Jet Streams and Turbulence

By
E.R. Reiter

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(Talk given at a special colloquium, Univ. of Melbourne, 9 October 1963)

Abstract: The term "clear-air turbulence" (CAT) actually is a misnomer because it includes the response characteristics of the aerospace vehicle experiencing CAT, and does not uniquely describe atmospheric conditions. The physical causes for CAT therefore may be different for different vehicles. A short review is given of possible atmospheric conditions leading to CAT in conventional jet aircraft, in supersonic transport aircraft (SST) and in vertically rising missiles.

1. INTRODUCTION

Most of the data available on CAT stem from subjective observations by military and civilian pilots of jet aircraft, and have been collected on routine flights. Normally, supplementary information on the meso- and micro-structure of the atmosphere is difficult to obtain for these clear-air turbulence encounters. The radiosonde and rawinsonde networks upon which one has to rely heavily in post-mortem analysis at best yield macro-scale information on the atmospheric structure.

In view of these difficulties the main emphasis in utilizing these data has been placed on statistical correlations of CAT occurrence with large-scale flow patterns in the upper troposphere, especially with jet streams (Bannon 1952, Colson 1962, Clodman et al. 1961). It has been brought out in several investigations (Jones 1953a, b, 1954), that a large percentage of CAT cases (71 per cent in the particular data sample investigated by Jones) occur in the immediate vicinity of jet streams, followed by approximately 20 per cent of cases associated with upper troughs and upper lows, while only approximately 9 per cent did not show any correlation with these flow patterns. Klemin and Pinus (1954) found that over the USSR approximately 50 per cent of CAT cases were associated with cyclonic conditions of flow and confluence, 27 per cent with anticyclonic conditions and confluence, and only 5 per cent with anticyclonic flow and diffluence.

From these and similar findings, the conclusion was drawn that the flow conditions peculiar to jet streams play an important role in the generation of CAT. Forecasting techniques were devised which utilized these findings, and which assumed a linkage between CAT and various atmospheric parameters which were readily obtained from routine meteorological observations, such as thermal instability, differential temperature advection, vertical and horizontal wind shears, and suitable combinations of these, as for example Richardson's turbulence criterion.

More detailed measurements by aircraft of the atmospheric structure near jet-streams revealed that CAT shows a preference to be associated with stable rather than unstable stratification (Reiter 1962). Moreover, uneven terrain seems to contribute significantly towards CAT generation over continents (Clodman et al. 1961). This suggested a gravity-wave type mechanism to be responsible for most CAT occurrences in the upper troposphere and in the stratosphere.

From most of these measurement flights CAT data were collected only as a by-product. (Only Hislop's (1951) data were obtained from CAT "hunting" missions). While su data gave us adequate information on CAT distribution around jet streams, the actual physic nature of CAT remained unexplored.

2. TURBULENCE AS A RESPONSE PROBLEM

CAT actually is a misnomer. What we really are concerned with is "bumpiness o aircraft in flight". Since clouds are usually expected to contain such bumpiness, especially those of the cumulus variety, the unexpected bumps encountered in clear-air are a major co cern.

With classical piston-engine and jet aircraft, the main input of the atmosphere in CAT comes from vertical and horizontal gusts. Since the latter produce a change in the lift the aircraft, they will also be felt in vertical accelerations, although not as strongly as vert gusts.

With some approximation the effect of a sharp-edged vertical gust on a rigid aircraft may be expressed by

$$\frac{\delta L}{W} = \frac{\rho}{2}\,\frac{A}{W}\,\frac{dC_L}{d\alpha}\,wV \qquad \ldots(1)$$

where L is the additional lift produced by the gust, W is the weight of the aircraft, ρ the air density, A the wing area, C_L the lift coefficient, α the angle of attack, w the gust velocit and V the horizontal velocity of the aircraft. (For literature see Krumhaar 1958).

Thus the bumpiness experienced by the aircraft is not only dependent on the atmos pheric input w, but also on various characteristics of the aircraft itself, like its weight and wingload, its aspect ratio and, last but not least, its elastic response properties which are r even included in Eq. (1). The response problem may be expressed in form of

$$\Phi_o(\omega) = |T(\omega)|^2 \cdot \Phi_i(\omega) \qquad \ldots(2)$$

where $\Phi_i(\omega)$ is the power spectrum of atmospheric input, (e.g. vertical accelera tions of the surrounding air), $\Phi_o(\omega)$ is the power spectrum of output (e.g. the vertical accelerations of the aircraft) and $T(\omega)$ is the frequency response function, which is controlle by the physical - mostly the elastic - properties of the aircraft.

We can easily see that in the range of critical response frequencies relatively sma atmospheric gusts may produce bumpiness in flight (Fig. 1).

Since the response characteristics of the airplane enter decisively into the CAT frequencies and intensities experienced by this aircraft, extrapolation to different vehicles, especially to SST (supersonic transport aircraft), becomes difficult. The turbulence charact istics as determined mainly from U-2 aircraft, showing a marked decrease of turbulence frequencies in the stratosphere (Fig. 2), may not be correct when applied in this form to SS]

For missiles traversing the atmosphere in a quasi-vertical direction the response problem is similar to the one expressed in Eq. (2), only that the atmospheric input will be o different nature from that with horizontally cruising vehicles. Small-scale vertical wind shears which, at times, may attain sizeable magnitudes (Fig. 3), may be a cause of vibratio especially when shears of alternating sign and/or magnitude are passed through with critical response frequencies. The missile, then, may experience something similar to CAT, altho the physical causes may be quite different from those of CAT experienced by aircraft.

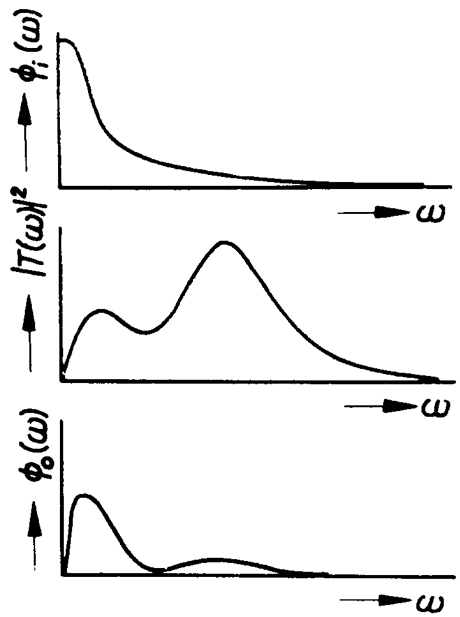


Fig. 1 Illustration to Equation 2.
(after Houbolt and Kordes 1954).
Schematic

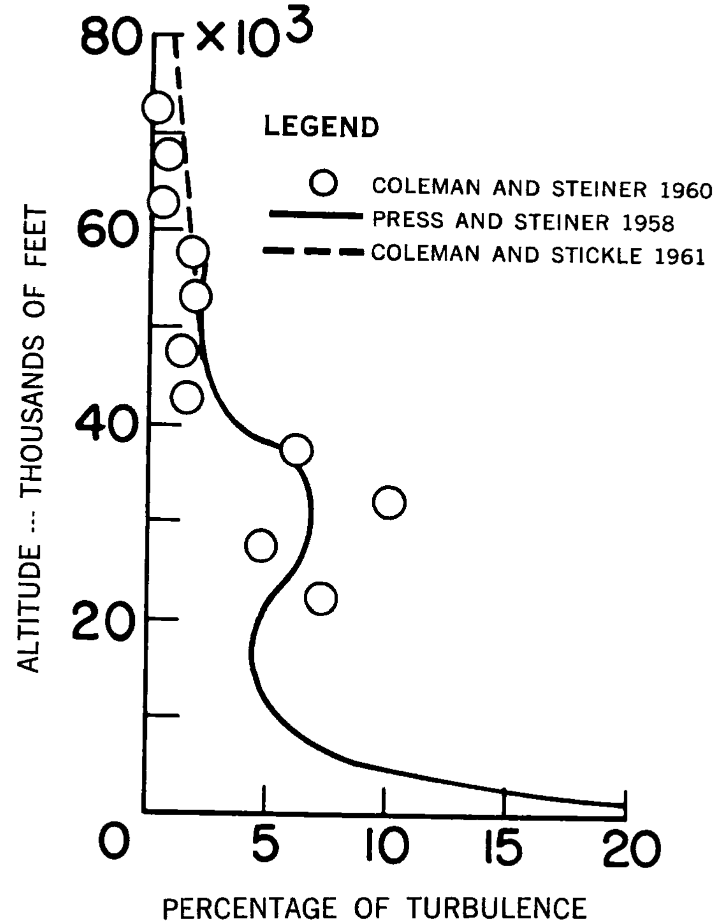


Fig. 2 Turbulence occurrence from U-2 data and from data presented by Press and Steiner and by Chandler and Stickle.

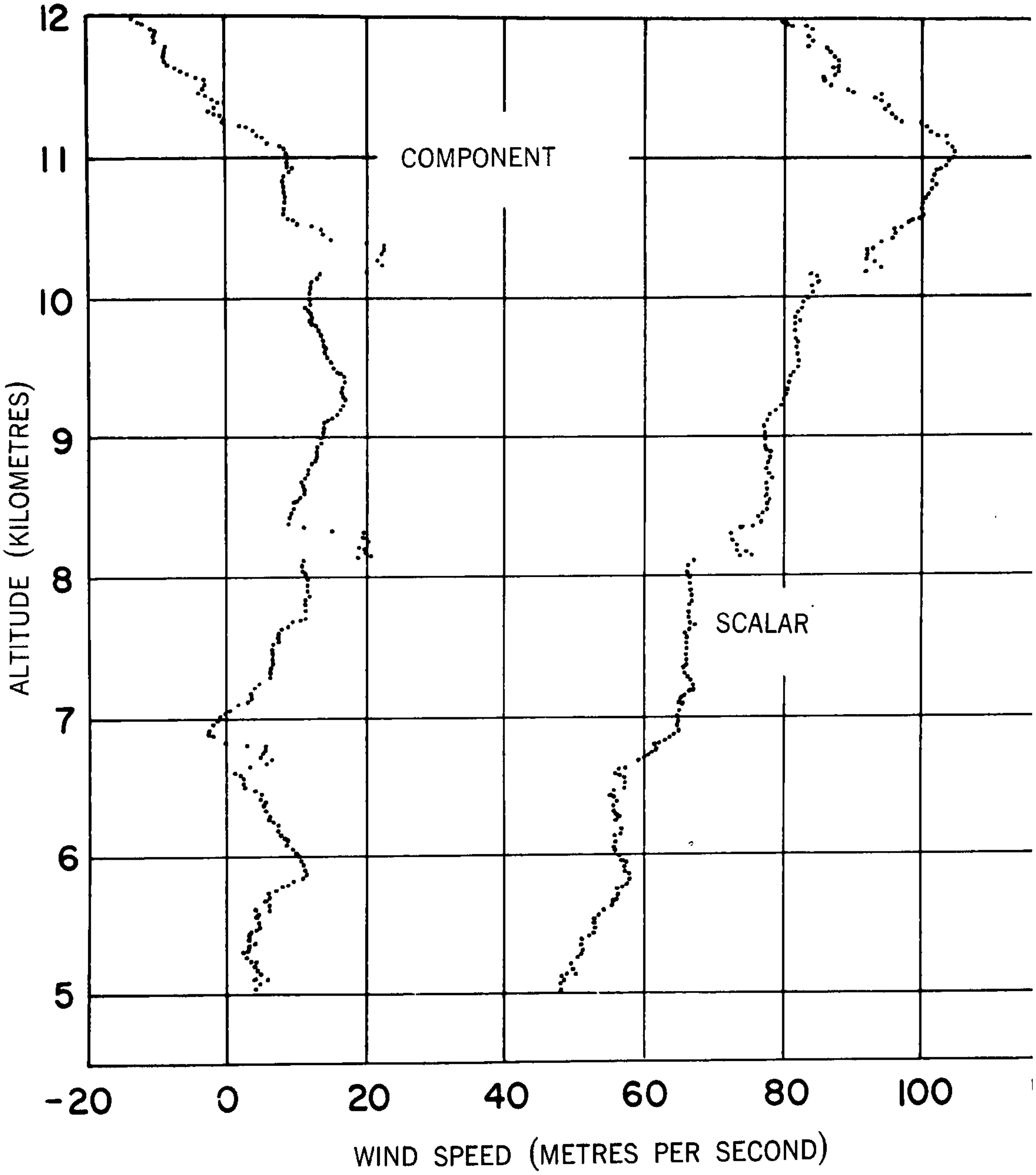


Fig. 3 Wind-speed profiles over Wallops Island; 30-sec. averaged winds measured by the smoke trail photographic technique. [Scoggins 1963a].

3. THE PHYSICAL NATURE OF C A T

Although CAT - or better termed "bumpiness in flight through clear air" - is an effect experienced off and on by all modern airborne vehicles, the peculiarities of their respective response characteristics lead us to suspect different causes for standard jet aircraft, SST and missiles. In the following we shall therefore attempt to outline possible causes of CAT separately for each of these three groups of airborne vehicles.

(a) CAT in Standard Jet Aircraft

When considering CAT we may usually rule out low level turbulence associated with convective motion in the mixing layer near the ground. The experienced pilot is well aware of this kind of turbulence. Although it cannot be totally avoided by aircraft since they have to pass through this layer in take-off and landing operations, the effects of this turbulence can be eliminated largely by proper flight manoeuvres. The presence of a convection layer near the ground usually poses no forecasting problem either. Furthermore, if such a layer extends over greater depths, it is usually heralded by the formation of cumulus-type clouds. In the following we shall concern ourselves, therefore, only with the occurrence of CAT at high levels, in the upper troposphere and in the stratosphere.

Radiosonde ascents frequently reveal the presence of nearly-adiabatic layers at jet stream level. Convective motion within such layers - sometimes evident from the presence of cirro-cumulus clouds - should therefore not be ruled out entirely as possible sources of CAT. As has been mentioned in the introduction, however, statistical evidence points towards a correlation between stable layers associated with vertical wind shears and CAT. Flight data from Project Jet Stream have brought this out rather clearly (Fig. 4) (Sasaki 1958, Reiter 1961a, b, 1962, 1963a, Endlich 1963).

Such stable layers with vertical wind shears would be conducive to the formation of gravity-type wave disturbances possibly of an unstable breaking nature (Haurwitz 1941, Reiter 1961b, 1963a). For an order-of-magnitude estimate of atmospheric conditions at an interface between two layers favouring the formation of gravitational shearing waves, we may take the equation of critical wave-length (L_c) of Helmholtz waves, below which any infinitesimal disturbance would grow exponentially,

$$L_c = \frac{2\pi}{g} \frac{(u_o - u_1)^2 \, T_o \, T_1}{(T_1 + T_o)\,(T_1 - T_o)} \qquad \ldots (3)$$

where u stands for wind speed, T for temperature and subscripts 0 and 1 refer to the lower and upper layers, respectively. The following table gives an estimate of wind-shears, $\Delta u = (u_1 - u_o)$, producing certain critical wave lengths with certain temperature discontinuities measured across the interface.

Table 1: Vertical wind shear Δu (m $\sec^{-1}$) for different temperature discontinuities T(°C) and vertical wave lengths (L_c) at an interface

T (°C)	L_c = 200 m	L_c = 100 m	L_c = 50 m
2°	2.3 m $\sec^{-1}$	1.6	1.2
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

More refined treatments of wave formation, using three-layer models of the atmosphere with a transition zone rather than a sharp discontinuity, have been given by Sekera (1948) and Sasaki (1958).

As is borne out by Eq. (3) the wind shear contributes to the generation of gravitati al shearing waves, but not the absolute magnitude of the mean wind velocity in the CAT regi Maximum requirements of 60 knots, as have been proposed by George (1961) in a CAT forecasting method, therefore do not have a direct physical relation with turbulence occurrence. Such considerations have been brought about by the general statistical relationship between jet-streams and turbulence mentioned earlier.

During recent investigations of CAT cases over the United States it became evider that CAT frequently may occur with relatively weak winds in the region of merging of two branches of the jet stream (Reiter and Nania 1964, Reiter 1963b, 1964a). Fig. 5 shows su an occurrence over the United States on 13 April 1962, 00 GMT.

From cross-sections through the CAT region it becomes evident that the northwesterly and southwesterly jet branches actually are not merging into a side-by-side flow. Instead, the northwesterly branch is dipping in underneath the southwesterly one, as may be seen by the isogon distribution of Fig. 6c. The wind speeds (Fig. 5 and Fig. 6b) in the CAT region are fairly light, in part below the threshold value given by George, and so are the vertical scalar wind shears. In view of the rapid backing of wind with height, the vertical vector wind shears are quite substantial, however.

As has been pointed out by Schwerdtfeger and Radok (1959), turning of wind with height, as sometimes found in regions of CAT, is indicative of differential temperature advection. While they were investigating cold advection aloft and de-stabilization of the atmos phere, the case presented above clearly indicates the sliding-in of cold air under the warm southwesterly current, thus a stabilization of the atmosphere.

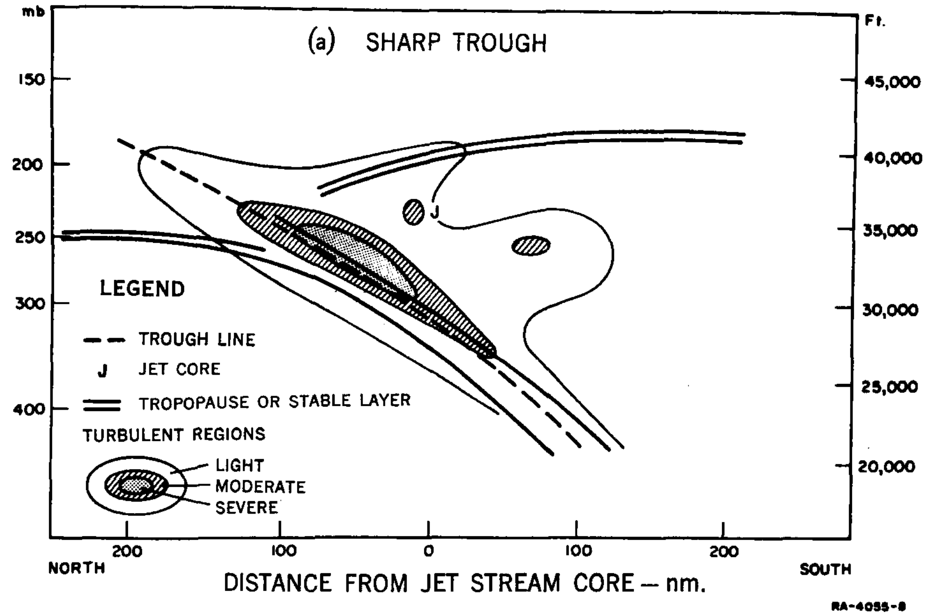
Fig. 6 presents only the macro-meteorological situation as obtained from radioso reports. The aircraft measurements - not too reliable because of the varying standards of wind-measuring equipment in use - have been entered for comparison. It will have to be su pected that the relatively deep layer of strong turning of wind with height breaks down into a sequence of shallow layers, in which the vertical vector wind shear is actually concentrated

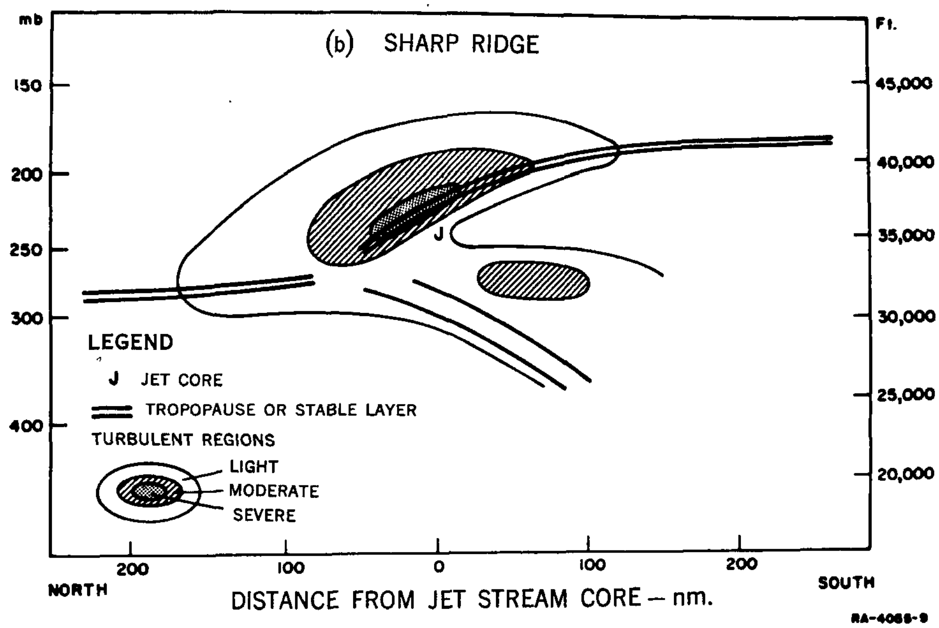
Such shallow shearing layers have actually been found during Project TOPCAT m surement flights over Australia (Reiter 1964b). In several cases it could be observed that smoke plumes released from the aircraft in CAT regions were shearing out into quasi-horizontal sheets. Cases of moderate CAT have actually been found during this project in areas where the wind speeds were less than 40 knots, but at the same time winds were turn rapidly with height.

From isentropic trajectory analyses it could be established that our old concepts "merging" and "splitting" of polar-front and subtropical jet-streams, derived mainly from isobaric analyses, have to be abandoned. In Fig. 7 - sequential to Fig. 5 - this "classical" concept has been indicated by heavy dashed jet axes. The heavy dotted lines indicate the ac cross-over that occurs between the northwesterly and the southwesterly jet-stream branche (Fig. 8). In the cross-over region most of the CAT seems to be concentrated.

A study of Gibbs (1952) shows that such a merging zone between two jet branches seems to be located frequently over western and central Australia. Due to this climatologi jet-stream pattern, CAT was encountered relatively frequently during Project TOPCAT wit rather shallow zones and in relatively weak winds.

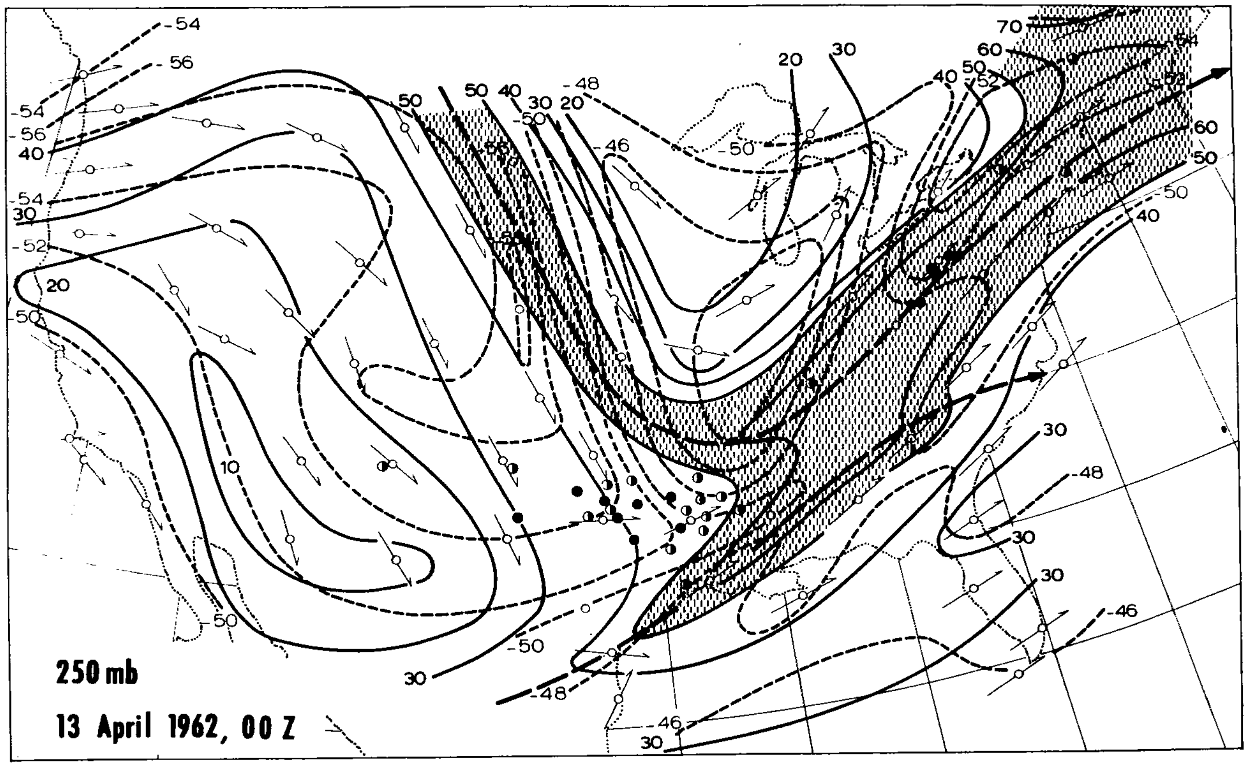
Underneath a well-developed jet maximum, wind directions usually are rather unif with height. On these occasions, turbulence may be encountered within the baroclinic zones below and above the jet-stream core (Fig. 4) where most of the vertical - and for that matte also the horizontal - wind shear is concentrated. Again the combination of thermal stabilit vertical shear provides a suitable setup for (stable or unstable) gravity waves. Such areas underneath jet maxima in the region of "jet-stream fronts" correspond well with George's C forecasting rules.





NOTE: Most of the CAT seems to occur in stable and shearing layers below and above the jet-stream core (Endlich 1963).

Fig. 4 Schematic model of turbulence occurrence near jet-streams, (a) in sharp troughs, (b) in sharp ridges, from research flight measurements of Project Jet Stream.



LEGEND

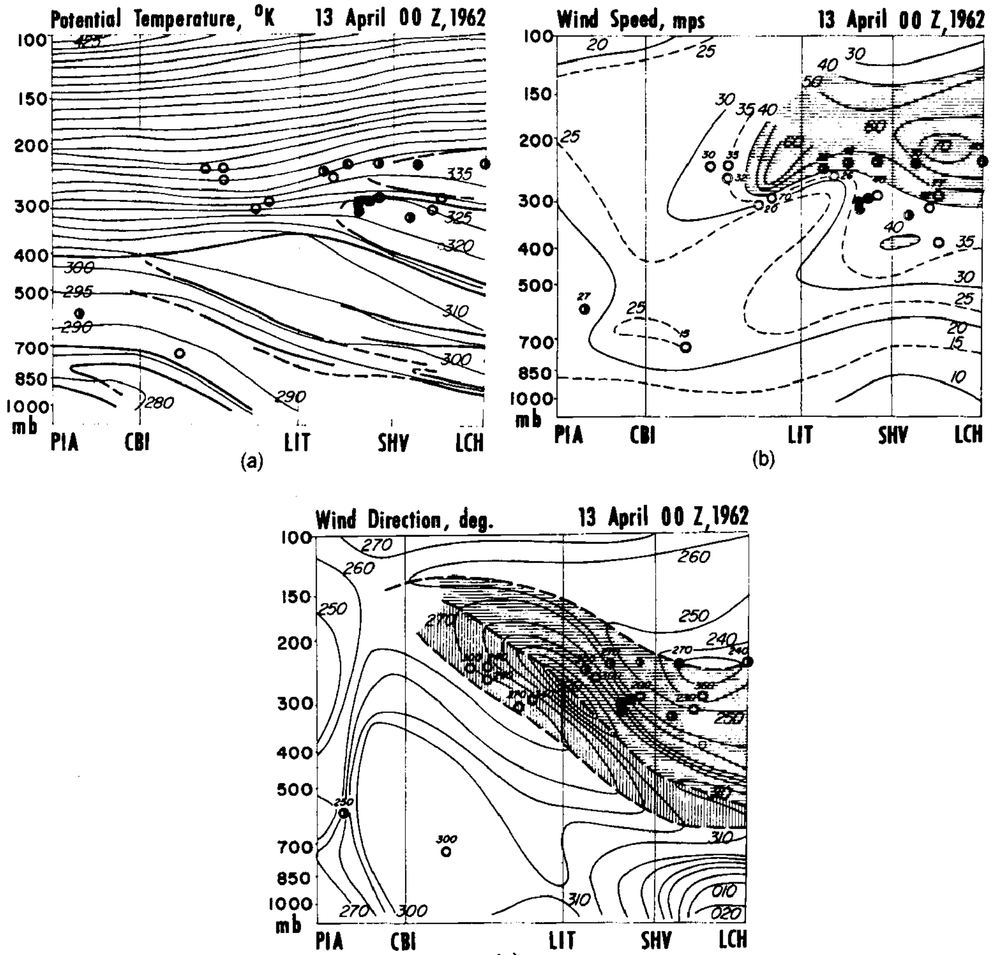
ISOTACHS [mps] — MODERATE CAT

ISOTHERMS [Centigrade] — SEVERE CAT

Regions with speeds > 50 mps. — JET AXES

(Numerous reports of light CAT have not been entered into this figure.)

Fig. 5 Isotachs and isotherms of the 250 mb surface, 00 GMT 13 April 1963.



(a) (b) (c)

LEGEND

—— STABLE LAYERS AND TROPOPAUSES

CAT OBSERVATIONS IN THE VICINITY OF THE CROSS-SECTIONAL PLANE

LIGHT CAT

MODERATE CAT

SEVERE CAT

THE BLACK PORTIONS OF THE OUTER RINGS INDICATE THE TIME OF THE CAT OBSERVATIONS (PLUS OR MINUS 6 HOURS FROM MAP TIME SHOWN BY A BLACK SEMI-CIRCLE TO RIGHT OR LEFT OF INNER CIRCLE).

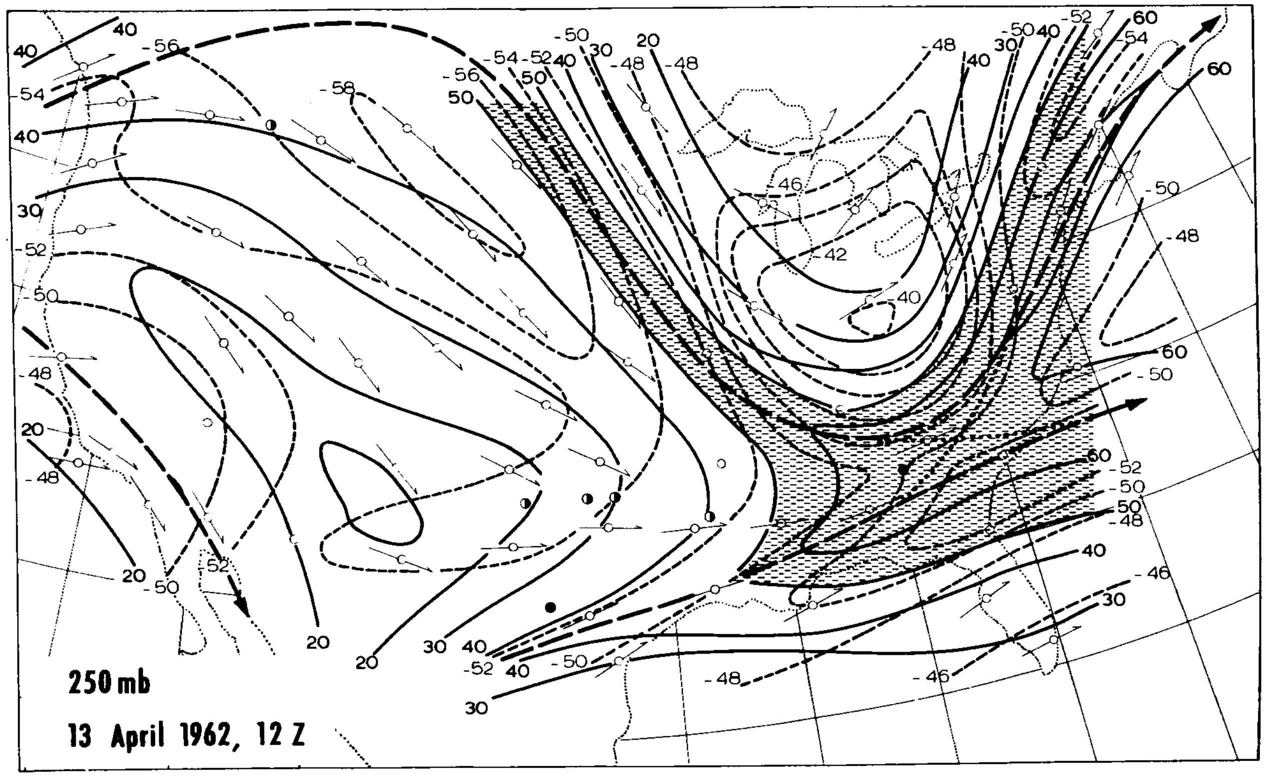
AIRCRAFT WIND REPORTS

REGION WITH WINDS > 40 mps.

— — MAXIMUM AND MINIMUM DIRECTIONS OF WIND

REGION OF STRONG TURNING OF WIND WITH HEIGHT

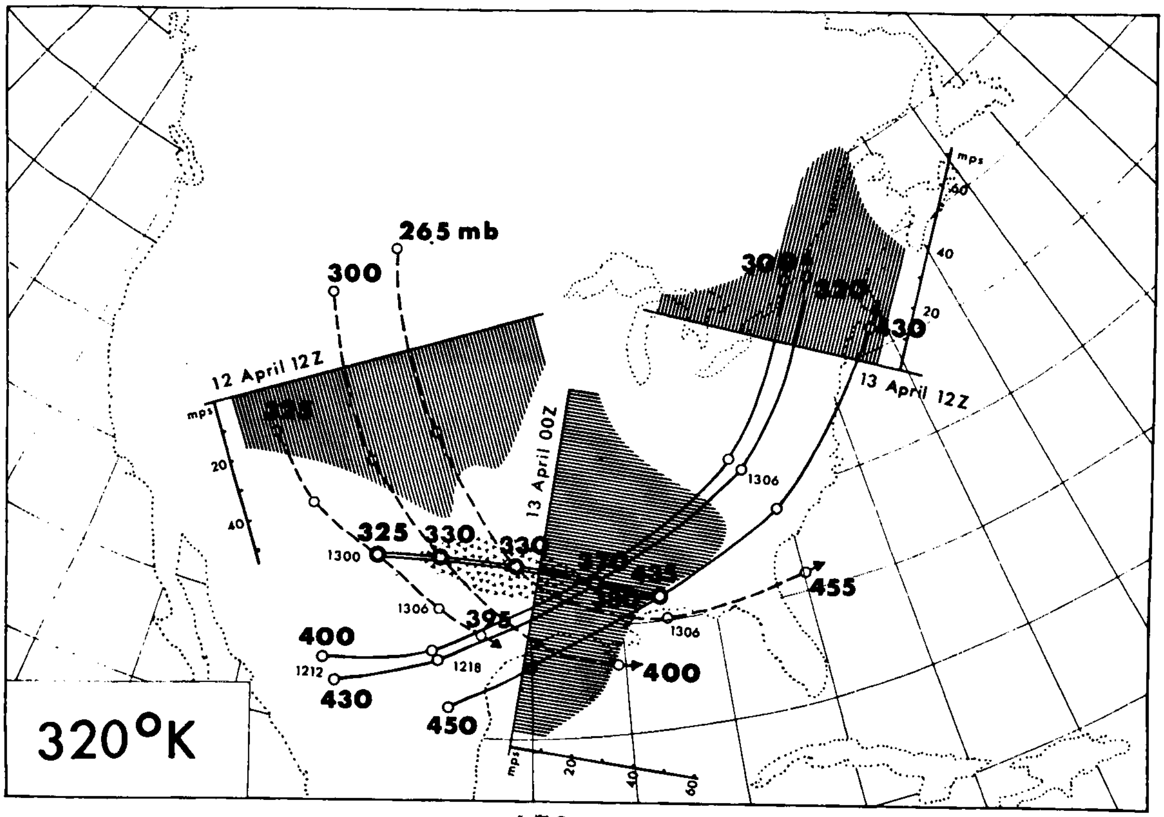
Fig. 6 Cross-section through the atmosphere from Peoria, Ill. (PIA) to Lake Charles, La. (LCH), at 00 GMT 13 April 1962. (a) Potential temperature (°K); (b) Wind speeds (mps); (c) Wind direction (degrees).



LEGEND

- ISOTACHS [mps]
- ISOTHERMS [Centigrade]
- Regions with speeds V 50 mps.
- MODERATE CAT
- SEVERE CAT
- JET AXES
- Cross over of the JET AXES

(Numerous reports of light CAT have not been entered into this figure.)



LEGEND

- TRAJECTORY POSITIONS AT 6 HOURLY INTERVALS
- NORTHWESTERN JET BRANCH
- SOUTHWESTERN JET BRANCH
- CAT REGION
- AXIS OF THE CAT REGION
- ISENTROPIC WIND PROFILES WITH SCALE IN mps ARE ENTERED ALONG THE SOLID BASE LINES, WHICH RUN APPROXIMATELY NORMAL TO THE UPPER FLOW. THE PROFILES HAVE BEEN CONSTRUCTED FOR MAP TIMES AS INDICATED

Fig. 8 Trajectories along isentropic surface 320° K, tracing the air motion backward and forward from the locations at 00 GMT 13 April 1962, marked by double circles.

So far we have assumed that infinitesimally small perturbations of random nature are amplifying under suitable conditions of thermal stability and vertical shear until they reach proportions recognizable as CAT. In reality, however, nature provides a number of sources of perturbation energy, which are by no means "random". Large-scale convective motions, squall lines, pressure-jump lines, etc., may generate disturbances which travel downstream.

The most obvious source of perturbations lies in orographic features of the underl terrain. Air flowing over mountain or hill ranges is forced to deviate from its horizontal path. The resulting perturbations of horizontal flow may be carried upward under favourabl conditions, sometimes even to stratospheric levels. Theoretical studies relating to the forr tion of lee-waves have been made by Lyra (1940, 1943), Queney (1941, 1947), Scorer (1949) others (for literature see Reiter 1960).

From photogrammetric cirrus-cloud studies in the vicinity of the Rocky Mountain (Reiter and Hayman 1962) it became evident that with the formation of large-scale lee-waves several kilometres in wave length as described by Scorer, frequently smaller-scale wave di turbances are generated with only a few hundred metres wave length. Some of these smalle waves, which have the same order of magnitude as would be required for CAT*, seemed to l standing gravity waves, others seemed to be travelling with the mean wind at their level wit noticeably changing their shape. The latter seem to represent "frozen images" of wave per turbations that have been active earlier and farther up-stream, but still were visible as a wave-cloud pattern because of the slow rate of evaporation from the once-formed cirrus-clo

If we consider conditions favorable for lee-wave formation to be also favorable fo smaller "CAT-wave" generation, we may use Scorer's parameter,

$$l^2 = \frac{g}{\theta}\frac{\partial \theta}{\partial z} \Big/ V^2 \qquad \ldots(4)$$

as a guide for CAT diagnosis (g = acceleration of gravity, θ = potential temperature, z = height coordinate, V = wind speed). Lee-waves will attain maximum amplitudes at a sta interface, if l^2 decreases uniformly throughout the troposphere up to the base of this stable layer. Such favorable conditions are frequently met underneath a jet maximum crossing a mountain range, if the low level flow shows a strong component normal to the range. Espec when a stable layer reaches to approximately the height of the mountain range, decreasing stability and increasing winds above this layer will assure a decrease of l^2 up to the base o "jet stream front" or to the tropopause. The three cases of severe CAT reported in Fig. 5 over the Allegheny Mountains were probably of orographic origin since they show these nece ary requirements in the l^2 parameter.

Similar conditions were encountered during the Project TOPCAT research flight September 4, 1963, to the lee of the Flinders Range over South Australia. The passage of a cold front with strong southwesterly flow onshore and across the mountains created a favor situation of lee-wave formation. The orographic effects of the mountain range in this case were accentuated by the frictional differences between the Australian Bight and continental conditions east of the gulf of St. Vincent (Reiter 1964b).

A sufficient amount of perturbation energy may be supplied even by small hill ran or by coast lines, to produce a significant pattern of CAT frequency aloft, as has been point out by Clodman et al. (1961).

(b) CAT in Supersonic Transport Aircraft (SST)

The presence of gravity-type wave disturbances should be suspected even at high stratospheric levels than are presently used by commercial jet aircraft. Again the effect o mountain ranges should be felt significantly. Stable regions as well as vertically shearing

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* A jet-aircraft of 400 knots true air speed would experience one bump per second if up- and down-drafts were spaced approximately 200 m.

layers are in evidence from radiosonde observations, especially in the region of the polar-night jet-stream. We should expect, therefore, that high-flying aircraft will encounter CAT at practically all levels of aircraft operations.

Data collected by U-2 aircraft confirm this conclusion (Fig. 2). They show a marked decrease in CAT frequency as we go higher up in the stratosphere. (The significance of the slight secondary frequency maximum near 55,000 ft has not yet been established.) It should be pointed out, however, that a supersonic transport aircraft will respond to an entirely different portion of the spectrum of atmospheric disturbances than does a U-2. The response characteristics of these two types of aircraft will also differ widely. A firm conclusion as to the CAT expectancy of the SST at stratospheric cruising levels, therefore, is not yet possible.

So far we have only dealt with possible CAT generation by the action of atmospheric gusts. The SST might, however, react to periodic changes in temperature with vibrations similar to CAT.

The drag coefficient, C_D, at supersonic flow depends on the Mach number $M = V/V_s$ (V = speed of the aircraft, V_s = speed of sound).

$$C_D = \frac{4\alpha^2}{\sqrt{M^2 - 1}} \qquad \ldots (5)$$

where α is the angle of attack. The speed of sound in dry air may be approximated by

$$V_s = \left(\frac{C_p}{C_V} \cdot \frac{RT}{m}\right)^{\frac{1}{2}} \qquad \ldots (6)$$

where C_p and C_V are the specific heats of dry air under constant pressure and constant volume, respectively, R is the universal gas constant, T the temperature and m the molecular weight of dry air.

The speed of sound, thus, is controlled by the temperature, and (in turn) influences the drag coefficient.

We may hypothesize a temperature discontinuity at the flight level of a SST which, by the action of some disturbance, may be "warped" into a wave pattern. The SST "skimming" along this wavy interface would experience periodic changes in its drag coefficient. If the wave length of these waves corresponded to a critical response frequency, the SST might very well experience CAT without any direct gust input from the atmosphere. The temperature effect upon the drag coefficient is most critical near Mach number M = 1 (Webb 1963). Specific attention, therefore, might have to be paid to the detailed atmospheric structure near the location where a SST penetrates the sound barrier.

(c) CAT in Missile Operations

As has been pointed out earlier, vertically rising vehicles will react to a different atmospheric input than horizontally flying aircraft. The main concern for missile operations lies with excessively large vertical wind shears on account of the bending momentum which they may exercise upon the tall and slender body of the missile, and with short term variations in sign and/or magnitude of the vertical wind shear because of resonance vibrations that might be triggered off in the missile as a whole or in its components.

While the presence of large vertical shears especially in the jet-stream region has been realized for quite some time and has been taken into account in the so-called "design wind profiles" (Sissenwine 1954, 1958), the existence of small-scale variations of vertical wind shears could be established with certainty only recently from very detailed measurements. The FPS-16 radar has a fine enough resolution to yield such detailed information (Scoggins and Vaughan 1963, Scoggins 1963a, b, Reiter 1963c). As a matter of fact, the wind measurements taken with this generation of radar instruments are accurate enough to pick up the erratic behaviour of balloons produced by the shedding of eddies under adverse Reynolds' numbers.

Even though some of the smaller variations in the vertical wind profiles measure by the FPS-16 radar may have been simulated by turbulence generated by the ascending balloon, there are quite a number of details present which have sufficient amplitude and con tinuity in time to assure atmospheric causes rather than erratic balloon behaviour.

Scoggins (1963a) published a wind profile measured with such refined equipment, showing three "embedded jetlets" mainly in one component of the wind vector (Fig. 3). Th vertical vector wind shears resulting from these embedded jetlets are quite appreciable.

A series of 18 wind measurements taken by FPS-16 radar over Cape Kennedy (th Cape Canaveral) on 3 January 1963 are shown in Fig. 9. The measurements were approxin ly 45 minutes apart in time. A series of meso-structural wind fluctuations is evident, especially above the 10-km level, showing remarkable persistence with time. While the sh appearing in these structural details are not excessively large, the presence of a certain periodicity as a missile would pass through these shears vertically might be of interest.

Sufficient data of this kind have not yet been accumulated to warrant an explanatic of the physical nature of these structural details. A preliminary analysis of the case prese in Fig. 9 shows that a moderately strong jet stream, moving in over the Cape Kennedy regi apparently advected the observed meso-structure. Fig. 10 shows the field of "basic flow" which remains after the meso-structure has been eliminated by smoothing the vertical wind profiles. Fig. 11 contains the meso-structure alone, which, added to the basic flow of Fig should yield the original wind profiles of Fig. 9. Fig. 12 shows the parameter of vertical stability ($\Gamma - \gamma$) where Γ is the dry adiabatic, γ the actual lapse rate. A certain – by no means perfect – correlation seems to be indicated between Fig. 11 and Fig. 12, suggesting certain controlling influence of the thermal structure of the atmosphere.

More detailed studies will be necessary in order to establish the physical nature the possible causes of such a correlation – if it actually existed. Short-range forecasts of meso-structure in vertical wind profiles might then become feasible.

4. CONCLUSIONS AND OUTLOOK

The problems of response of aerospace vehicles to small-scale atmospheric dist ances in the fields of wind and temperature have helped initiate a vast field of research intc the microstructure of the free atmosphere. Some of our present ideas on the physical natu of this microstructure still are rather crude. Measurement programs, like the one of Project TOPCAT, are contributing significantly to the understanding of the nature of clear· turbulence.

Although the hypothesis of CAT in horizontally flying aircraft being mostly a gra type wave phenomenon seems to produce working results, there are still a number of quest waiting for a solution.

Are these waves of a stable or unstable nature?

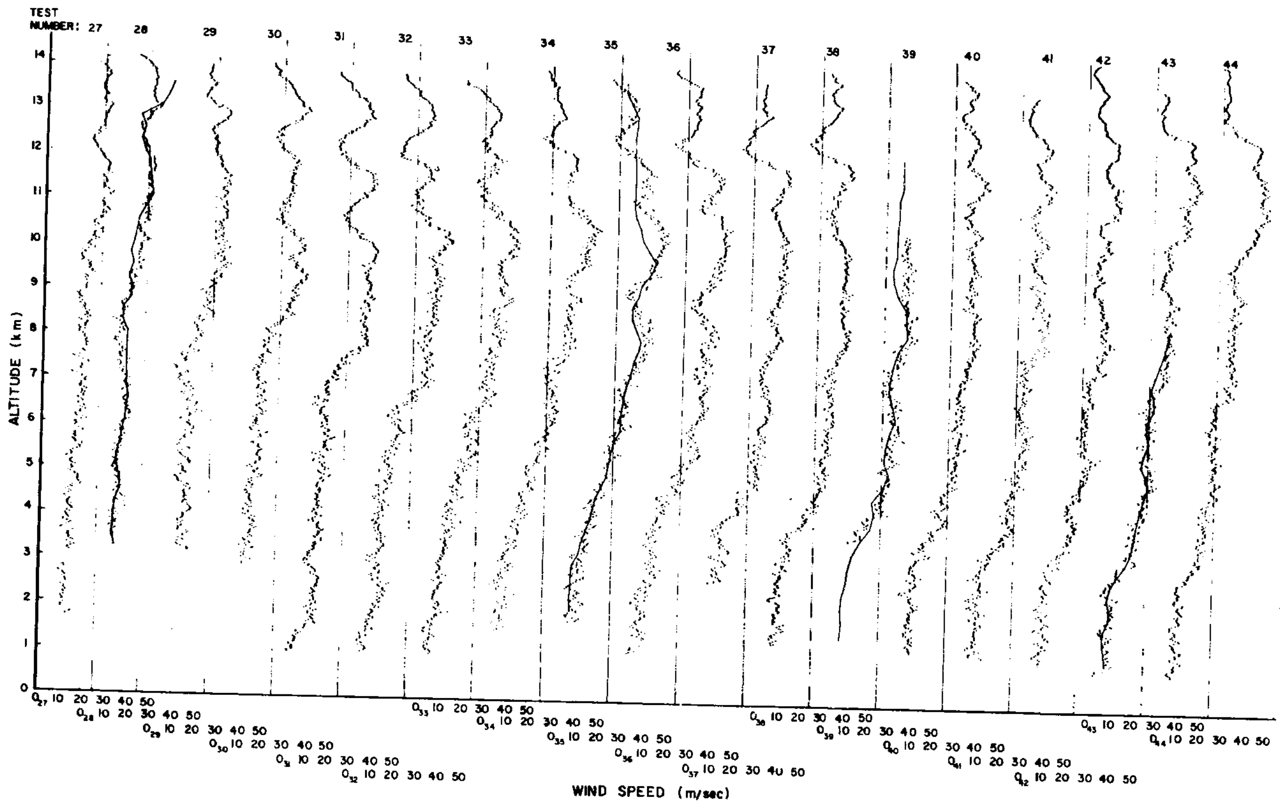
Are "turbulent" patches embedded at random in a surrounding of smooth flying conditions?

What are the critical meso-structural requirements to produce CAT?

May lee-wave formation produce CAT even at flight levels of the SST?

There are many more questions of a similar nature, which can only be answerec attacking the atmosphere with instruments rather than with paper and pencil.

The rather stable jet-stream conditions of the Southern Hemisphere apparently a great asset to Project TOPCAT. Similar measurement programs might make use of var underlying terrain. The vast plains of the interior of Australia as compared with the stee rising mountains of New Zealand, disturbing an atmospheric flow which has travelled over large stretch of ocean, thus establishing a genuine orographic input into CAT, should prov a suitable background for investigation.



NOTE: The solid curves indicate wind measurements by standard rawinsonde equipment at 11, 17, 20 and 23 hours GMT, 3 January 1963. A shifting scale has been used for the indication of wind speeds (mps) along the abcissa (Scoggins and Vaughan, 1963).

Fig. 9 Vertical wind profiles measured at approximately 45-minute intervals by FPS-16 radar over Cape Kennedy on 3 January 1963.

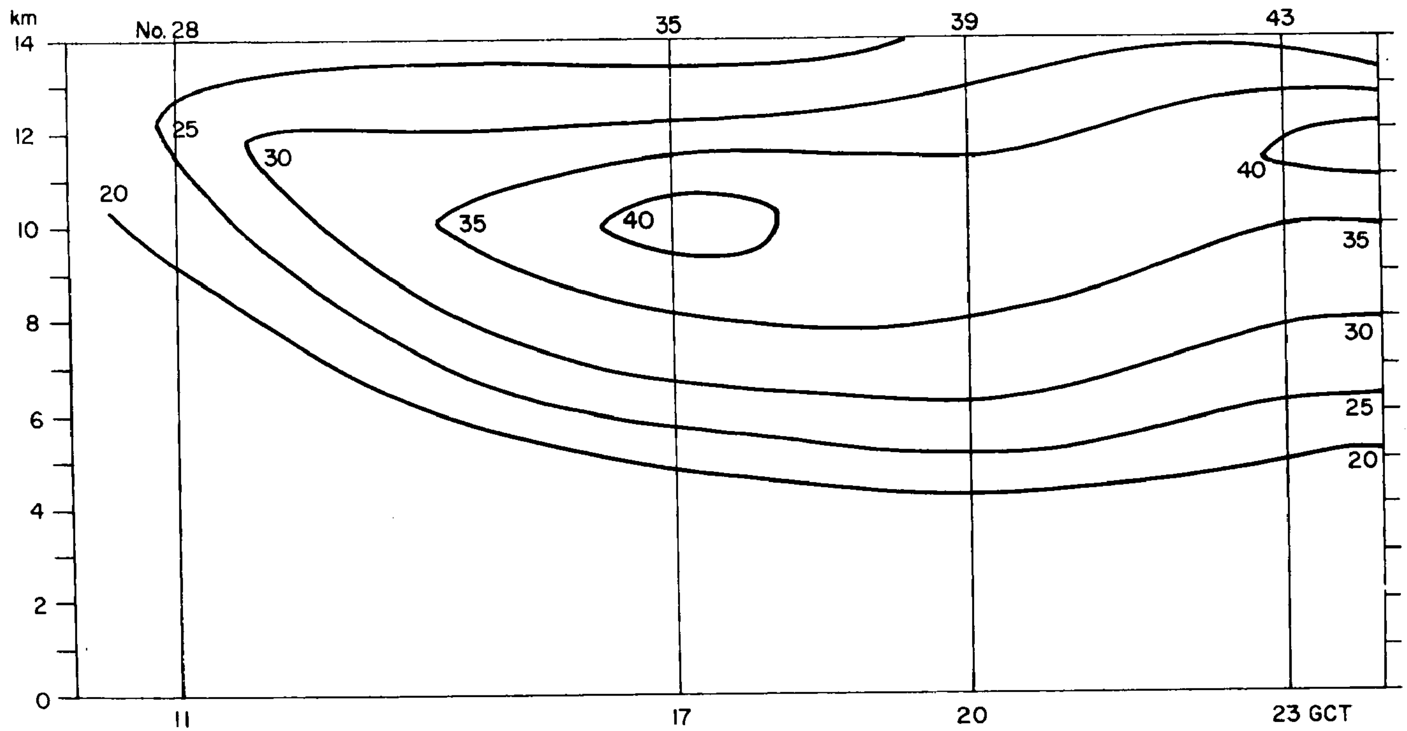


Fig. 10 Time section of wind speed (mps) of "basic flow" over Cape Kennedy for 11, 17, 20 and 23 hours GMT 3 January 1963.

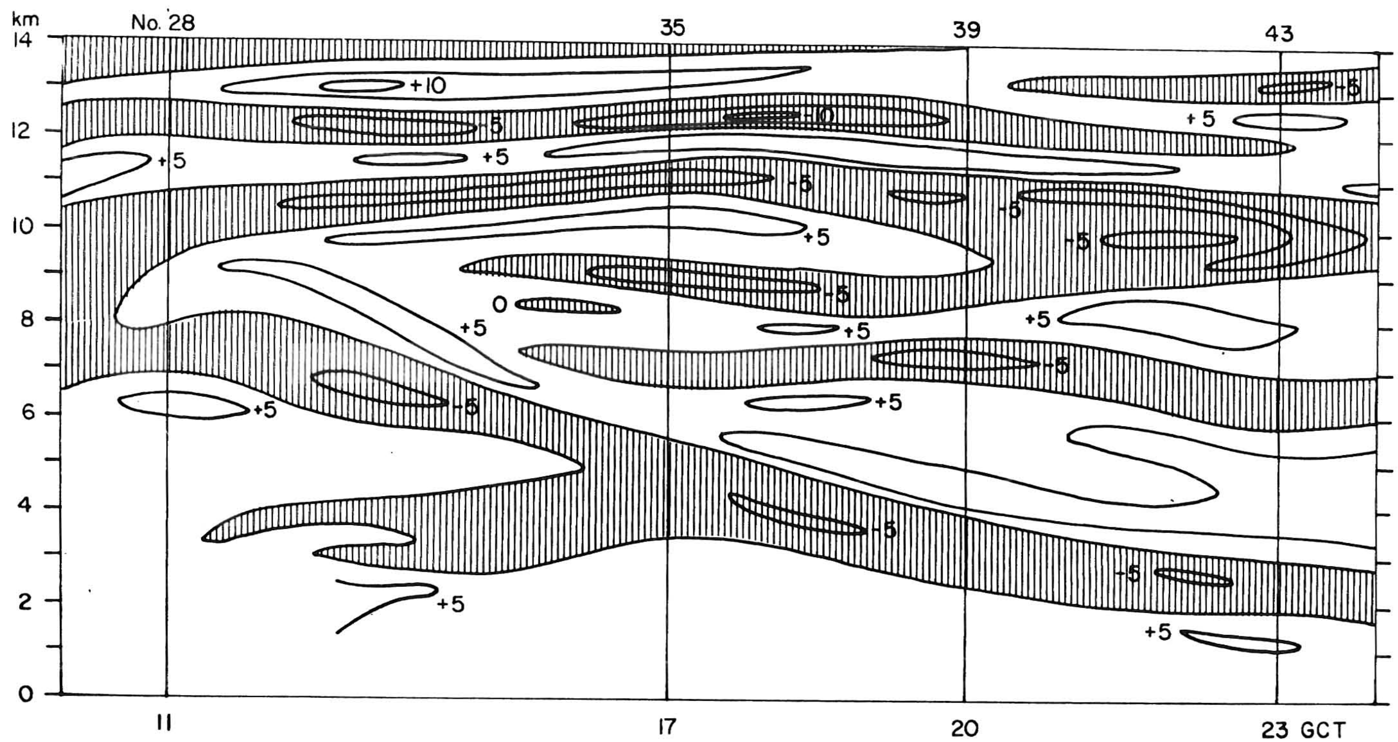


Fig. 11 Time section of mesostructure of wind speeds, Cape Kennedy, 3 January 1963 expressed in terms of anomalies (mps) from the analysis presented in Fig. 10.

Time scale is the same as in Fig. 10 Negative anomalies are shaded.

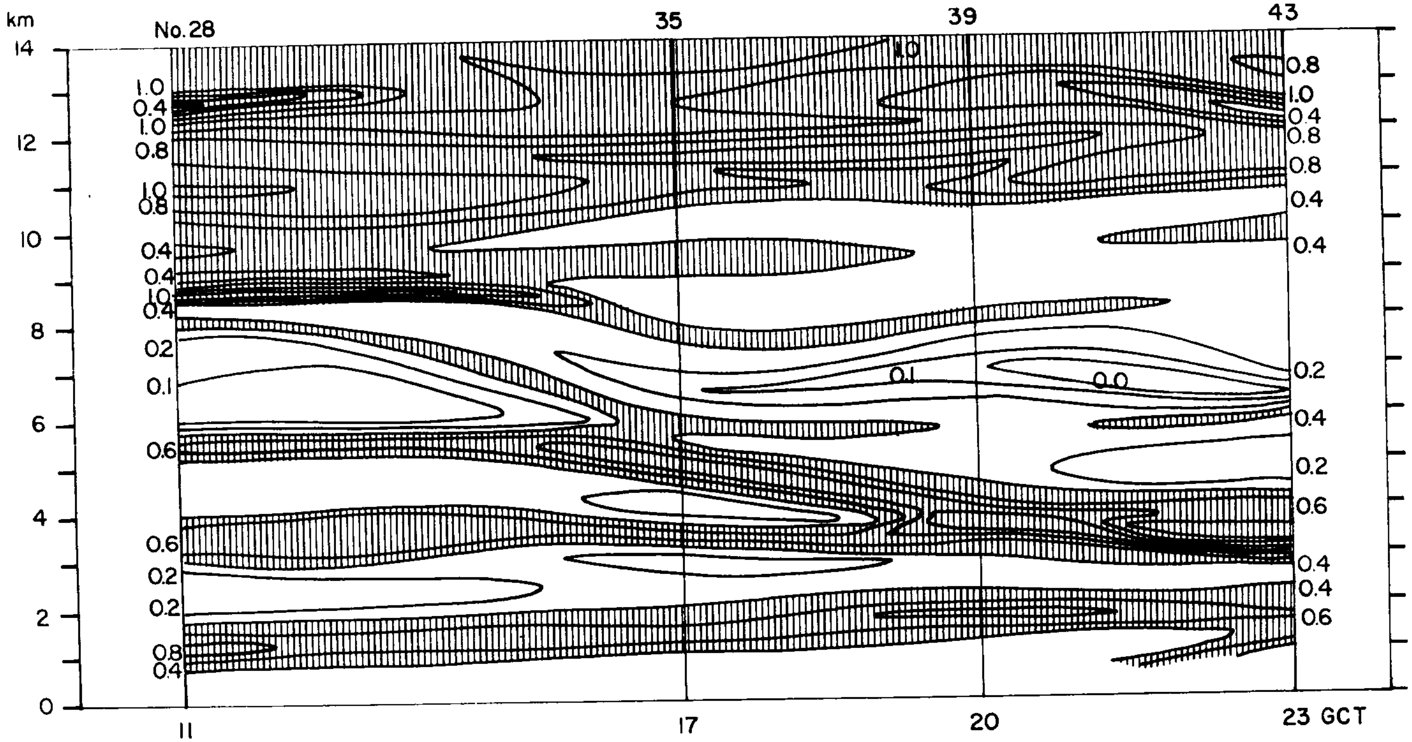


Fig. 12 Time section of stability $(\Gamma + \partial T/\partial z)$, Cape Kennedy, 3 January 1963.

Time scale is the same as in Fig. 10

LAYERS WITH STABILITY > 0.4° C/100 m are shaded.

A correlation of details of vertical profiles as measured with FPS-16 radar, with CAT observed by aircraft has not yet been attempted. A combined ground-based and air-born measurement program might bring us one step closer to the elimination of CAT as a serious flight hazard.

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