrum of Wavelengths	Continuous Spectrum of Wavelengths
Causes	
Flow over mountains (Lee Waves)	Mechanical Stirring
Convective Activity in adjacent layers	Convection
Shear flow across stable layer	Instability in shear flow

In the atmosphere we have gravity waves which travel horizontally with the particles oscillating vertically with gravity as the restoring force. Inertia waves are also experienced - these travel horizontally but the particles also oscillate horizontally perpendicular to the direction of propagation, with inertia as the restoring force. There is another type of atmospheric motion which is longitudinal, involving compressions and rarefactions in the direction of propagation - the sound waves. Of all these wave motions it is the gravity wave which causes CAT in the main. It is uncertain whether inertial waves can be of the right length, period or frequency and amplitude to cause bumpiness. Of course, the wavelengths of acoustic waves are too short.

In general terms, turbulence predominates in the near surface layers, undulance and turbulence co-exist in the upper troposphere and in the lower stratosphere where both contribute to Clear Air Turbulence, but undulance is considered to be the main source of CAT in the stratosphere.

The waves which appear to be most important in causing undulance at high altitudes are internal waves, i.e. they have no motion at the boundary. External waves have maximum "motion at the earth's boundary". The energy propagates in the direction of motion along the boundary and the wave decays exponentially with height. Internal waves, on the other hand, may be cellular: they may repeat their characteristics in all component directions and the energy may propagate in any direction.

Now unless there is sufficient water vapour present in the layer in which the internal wave action is operating the only way they can be detected is by the associated changes of temperature, pressure or velocity. The energy of the wave is the square of its amplitude and is reflected in the pressure variations.

It is through the variations in these properties that research into the structural characteristics of the atmosphere associated with CAT are being studied.

CAT RESEARCH

Research into CAT is required for two main purposes:

(1) For aircraft design - a knowledge of the whole power spectrum of atmospheric turbulence independent of the measuring instrument so that aerodynamics and aircraft designers can make due allowance for the effects of turbulence on the structure and control surfaces of the aircraft they design. In this field a harmonic analysis of all turbulence reports provides a statistical frequency distribution of either waves (undulance) or recurring eddies (turbulence) which are operating to provide the observed time sequence of the motion. The tool does not differentiate between the continuous waves of undulance, and recurring eddies. It indicates the fraction of the total energy of movement that is associated with each wavelength, and it does provide us with the spectrum of all the waves, eddies or vortices operating and their contribution to the energy of the moving atmosphere.

Several concerted research projects have been launched to determine the turbulence spectrum of the free atmosphere rather than the earlier statistical approach of obtaining the relationship between discrete gust velocities and their frequency of occurrence.

(2) For the development of a physical model of turbulence which can be used for the precise forecasting of CAT. In this instance a detailed knowledge of the locations of CAT and the associated physical and dynamical characteristics of the atmosphere must be obtained.

OBSERVATIONS OF TURBULENCE

Most observations of CAT highlight its patchiness - it is generally found in layers 2,000 - 3,000 ft thick and with an areal extent of 100 sq. miles on the average.

Data has been collected from:

(1) routine aircraft flights

(2) during special reporting periods

(3) during special CAT investigations e.g. R.A.E. High Altitude Gust Investigation (1948)

TOP-CAT in Australia (1963)

HIGHCAT in various locations in the stratosphere (1965-67)

In these latter, quantitative measurements of small scale atmospheric motions have been made by:

(1) using the aircraft as a 'sensor' and recording accelerometer records;

(2) using the aircraft as a 'platform' carrying a gust probe on a nose boom and measuring differential pressure variations as in TOPCAT, or, as in HIGHCAT, a sensor which consists of a pitot tube and a double vane system;

(3) by Doppler-wind measurements.

The analysis of these data indicate that:

Light bumpiness in clear air can and does occur at any place at any season and at any height yet obtained by aircraft and under a wide variety of meteorological conditions.

However, moderate or severe bumpiness in clear air has definite associations with only a few meteorological and geophysical conditions:-

70 percent associated with jet streams;
20 percent associated with mountain waves;
10 percent associated with troughs, cold core lows and areas of differential heating and advection.

Moderate to severe CAT has a maximum occurrence below 5,000 ft and again at 30,000 to 40,000 ft. It also, on the average, is about four times as frequent in the winter than in summer, and it occurs at lower altitudes in the winter. This is to be expected because of its close association with jet streams.

The association of mesoscale regions with relatively high or changing static stability, e.g. fronts, the tropopause or other stable layers, and macroscale regions of strong wind shear, (horizontal and/or vertical) are preferred conditions for moderate to severe CAT. However, some association of rough air with sloping baroclinic layers has been reported mostly in or near adiabatic layers.

In general, there are several locations in the vicinity of jet streams where the occurrence of CAT appears more frequent. The investigations and conclusions of Bannon (1952) still hold good. The preferred locations are on the cold air (polar) side of, above and below the jet stream core. In addition, other preferred locations are on the warm side in the troposphere, in the jet stream front and above the jet in the stratosphere.

These distributions coincide with the location of sloping stable zones associated with large vertical and horizontal wind shears.

There are variations, of course, to this generalised distribution - the most noticeable being the distribution of CAT when the jet stream is over the sea. Clodman (1960) found most CAT above and on the warm (equatorward) side of the core in the troposphere. Clodman attributed the different distribution to the different mechanisms working. He considered that over the land topography initiates perturbations and gravity waves are operating to cause the CAT, whereas over the sea CAT is the result of dynamic instability and low Richardson number.

CAT has not been found along the whole length of jet streams. The preferred locations are in the vicinity of maxima of wind velocity and in the entrance and exit regions. In the case of the latter the vertical circulations present probably contribute to the generation of CAT and in the former CAT is probably due to the increased associated shears.

Other cases of strong CAT have been reported with two converging jet streams or with jet fingers at different altitudes impinging. In this case CAT generally occurs in the region of relatively light winds with the wind turning with height. This is associated with differential temperature advection and changing stability.

CAT in the clear air to the lee of mountains could be severe but most observed cases fall into the light to moderate class. It has been observed in the well known standing wave configuration and as a travelling wave packet. All cases are downwind from the mountain range and they are found in any stable layer above the mountains.

THEORETICAL MODELS OF TURBULENCE AND UNDULANCE

Dynamic Instability occurs whenever the character of the mean flow is such that perturbations of this flow accelerate or increase in amplitude with time and the character of flow changes from laminar to turbulent. The breakdown from laminar to turbulent flow has been studied for many years. Mostly the study in the early days concentrated on the motion of incompressible homogeneous fluid flow, e.g. Reynolds in his classical experiments on flow in long straight pipes concluded that there exists a dimensionless parameter $\frac{ur}{\nu}$ where u is the average velocity, r the radius of pipe and ν the kinematic viscosity, the critical value of which determines whether the flow is laminar or turbulent.

Richardson extended the work of Reynolds to the motion of a fluid having variable density gradient - the atmosphere - and investigated the effects of gravity on turbulence. Richardson assumed that Kinetic Energy is created by shearing stresses, i.e. $T = \mu \frac{du}{dz}$ the property of viscosity whereby it transfers momentum, and is destroyed by dissipation in work to offset gravity.

Again a non-dimensional quantity was evolved which has critical value for increasing or subsiding turbulence.

When the wind shear becomes large enough relative to the density gradient, the rate of change of energy of the turbulent fluctuations becomes larger than the dissipation and the perturbation can grow.

Richardson's Number is defined as:

$$Ri = \frac{g\left(\frac{\partial T}{\partial z}\right) + \Gamma}{T\left(\frac{\partial u}{\partial z}\right)^2}$$

Richardson considered the critical value to be unity, but later investigators have found it to be smaller; 0.65, Petterson and Swinbank (1947) and 0.25, Schlichting (1955).

More recently workers in this field have found that the Richardson criteria represent only a special case and that criteria which in addition take into account the horizontal shear, the vertical curvature of the wind profile, the horizontal change of vertical shear, and coriolis accelerations are more reliable tools for forecasting the perturbation wave lengths which will become unstable.

CONVECTION

Convection due to the differential advection of air, as distinct from heating of air from below, e.g. the advection of a layer of warmer air below a cold layer can lead to a reduction of R_i below the critical value and dynamic instability can result.

WAVE MOTION

Many investigators have produced models which can be used to predict the development rate of disturbances once they have been generated by use of the perturbation theory. Scorer (1940) was one of the first in this field and the value of his parameter ℓ^2 has been used as a criterion for the production of lee waves.

Such disturbances over mountains may disperse and move far downwind or they may set up standing waves downstream. Most of these disturbances are, however, random due partly to interaction of several wave trains and of varying atmospheric conditions. Most waves usually attain greatest amplitude and hence greatest changes in velocity in the mid to high troposphere. Some under favourable conditions attain their maximum amplitude in the stratosphere - these theoretically are of longer wavelengths, as the shorter wavelengths should be damped out or reflected at the base of the stable layer of the stratosphere.

Significant changes in surface roughness, e.g. coastlines may increase high altitude turbulence.

Surface characteristics affect heating of the atmosphere and create effects similar to the "equivalent thermal mountain" of Stern and Malkus (1953).

Unfortunately, to date no satisfactory theory has been developed which enables the breakdown of laminar flow or stable wave motions into turbulent flow to be forecast.

FORECASTING TECHNIQUES

The forecasting techniques rely mainly on our present meagre knowledge of the bumpiness phenomena with the result that the identification of synoptic scale features associated with certain mesoscale features remains our main forecasting tool.

Some quantitative or empirical rules have been suggested and these are successful only to a moderate degree. George (1961) for instance, looks for areas in which the horizontal wind shear exceeds 50 kt/150 nm and in which the vertical wind shear simultaneously reached

6 kt/1000 ft with wind speeds in excess of 60 kt. In these regions he forecasts moderate to severe CAT in the layer which extends from 3,000 ft below to 7,000 ft above the layer in question. This technique was used in TOPCAT but it was found wanting as a forecasting tool.

Reiter (1964) for TOPCAT used the George technique. He also sought out areas where stable layers were evidenced in the temperature soundings on the assumption that gravitational shearing waves may give rise to CAT. However, he experienced difficulty in that the detail required for such gravity waves was not available from the coarse temperature and wind soundings and a fair element of chance was introduced by his assumed values. If no such layers were present he despatched the aircraft to the vicinity of the tropopause. He also used the significance of the vertical vector shear - wind turning with height in the regions of relatively light winds between converging jets and was successful.

Smoke puffs released to identify turbulence patches under these conditions should show the patch persists with time, and how the meso-structural details persist as they are advected with the mean wind. This supports the theory that small-scale phenomenon causing CAT derive their energy from the meso-scale disturbances.

Orographic effects were also considered as a source of CAT but no conclusive evidence has been given of their success. Scorer's parameter was used. On one occasion a cold front reaching the tropopause gave the required distribution of the Scorer parameter and moderate to strong turbulence was encountered.

Work is going on in this field and some optimism has been expressed by Reiter and Foltz (1957) who have applied the energy decay arguments of diffusive turbulence to lee waves and produced a physical model of CAT which is supported by observation. It is based, however, on the known wavelength of existing waves and can only be regarded as a short period warning device rather than a forecasting tool on the synoptic scale.

Forecasting techniques used by the New Zealand Meteorological Service in the HIGHCAT investigation based on Christchurch had moderate success. They were based on results obtained from the stratospheric search flights in the northern hemisphere. These indicated that CAT was found:

(1) Near Jet Streams;
(2) In thermally stable layers;
(3) Above areas of considerable tropospheric convective activity;
(4) Near sharp upper level troughs;
(5) In association with mountain waves.

Twelve flights were made and on ten of these turbulence was encountered. (Hickman 1967).

USE OF METEOROLOGICAL SATELLITES

The use of satellite photographs to identify regions of likely CAT is now being used extensively.

Locations of jet streams can be identified either (i) by shadows cast on lower cloud sheets by jet stream cirrus, (ii) by small transverse lines immediately poleward of a frontal band of cloud, (iii) transverse lines in a cirrus band, (iv) the change of type of cloud patterns - open cells characterising instability in lower levels and closed cells characterising stable anti-cyclonic lower level flow. If a jet is present then there is strong correlation between the boundaries of the two patterns.

DETECTION OF CAT

As you have just heard we are still a long way from being able to forecast the occurrence of CAT. It is obviously a small-scale phenomenon and the meteorologist has only as his working tools macro-scale (synoptic) data. Although a great deal is known about the possible location of CAT, little is yet known about how the air in these likely areas will break down into turbulent motion.

The other approach is whether the areas where turbulence is occurring can be detected instrumentally either from the ground or preferably in the air.

Many methods of detection are being tried; to date without any degree of success or even showing promise of an early success for operational use.

In the United States a National Clear Air Turbulence Committee has been formed which is co-ordinating the efforts of all interested parties and ensuring that there is no wasteful duplication of effort.

Detection methods to date include:

(1) Temperature gradient measurements;
(2) Remote sensing of air temperature using infra-red radiometer;
(3) Optical radar detection - laser beam;
(4) Conventional radar detection;
(5) Aircraft electrical activity;
(6) Low frequency electrical characteristics;
(7) General - Satellites, Kites, Balloons, fixed co-ordinate system for local area investigation.

Temperature Gradient Measurements

A temperature sensor mounted on a probe just ahead of the aircraft has been developed and used by Eastern Airlines in the hope that an indication of a critical horizontal temperature gradient together with wind measurements will alert a pilot of the possibility of encountering CAT. In theory, this is alright for flights across a jet stream region in the vicinity of the core, but when the flight parallels the jet stream changes in temperature let alone any change in temperature gradient may not be experienced and yet CAT could well be encountered. Therefore, this does not provide a universal answer to the detection problem and furthermore the observed change and the occurrence of CAT may be more or less simultaneous and no evasive manoeuvre would be possible.

Remote Temperature Measurements

The use of an Infra Red Radiometer to measure the radiation from CO_2 in the column of air ahead of the aircraft, ranges out to 25 nm. The ability to detect a temperature change of 0.2 degree C has been developed. More work is required to develop a satisfactory unit for pure jet operations if evasive action is to be made possible.

Optical Radar

It is thought that changes in the concentration of layers of particulate matter in regions of CAT may be possible and experiments with a laser unit mounted in a light aircraft have been carried out. They have shown unusual distributions of particles alone, unusual distributions and turbulence, and turbulence alone to exist. They have also detected laminar sheets of ice crystals only 1 micron in diameter at a distance of 1 km. Again the development of equipment for longer range operation is required but this will involve a very powerful airborne laser which for the present is not a serious possibility.

North American Aviation have experimented with a laser in a different manner - they have experimented to show that it may be possible to detect gust velocities of the order of 25 ft/sec by measuring the Doppler frequency shift in a back scattered laser radiation. This will prove to be a highly complex system involving two closely spaced pulses and the measurement of the relative shift between them after back scattering from airborne aerosols. However, the system is useless if aerosols are not present.

Radar Detection

Boeing have experimented with metre-radar and found some correlation with back scatter from refractive index gradients associated with CAT. Their ground based radar results have encouraged them to experiment with airborne equipment but no conclusive results have been forthcoming to date - they consider detection out to 1/3 of a mile should be possible.

Aircraft Electrical Activity

Increased static discharge activity in the presence of CAT has been observed or appears to have been so. United Airlines and the Stanford Research Institute are experimenting in this field and 10 DC8 aircraft are instrumented to measure the discharge - they have yet to determine the degree of correlation of discharge with CAT if any.

Low Frequency Electrical Characteristics

North West Orient Airlines are experimenting with an airborne sensor to prove the existence and detection of low frequency electrostatic return signals from regions of CAT. Little progress to date.

Photometric measurements of Star Scintillations

These are also being investigated but obvious difficulties are daylight and cloud obstructions and they are unlikely to be successful operationally.

"Jet Upset" and Flying Techniques

In a jet-upset the aircraft enters a more or less steep dive following loss of control, the latter occurring primarily in pitch. Recovery from this dive is difficult and much height may be lost.

Encounters with turbulence have been found to cause the initiation of a jet-upset in several cases. Attempts by the pilot to 'chase' airspeed or height by over-correcting thus increasing the oscillation in the pitching plane which ultimately results in a dive. There has been one reported case where the pilots reported their inability to read the flight instruments owing to the high-level of turbulence-induced vibration in the cockpit. This was probably due to the excitation of the natural frequency of the fuselage which is close to one of the resonant frequencies of the human body.

The recovery from high Mach number dives is most difficult and the difficulties can be ascribed to the reduced effectiveness of the control surfaces of the aircraft with increasing Mach number and the tendency for the aircraft to increase its nose-down attitude under these circumstances.

If rough air flight is anticipated or encountered the important things to consider are:

(1) The selection of altitude which gives a sufficient margin from 'coffin corner', and any attempts to maintain altitude in turbulence should be restricted to those which only involve a small change in pitch attitude;

(2) The setting up of the recommended rough air speed for the aircraft, then leaving the power and trim settings locked until the penetration has been completed; (no attempts to 'chase' airspeed lost as a result of turbulence should be attempted);

(3) The acceptance of variations in pressure instruments as being a result of the turbulence;

(4) The maintenance of the desired attitude within reasonable tolerances, say 3 to 4 degrees of pitch and 10 degrees in bank, and if changes are necessary or turns required, making these gently.

Progress in all fields of CAT research is bound to be slow. In fact, at present it is doubtful whether an airborne warning device will ever be developed which will give a pilot direct and precise evidence of the existence of CAT at a sufficient distance for him to take evasive action. The problems of forecasting such small scale phenomena in space and time using data of the much larger synoptic scales are not insuperable and some progress can be expected towards greater precision and with this precision so the incidence of serious CAT incidents will become less frequent and the element of unexpectedness will be reduced.

In conclusion, it will be appreciated that the position of the meteorologist in regard to CAT is an unenviable one, as is that of the pilot who encounters it.

By highlighting the problems facing the meteorologists it is hoped that your interests have been stimulated and that when you have the opportunity of assisting with the collection of, or providing information that will lead to a better understanding of the mechanisms involved, you will do so, appreciating the value of your efforts.

SUMMARY OF KEY PUBLICATIONS USED IN SURVEY

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