

# The nature of Clear Air Turbulence

by Prof. E. R. Reiter, Colorado State University, Fort Collins, USA

Presented at the 9th OSTIV-Congress, Junin, Argentine, February 1963

## Summary

The possible nature of Clear Air Turbulence (CAT) is discussed in the light of recent investigations. Its detrimental effects on aircraft structures and passenger safety call for the development of forecasting procedures which should be based on a physical understanding of the phenomenon. The development of supersonic transport aircraft will have to incorporate into its design the possibility of Clear Air Turbulence even at stratospheric flights levels.

## Introduction

Ever since flying aircraft have penetrated the tropopause and have chosen the stratosphere for their operational field, it became evident that the encounter of severe bumpiness is by no means confined to the lowest layers of the atmosphere near the ground. A long list of accidents, more or less severe in nature, has contributed to the opinion that Clear Air Turbulence still is one of the major hazards of modern jet aviation.

Clear Air Turbulence also turns out to be an economic problem, because the gust loads experienced by an aircraft diminish its life expectancy, and make costly overhauls

necessary. Furthermore, passengers who have experienced severe cases of CAT may on future trips prefer the stage coach to an aircraft.

The exploration of the physical nature of Clear Air Turbulence becomes exceedingly difficult because in measuring the conditions which might lead to bumpiness in flight, we are depending on the airplane as an instrument carrier. Our measurements, therefore, will be «contaminated» by the response of the aircraft to atmospheric gusts. Thus, Clear Air Turbulence is not only a meteorological, but also an engineering problem.

## (2) What We Observe

An airplane flying through a region of CAT usually experiences a number of more or less severe jolts in an upward or downward direction. The frequency of the severe bumps usually lies close to the response frequency of the aircraft, which is determined by a number of factors including the weight and the elastic characteristics of the aircraft. Thus the bumpiness which a passenger may experience in the aircraft may not all be a true reflection of the gust distribution in the surrounding atmosphere. Need-

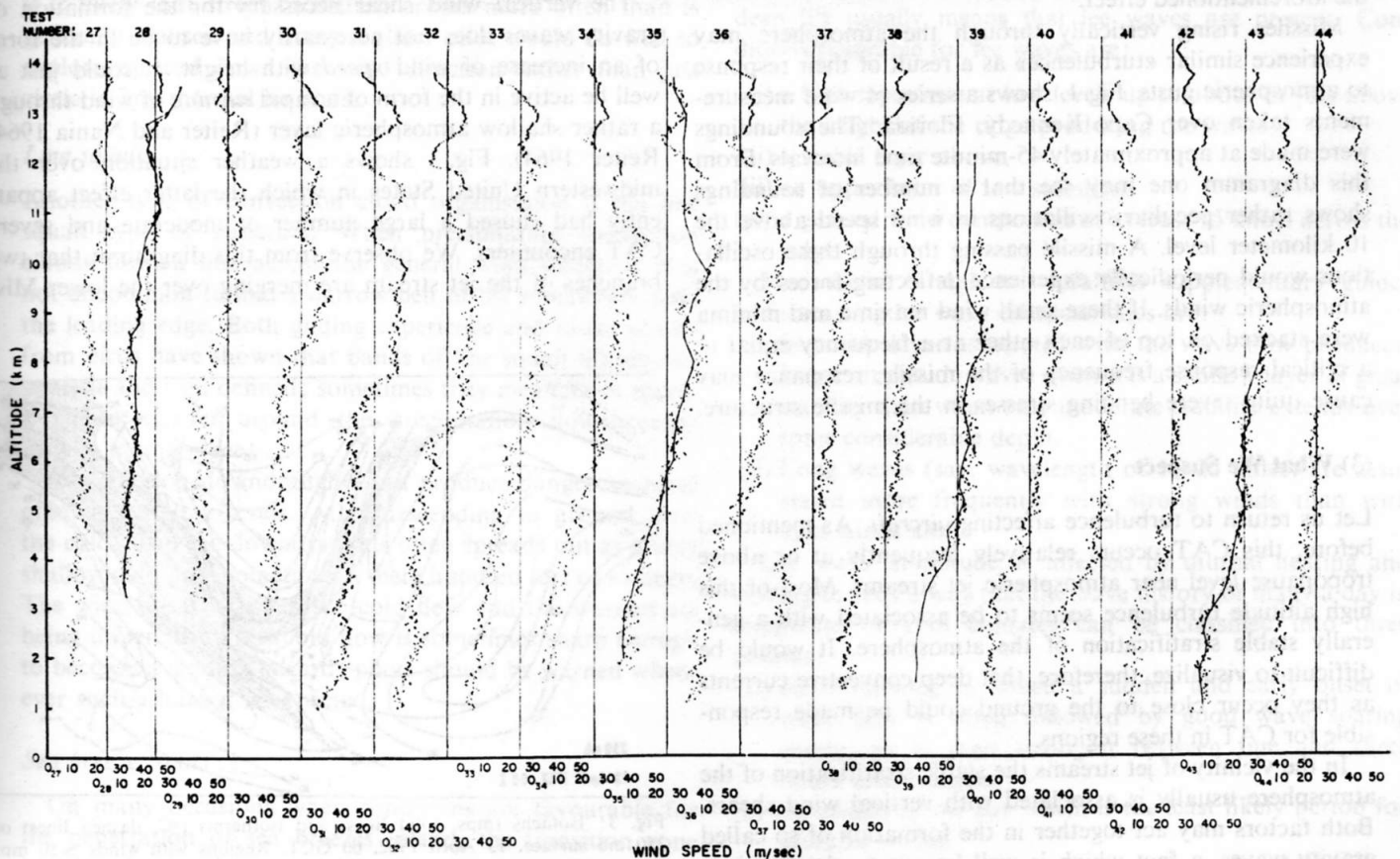


Fig. 1: Vertical wind profiles measured at approximately 45-minute intervals by FPS-16 radar over Cape Kennedy on 3 January, 1963. Solid curves indicate wind measurements by standard radiosonde equipment at 11, 17, 20 and 23 GCT, of the same day. A shifting scale has been used for the indication of wind speeds (mps) along the abscissa (Scoggins and Vaughan, 1963).

less to say that meteorologists and engineers have to do a lot of extrapolation in extracting the atmospheric conditions from accelerometer recordings taken in an aircraft.

To establish the state of turbulence in the surrounding atmosphere, rather than merely stating the behavior of a specific type of aircraft, becomes important when the reactions of a new, and not yet tested, type of aircraft should be predetermined. This presents a problem especially when the flight characteristics of a supersonic transport aircraft (SST) should be calculated from measurements and observations taken by subsonic aircraft. Not only may vertical and horizontal gusts influence a supersonic transport aircraft (SST) in a similar way as they would for instance a B-707 or DC8, but the temperature effects upon speed of sound and drag coefficient might conceivably simulate turbulence, when there actually is none (Webb, 1963).

Especially in the transition from subsonic to supersonic flight the drag coefficient of an SST is very sensitive to Mach number and to the temperature in the surrounding air. We could think of the following conditions: Let a supersonic aircraft fly at approximately Mach 1 along an interface between two air masses that differ only slightly, maybe by one to two degrees centigrade, in temperature. Let us furthermore assume that this horizontal interface between the two air masses is corrugated into a «washboard» with waves of approximately two kilometers in length. The aircraft skimming along this corrugated interface would periodically be exposed to changes in the drag coefficient. This might conceivably result in a bumpy flight. Unfortunately, at this time there is not yet enough knowledge on the detailed temperature and wind structure of the stratosphere at flight levels of the future SST to allow any predictions of the aforementioned effect.

Missiles rising vertically through the atmosphere may experience similar «turbulence» as a result of their response to atmospheric gusts. Fig 1. shows a series of wind measurements taken over Cape Kennedy, Florida. The soundings were made at approximately 45-minute time intervals. From this diagram one may see that a number of soundings shows rather peculiar oscillations in wind speed above the 10 kilometer level. A missile passing through these oscillations would periodically experience deflecting forces by the atmospheric winds. If these small wind maxima and minima were stacked on top of each other at a frequency equal to a critical response frequency of the missile, resonance may cause quite severe bending stresses in the missile structure.

### (3) What We Suspect

Let us return to turbulence affecting *aircraft*. As mentioned before, this CAT occurs relatively frequently at or above tropopause level near atmospheric jet streams. Most of this high altitude turbulence seems to be associated with a generally stable stratification of the atmosphere. It would be difficult to visualize, therefore, that deep convective currents as they occur close to the ground could be made responsible for CAT in these regions.

In the vicinity of jet streams the stable stratification of the atmosphere usually is associated with vertical wind shears. Both factors may act together in the formation of so called gravity waves, a fact which is well known to theoreticians as well as the weather minded observer of wave clouds and billow clouds which form along such interfaces.

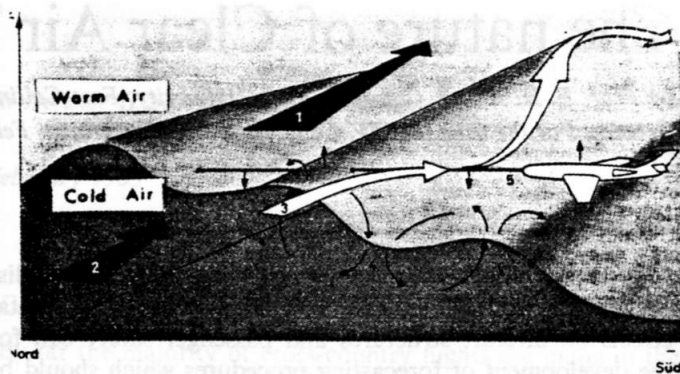


Fig. 2: One possible cause of CAT: a warped interface between cold and warm air. Heavy black arrows (1 and 2) indicate wind speeds in the two atmospheric layers. White arrows (3) outline particle trajectories along interface. Thin arrows (4) schematically portray vertical motions causing accelerations of the aircraft (5).

Fig. 2 shows what a might happen if an aircraft flies along such a temperature discontinuity along which vertical shear has generated a chain of waves. The aircraft would be subject to more or less periodic up and down drafts, caused by the atmosphere moving through these waves. The up and down drafts naturally would cause accelerations, and these would be experienced as bumpiness or CAT. The waves described in Fig. 2 would not necessarily have to be stable in nature. Depending on the conditions of vertical temperature lapse rate and of vertical wind shear they may amplify in time and break, thus giving rise to genuine turbulence. This would be an effect similar to the one of breaking water waves, which form under the influence of a strong wind blowing over a water surface.

The vertical wind shear necessary for the formation of gravity waves does not necessarily have to be in the form of an increase of wind *speed* with height. It could just as well be active in the form of a rapid *turning* of wind through a rather shallow atmospheric layer (Reiter and Nania 1964; Reiter 1964). Fig. 3 shows a weather situation over the midwestern United States in which the latter effect apparently had caused a large number of moderate and severe CAT encounters. We observe from this diagram that two branches of the jet stream are merging over the lower Mis-

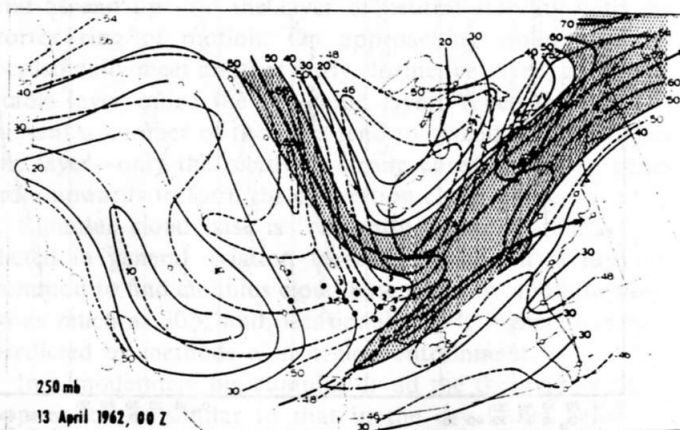


Fig. 3: Isotachs (mps, solid lines) and isotherms ( $^{\circ}\text{C}$ , dashed lines) of 250 mb surface, 13 April 1962, 00 GCT. Regions with winds  $> 50$  mps are shaded. Jet axes are indicated by heavy dashed lines with arrows. Half-black dots stand for moderate CAT, fully black dots for severe CAT observed within plus or minus 6 hours from map time. Reports of light CAT have been omitted.

The picture built up so far of the main convection characteristics refers to hot days with light or moderate winds and appreciable direct sunshine. A cover of cirrostratus or thin medium cloud may not change the picture from the aviation and general public point of view, but this upper cloud will reduce the instability of the low level superadiabatic layer, and heat from ground level is transported upwards more by numerous but small, disorganised thermals than by the relatively few larger thermals which are needed for soaring.

The ideal conditions for cross-country thermal soaring are about 2/8 to 3/8 of small cumulus cloud rather than large amounts of deep convection cloud.

The glider pilot also needs to know whether or not the convection cloud will spread out to form stratocumulus and literally cast a shadow over thermal soaring prospects. Experience suggests that the higher the humidity of the environment the greater the risk of spreading out, and the tendency for such spreading out often becomes apparent by about midday, leaving mid-morning and mid-afternoon the optimum periods for thermal soaring.

Wind shear is another factor to take into account when predicting thermal soaring prospects. A wind shear will tend to distort thermals, and as a rough guide we can take it that if the wind shear is greater than about 2½ knots per thousand feet the thermal structure may be difficult to diagnose and use.

However, wind shear is not entirely a disadvantage. When the wind direction does not change much with height and the wind speed has a maximum in the top half of the convection layer, thermal or cloud streets may form. The spacing between such streets is often about 2½ times the depth of convection. Although streets can form or disperse erratically, it is likely that street formation occurs more often than is generally realised and many a glider pilot would do well to explore up and down the wind direction rather than just circle in any thermal he finds.

#### *Line squalls*

Another type of convection cloud organisation is the line squall type of structure. When precipitating convection clouds form a line across the general wind direction it is not uncommon to find a narrow belt of lift somewhere near the leading edge. Both gliding experience and radar echoes from birds have shown that bands of line squall lift are not straight and well defined; sometimes they meander in rather a vague manner around the precipitation downdraught usually taking place.

Precipitation downdraughts can produce dangerous wind gradients at low levels. After descending to ground level the cold air in the downdraughts often spreads out as a very shallow cold pool sometimes a mere hundred feet or so deep. The wind shear between the cold flow and the warmer air being undercut by this cold flow is sometimes sharp enough to become a landing hazard; pilots should be warned whenever such a hazard is expected.

#### *Sea breeze fronts*

On many occasions when conditions are favourable for the penetration of sea breezes inland, the transition zone between the cool moist sea air and the drier air inland is very narrow and can be considered as a shallow ephemeral species of cold front. Warm air inland rises ahead of the

wedgelike advance of cool air from the sea, and, if the inland air is not too dry, the ascending air is marked by a line of cumiliform cloud. Sometimes the front is also marked by cloud with a peculiar, vertically striated form resembling a tattered translucent veil of cloud. Whether marked by cloud or not, the upward motion at the sea breeze front is occasionally strong enough for soaring flight. However, the belt of lift is narrow (only about 100–300 yards wide) and in plan view the fronts have indentations which need to be followed when soaring along them. Conditions in which moderately deep convection takes place inland in airstreams with winds of about 10–25 knots almost parallel to the coast-line seem to be particularly favourable to sea breeze frontal development. When the air is too dry for cloud to form a sea breeze front can sometimes be detected by a visibility contrast between the sea and inland air. Once a front is well formed it does not suddenly disappear after the heating inland has ceased; a well marked front often maintains its identity well into the evening or night, and many a glider pilot has soared in sea breeze fronts until late in the evening.

While we are considering sea breeze effects we should also consider pseudo-sea breeze fronts. If a sheet of cloud has a long sharp edge then the differential heating between the ground exposed to sunshine and the ground under the cloud can produce effects like sea breezes. A pseudo-sea breeze front can form almost parallel to the edge of the cloud layer and move slowly away towards the warmer ground. The edge of the layer cloud acts as a coastline.

#### *Lee Waves*

Glider pilots at mountain sites occasionally find themselves able to soar to thousands of feet above the terrain. Such deep lift usually means that lee waves are present. Conditions favorable for lee waves are:

- (i) a high lapse rate at low levels up to about or just above the height of the ridge producing the waves,
- (ii) a stable layer above,
- (iii) an upper layer of low stability,
- (iv) a general wind component of at least 15 knots across the ridge.

Two useful though not infallible supplementary guides to forecasting lee wave characteristics are:

- (i) the stable layer associated with the wave flow produces larger amplitude waves when it is a shallow layer of great stability than when only moderate stability extends over some considerable depth.
- (ii) Long waves (say, wavelength of 15–25 miles) are associated more frequently with strong winds than with light winds aloft.

Lee wave amplitude is affected by diurnal heating and cooling in such a way that the wave history of many a day in temperate or cool climates can be classified into three periods:

- (i) *Early morning* in which a sudden and early onset of wave flow is often followed by good wave soaring conditions at their strongest between one and three hours after sunrise.
- (ii) *The middle of the day* which is the least likely period for soarable waves.
- (iii) *Late afternoon and evening* when wave flow is re-established and waves are often at their strongest from about three hours to one hour before sunset.

In regions where the diurnal heating is more intense, however, this heating tends to increase the lee wave amplitude in the mid-afternoon.

Flight conditions in lee waves are often remarkably smooth, but lee wave conditions can also produce some of the most violent turbulence likely to be encountered by glider pilots. Innocuous looking patches of stratocumulus in wave crests may in fact be extremely turbulent "roll cloud" in a "rotor flow". When such a flow exists the transition between the turbulent and smooth zones is often very sharp and occurs either at the top of the roll cloud or at about the base of the stable layer. Usually low level turbulence extends to the ground and causes sudden and erratic changes of surface winds below the lee wave crests.

Observations suggest that if the wind speed decreases with height in and just above the stable layer, then low level rotor flow is very likely. Although it is not easy for a forecaster to predict the strength of lift in lee waves, he can usually assume that this lift will be greatest in the stable layer associated with the wave flow conditions, and it is a great help to the glider pilot to know what height this maximum lift is likely to be. When the wind speed aloft decreases with height, such that the component across a wave producing ridge becomes zero at some level, the wave amplitude may be large at low levels, but above the stable layer it decreases quickly to become zero at about the same level as the zero wind component.

Lee waves produce hazards, such as downdraughts, and the turbulence and erratic surface winds already mentioned. In addition the glider pilot should remember that the gaps between wave clouds can soon fill up and blot out the landscape to pilots flying above cloud. The freezing level is lower in wave crests than in the troughs, and freezing rain can be encountered ahead of warm fronts which often bring wind and stability conditions favourable for waves. Finally, the pilot should note that wave clouds are not always stationary. They can move somewhat erratically, and a particular characteristic of some types of flow is the "upwind jump". In some conditions, which are not clearly classified yet, wave clouds are seen to move slowly downwind for about half a mile before jumping (i. e. re-forming) suddenly, in a few seconds, back to their original position. This process is then repeated over and over again.

#### *Anabatic soaring*

When heating from the sun is communicated via the ground to air close to a hill slope quicker than it is to the air at the

same level over the adjacent lowland, the associated density variation produces a wind (an anabatic wind) up the hillside. This anabatic flow is usually confined to a shallow layer on the hill slope and a pilot must fly very close to the mountainside to soar in the anabatic lift. Occasionally, the lift is more than 1000 feet/minute on a 45-degree slope, but often the general anabatic soaring conditions along a mountain range are marginal.

#### *Gliding Forecasts*

The basic preliminaries in preparing a forecast for gliding are:

- (i) Anticipation, based on an upper wind forecast of the glider pilots requirements so as to narrow down the area for which a detailed forecast is required.
- (ii) Meso-scale analyses using hourly charts, if available, of whatever elements such as upper cloud, visibility, etc., that appear to be relevant in the particular situation.
- (iii) A detailed study of the radio-sonde (or aircraft) temperatures with a view to forecasting the depth of convection at various times and places.

The normal national networks of radio-sonde and regular pilot balloon stations are usually too coarse for gliding requirements, so for the more important gliding forecasts it is usually necessary to supplement the normal soundings with local pilot balloons and aircraft soundings.

The details of the forecast will, of course, vary according to the synoptic data but the general headings should include:

- A. Area and period of forecast
- B. Brief description of the synoptic situation
- C. Surface winds
- D. Upper winds
- E. Weather
- F. Depth of dry thermal activity
- G. Character and distribution of dry thermals
- H. Amount, base and tops of convection cloud
- I. Distribution of layer cloud
- J. Visibility
- K. Sea breeze effects
- L. Lee waves
- M. Height of maximum lee wave amplitude
- N. Height of 0°C isotherm and icing risk
- O. Warnings and remarks
- P. M.S.L. pressure

(Swiss Aero-Revue 3/1965)

Mississippi valley. In the regions where the wind arrows show a rapid turning from a northwesterly into a westerly and even a southwesterly direction we find a concentration of reports of severe bumpiness.

Fig. 4 shows a cross section through the atmosphere from Peoria (PIA) Illinois, to Lake Charles (LCH), Louisiana, constructed for the same time as Fig. 3. The wind speeds analyzed in this diagram do not show any excessive increases or decreases in the region in which turbulence is reported. Fig. 5 shows an analysis of wind directions in the same cross as Fig. 4. As may be seen clearly from this diagram all turbulence reports lie within a zone in which the wind turns rapidly with height.

A large number of other case studies and aircraft reports lend further evidence to the hypothesis that many cases of Clear Air Turbulence, reported near the tropopause and in the lower stratosphere, are generated similar to the formation of gravity type waves.

#### (4) What Should Be Done

Clear Air Turbulence is a very patchy phenomenon which defies precise forecasting. All that could be done so far is outline certain regions in the atmosphere in which rather large wind shears may trigger the formation of CAT. This

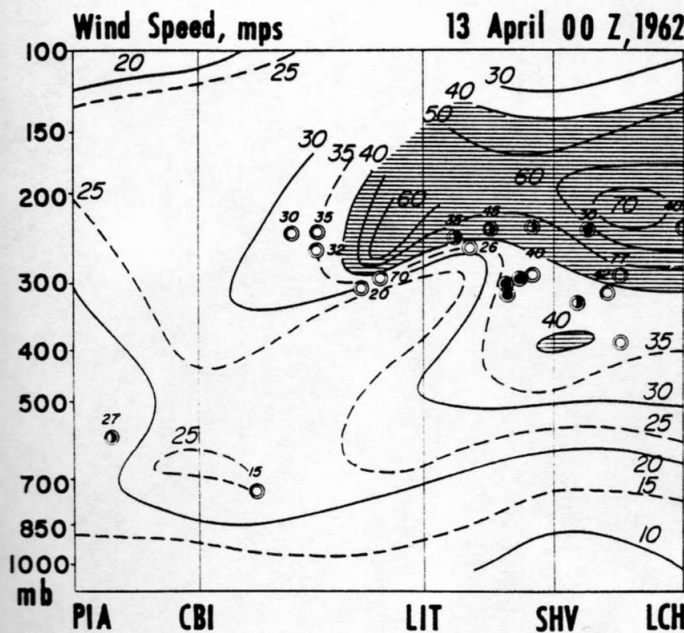


Fig. 4: Cross-section of wind speeds (mps) through the atmosphere from Peoria (PIA), Illinois, to Lake Charles (LCH), Louisiana, 13 April 1962, 00 GCT. Regions with speeds  $> 40$  mps are shaded. Inner circles represent CAT reports similar as in Fig. 3 (open circles stand for light CAT). The black portions of the outer circles indicate the time of observation: semi-circle to the left equivalent to 6 hours before map time, semicircle to the right corresponding to 6 hours past map time. Numerical values next to CAT reports give wind speeds observed by aircraft.

does not mean however that an aircraft flying through a region for which CAT had been forecast would necessarily encounter turbulence. On the other hand, it is by no means a rare event that CAT is found where it has not been forecast. In view of all these undesirable facts we would wish for some kind of advance warning system which could be built into an aircraft, and which would give an indication whenever a zone of Clear Air Turbulence is being approach-

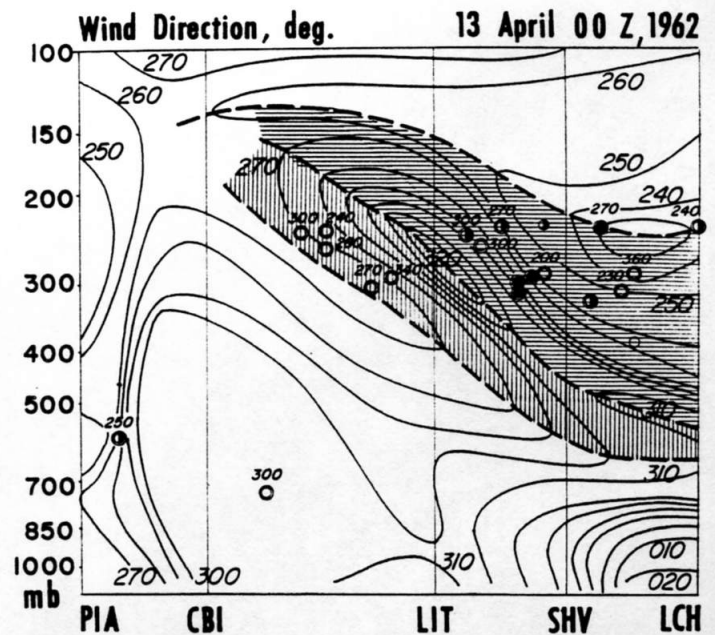


Fig. 5: Wind directions in degrees for same cross-section as Fig. 4. Different shading indicates strong veering and backing of wind with height. For more explanation see legend to Fig. 4.

ched. Such an instrumentation may be quite feasible as soon as we know precisely which factors are causing Clear Air Turbulence, and what is its exact physical nature.

In order to find this out, it will be necessary to measure as detailed as possible the atmospheric structure at and above the tropopause level. This would call for highly sensitive instruments being carried by an aircraft which shows very well known response characteristics, and which flies slow enough to warrant a detailed resolution of the collected data. It would seem that a glider, possibly equipped with an auxiliary engine, might be the ideal vehicle to conduct such measurements.

Especially the determination of the fine structure of temperature leaves quite a bit to be desired. The present radiosonde equipment does not have the necessary resolution, and furthermore suffers from radiation effects at these higher altitudes. Again, a slow flying airplane, possibly a glider, could serve as an ideal instrument platform.

Our efforts to launch a supersonic transport aircraft, and our frustrations experienced in anticipating Clear Air Turbulence bring home the point that the atmosphere harbors more interesting details than could be fathomed by the routine aerological measurements conducted so far.

#### REFERENCES

- Houbolt, J. C., and E. E. Kordes, 1954: Structural response to discrete and continuous gusts of an airplane having wingbending flexibility and a correlation of calculated and flight results. NACA Rep. 1181.
- Reiter, E. R., 1964: Clear Air Turbulence models and forecasting for Project TOPCAT, Second Phase. Univ. of Melbourne, Meteorol. Dept., Project TOPCAT, Meteorol. Reports, No. 3., May, pp 26.
- Reiter, E. R., and A. Nania, 1964: Jet-stream structure and Clear Air Turbulence (CAT). J. Appl. Met., 3(3): 247-260.
- Scoggins, J. R. and W. W. Vaughan, 1963: Problems of atmospheric wind inputs for missile and space vehicle design. Paper presented at AIAA-AMS meeting, Fort Collins, Colorado, July 10-12.
- Webb, W. L., 1963: Acoustic component of turbulence. J. Appl. Met. 2, 286-291.