CAT and SCAT
Development of a Practical Technique to Predict Clear-Air Turbulence will be a Milestone in Supersonic Transport Conquest of the Lower Stratosphere

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Although the atmosphere is man's natural environment, gaps in our knowledge about its behavior remain enormous. One of these gaps, which deserves wide attention and must be closed, concerns clear-air turbulence (CAT) within the 12 to 16-mi.-high corridors most attractive for supersonic commercial air transport (SCAT) operations.

Lending emphasis to this thesis is the havoc already wrought by turbulence to military as well as commercial aircraft—not to mention the toll in lives—even though we have not yet approached the Mach 2.5–3.0 flight speeds to become commonplace in commercial aviation during the next decade. The Air Force photos at the top of the opposite page illustrate CAT damage. They are mute evidence of the effects of CAT on aircraft structure—prime exhibits in the case for passenger comfort and safety, and for rugged aircraft-control systems to permit maneuverability under the stresses of CAT conditions.

From the beginning of man's first flight, weather and its vagaries have had to be tolerated as a force of nature. While the development of meteorological services for commercial aviation is well-punctuated with significant milestones, the one now most important to modern flight is our ability to obtain detailed wind and temperature information for flight planning in the lower stratosphere. Reference is, of course, to the radiosonde network. This has adequately increased its quality as well as its coverage, at least over the heavily populated and well-traveled regions of our globe. Analyzing the 100-mb charts over these areas nowadays presents no more of a problem than did the 500-mb charts two decades ago.

It was with the advent of the radiosonde technique that our naive notions of the stratosphere being a region of smoothness and quietness because of "its great thermal stability" were dispelled. (The original concept was that it was a layer of the atmosphere in which gaseous constituents stratified themselves according to molecular weight, all because it was thought there should be no convective motions to keep them mixed.)

There is no denying that continuous study has contributed much to our knowledge of the stratosphere; unfortunately many factors involved in detailed atmospheric structure are not yet established to a degree of accuracy which is sufficient to let us estimate their effects upon a supersonic commercial air transport. Clear-air turbulence is one of them.

The difficulty which the meteorologist has been—and still is—facing in assessing the impact of CAT on commercial and military aviation stems from a noteworthy fact. This is that turbulence is a small-scale phenomenon which, as such, eludes the wide-meshed radiosonde network completely. Even with a network more dense, the situation would be unchanged because presently there is no sensor on the sonde to measure turbulence.

Let us now take stock of what we know, what we may project and what we don't know about CAT.

Emerging from the experiences of low-level flying under convective weather conditions, CAT originally was thought to be associated with unstable thermal conditions. Updrafts and downdrafts associated with convection currents in an adiabatic or superadiabatic layer could, of course, cause severe bumpiness in flight. The difficulties with this turbulence "model" lie firstly in the fact that CAT is frequently found in the stratosphere, where thermally stable conditions prevail. Secondly, convective cur-

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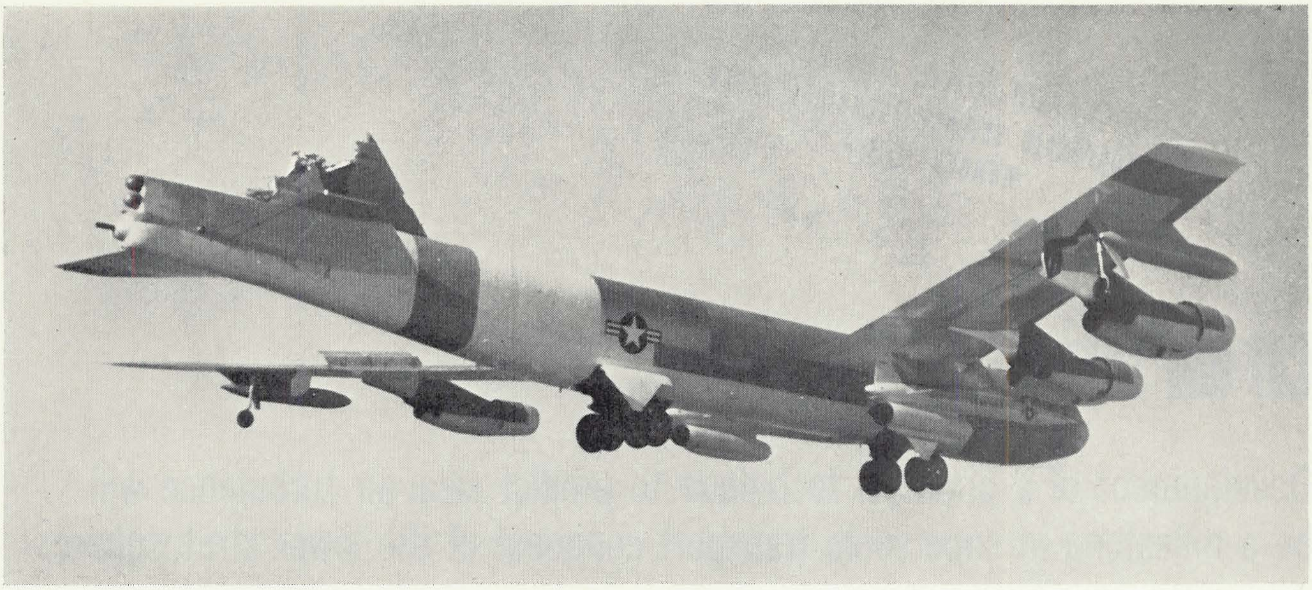


Clear-air turbulence (CAT) at 9000 ft over a Colorado mountain range last January severely damaged this USAF B52-H, pictured struggling to a safe landing despite almost total loss of its vertical stabilizer. Lower photo gives close-up view of damaged area.

rents in the troposphere, when strong enough to produce severe bumpiness, and when reaching through a deep layer, are usually associated with cumulus-type cloud forms, hence do not qualify as "clear-air" turbulence.

Various atmospheric parameters and conditions of flow have subsequently been investigated for possible correlations with CAT, such as Richardson's turbulence criterion:

$$Ri = \frac{g}{\theta}\frac{\partial\theta}{\partial z}\Big/\left(\frac{\partial v}{\partial z}\right)^2 \qquad (1)$$

which indicates the ratio of the turbulence alleviating factor of stability (g = acceleration of gravity, θ = potential temperature, z = height coordinate) and the turbulence generating factor of vertical-wind shear (V = magnitude of wind speed). Results of these correlations have shown large discrepancies.[1-13] The main reason for this, as well as for the disappointing results of several other correlation studies, is that CAT is a microscale phenomenon, while the parameters with which a correlation is attempted, are measured in a macroscale network and do not have a fine enough resolution of detail to warrant an immediate physical interpretation of observed CAT. (For an aircraft flying at 400 K and experiencing one upward or downward bump per second, the "wavelength" of the "turbulence"-generating disturbances would have to be approximately 200 m or 600 ft. Wind and temperature fluctuations would have to be measured to at least the same degree of resolution in order to make the atmospheric gusts recognizable as input into the bumpiness experienced by the aircraft. This, of course, is far from being realized at the present.)

Other parameters correlated with CAT were: The rate of change of Richardson's number with time; differential vertical temperature advection;[14,15] horizontal and vertical wind shear.[16-19] Correlations with flow patterns showed that jet streams produced more CAT than areas with weak winds,[11,20-22] especially on their cyclonic side and near the tropopause where strong wind shears prevail.[23,24] This is illustrated by the drawings on page 62.

Troughs and confluent regions between two jet streams also seem to harbor a certain amount of CAT.[8,26,27] Even at the present a good deal of research on CAT is still being done along these lines, trying to correlate observed cases of CAT with large-scale weather patterns and meteorological parameters derived from them. The ultimate goal of all these studies is, of course, to achieve a better understanding of the physical nature of CAT and thus to bring it into the realm of predictability.

In a different approach we may look for physical causes of CAT, rather than for a multi-discriminate correlation with atmospheric parameters, and then—as a second step—we may search for a combination of atmospheric parameters that might bring about the necessary conditions to make these physical causes active.

As one such possible cause, the formation of gravity-type wave disturbances of stable or unstable character along a quasi-horizontal interface with warm air on top of cold air—thus with stable conditions—and with a vertical-wind shear, has been recognized.[28,29] An aircraft "skimming" along such a warped "roadbed" will experience gusts which may lead to a considerable amount of bumpiness at a critical response frequency.

This condition is illustrated by the schematic diagram on page 63. The flight path of our SCAT is indicated by the thin line, 5. The black arrows, 1 and 2, show different wind speeds. Air parcels in the vicinity of the interface follow the motions of a helical vortex (white arrows and dashed area) producing updrafts and downdrafts (small black arrows). During supersonic flight, periodic temperature changes may affect the drag coefficient as the SCAT flies through the interface wave pattern. The *initial* perturbations leading to CAT-bearing wave formation may be infinitesimal, then amplify in time under the prevailing conditions of shear and temperature stratification. The perturbations also may be of finite dimensions and of a definite origin, possibly decaying in time under stable temperature and shearing conditions.

Among the latter would probably qualify many of the frequent encounters of CAT over mountain and hill ranges where the terrain provides enough perturbation energy to disturb the flow even at high levels.[30] Modes by which such orographically generated perturbations motions may reach even stratospheric levels have been studied.[31-35] Although their theories encompass larger-scale disturbances of several kilometers wavelength—the so-called lee-waves—there is ample evidence that CAT is frequently associated with lee-wave formation.[36,37] There are indications that under suitable atmospheric conditions lee-waves may even reach into the ozonosphere.[38] Wave formations have been observed visually in layers of noctilucent clouds as high as 90 km.

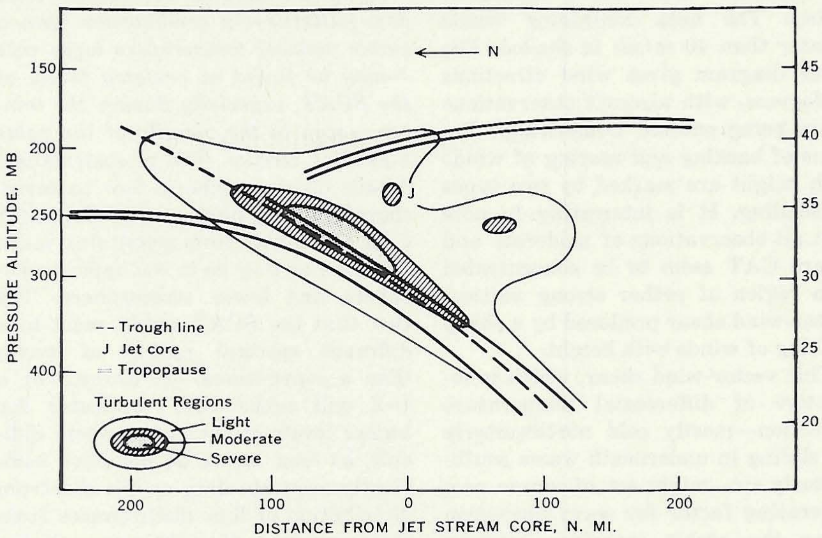
Cat associated with lee-wave formation, therefore, has definitely to be considered as a harassing feature of SCAT operations, at least over larger mountain ranges.

As stated before, CAT also may erupt from infinitesimal initial perturbations without any visible source. An interesting encounter of this kind has been made during project TOPCAT, a clear-air turbulence measurement program carried out over South Australia from June to October last year with an instrumented Canberra.[29] The aircraft was equipped with a smoke generator so that turbulent patches could be marked by a smoke puff and could be identified again during subsequent traverses. On September 12, the aircraft encountered a turbulent patch about 15 mi. in diam and slightly over 2000 ft in thickness embedded in perfectly smooth surroundings and over level terrain (salt flats near Lake Dutton). By using smoke markers, the aircraft was able to follow this patch of turbulence for about 45 min while it was drifting downstream with the mean wind for approximately 100 mi. The intensity level of CAT, as well as the size of the patch stayed about the same during this whole time.

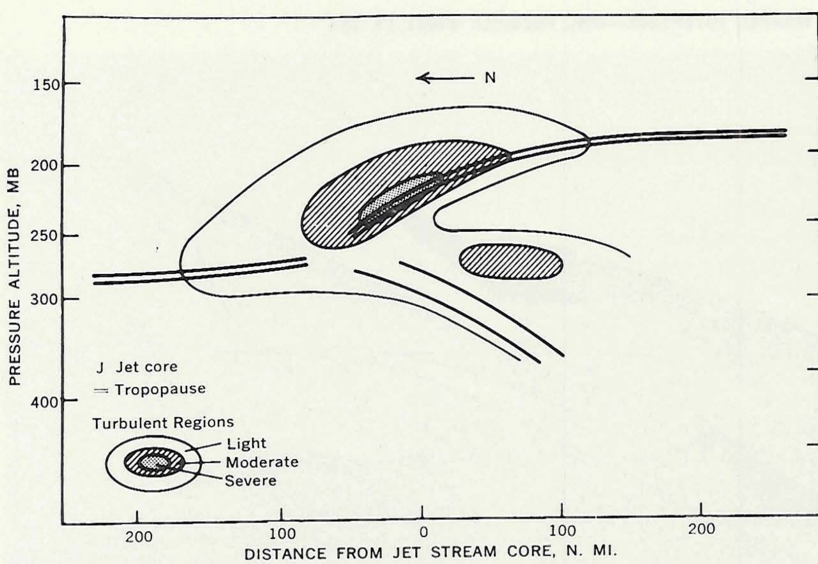
Most of the cases of CAT of nonorographic origin seem to be associated with rather marked vertical vector-wind shears, produced by drastic changes of wind direction through relatively shallow layers. Such layers frequently are found in the region between two merging jet branches.[26,39] This condition is illustrated by the "bird's-eye view" diagram on page 63, and by the three grouped diagrams on page 64. Time and date for each of the

IDEALIZED MODEL OF CAT IN THE JET-STREAM REGION

Note: From Project Jet Stream aircraft data.[25]



A. Sharp-trough vicinity—cyclonic flow aloft.



B. Sharp-ridge vicinity—anticyclonic flow aloft.

four is the same—April 13, 1962, at 00 GCT. In the former, 250-mb isotachs, the solid lines indicating meters per second (m/sec), and isotherms, the dashed lines, indicating degrees Centigrade (C), are shown. Areas containing speeds greater than 50 m/sec are shaded. Wind directions observed by radiosondes are entered as arrows flying with the wind at each measuring station. Cases of strong CAT (full black circles) and of moderate CAT (black semicircles) are concentrated in a region where a northwesterly and a southwesterly jet-stream branch merge. Jet axes are indicated by heavy dashed lines with arrows. Winds in the CAT region blow across the isotherms from cold toward warm, indicating relatively strong sinking motion within the northwesterly flow; this jet branch evidently is sliding in under the southwesterly one.

In the grouped diagrams, the cross-section shown extends from Peoria, Ill., (PIA) to Lake Charles, La. (LCH), 675 n. mi., and their plane runs through the CAT region just discussed. Again, circle densities indicate strong, moderate, or light turbulence. (the latter indicated by open circles). In addition, blacked-in portions of the outer circles indicate the time of each CAT observation. Blacked-in half-circle to the left stands for 6 hr *before* map time; similar areas to the right stand for 6 hr *after* map time. The upper diagram shows potential temperature in degrees absolute. Boundaries of stable layers and tropopauses are marked by heavy lines. In the center diagram, wind speeds are shown in m/sec. Aircraft observations, again, are entered with their numerical values. The area containing winds greater than 40 m/sec is shaded. The lower diagram gives wind directions in degrees, with aircraft observations again being entered numerically. Regions of backing and veering of winds with height are marked by two types of shading. It is interesting to note that all observations of moderate and severe CAT seem to be concentrated in a region of rather strong vertical vector-wind shear produced by a sharp backing of winds with height.

This vector-wind shear, which is indicative of differential temperature advection—mostly cold northwesterly air sliding in underneath warm southwesterly air—might act, of course, as a generating factor for wave formation along the stable interface between cold and warm masses of air.

Again we have to assume that such flow patterns—in combination with a stable vertical temperature lapse rate—may be found at cruising levels of the SCAT, especially during the winter season in the vicinity of the polar night jet stream. The mesostructural details of stratospheric flow patterns, therefore, may harbor possibilities for CAT even away from mountains, much the same as they do in the upper troposphere and lower stratosphere. The fact that the SCAT would react to a different spectral range[40] of waves than a conventional jet aircraft or a U-2 will make CAT estimates for higher levels of the stratosphere difficult, as long as we do not have sufficiently accurate data on the spectrum distribution of flow disturbances from these levels. A straight extrapolation of U-2 data, given in the diagram on page 65, to SCAT conditions may be of questionable value. Data diagrammed was obtained from three sources indicated by the circles, solid line, and dashed line.[41-43]

While the wind-generated input into CAT so far has been the primary concern for conventional jet aircraft, we may anticipate additional effects upon SCATs from the acoustic structure of the atmosphere.[44]

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

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

The speed of sound in dry air, in approximation, may be expressed by

$$V_s = \left(\frac{c_p}{c_v}\frac{RT}{m}\right)^{1/2} \qquad (3)$$

α is the angle of attack of the air foil, c_p and c_v are the specific heats of air under constant pressure and constant volume, R is the universal gas constant, T the temperature, and m the molecular weight.

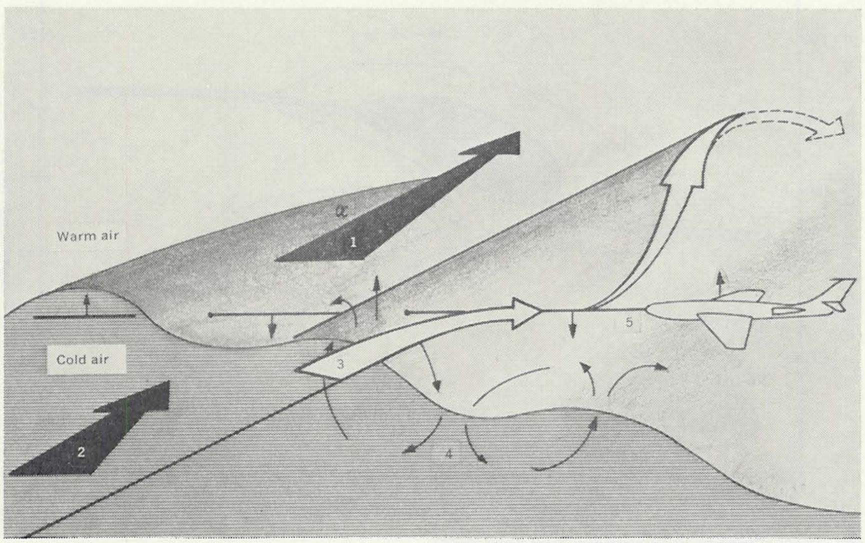
As may be seen from these two expressions, small changes in Mach number may be expected, whenever the environmental temperature changes. At approximately −50 C, a temperature change of about 4.5 deg would bring about a change in the speed of sound of 1%. This, in turn, would alter the Mach number at which the SCAT is flying, assuming that its speed relative to the environment remains the same (homogeneous wind conditions).

Changes of M have their most drastic effects upon C_D near M = 1.05.[44] But even at higher supersonic speeds of the aircraft its drag coefficient will change with changes in Mach number.

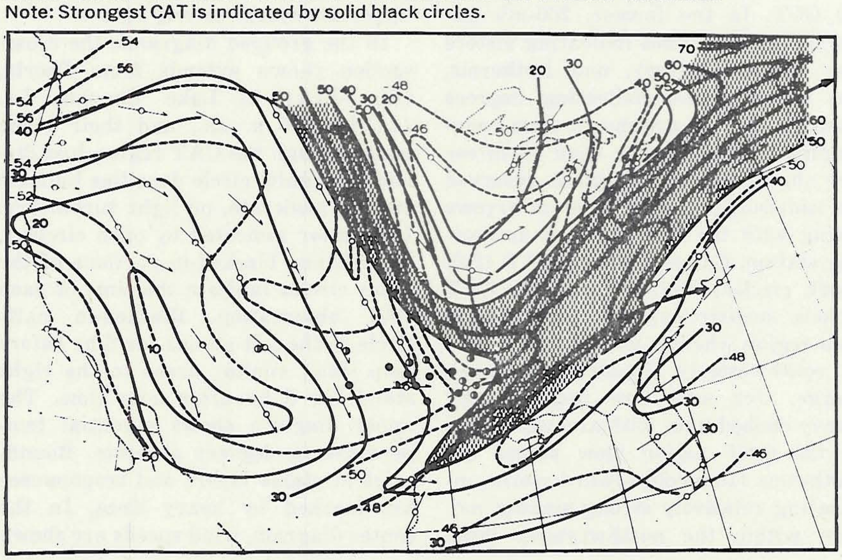
From detailed radiosonde and aircraft measurements we know that sharply defined inversions may at times exist near tropopause levels and in the stratosphere. *Even disregarding the possible effects of wind shears that might be associated with such inversions, the existence of a temperature discontinuity alone may already lead to changes in the speed of a supersonic aircraft via its effect upon the drag coefficient.*

Let us suppose now, that the "interface" which constitutes the temperature discontinuity is not plane but "warped" into a wavelike pattern. It is conceivable, that a SCAT "skimming" along those waves may experience vibrations similar to CAT, which are entirely a product of the temperature structure of the atmosphere, and have nothing whatever to do with gusts or "turbulence."

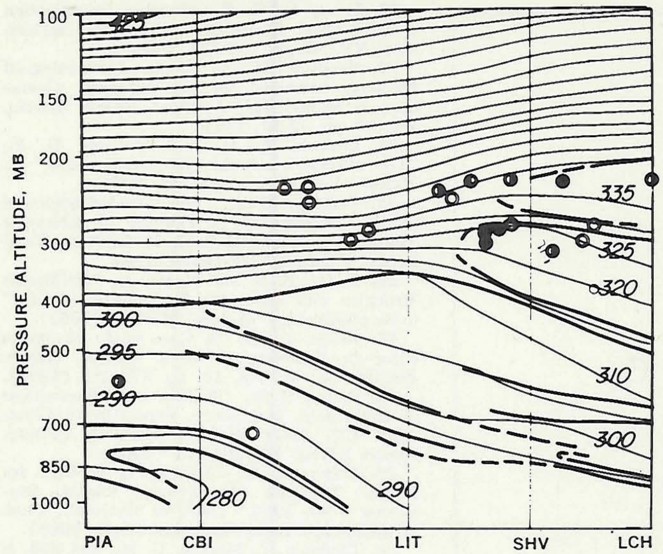
THE WARPED INTERFACE—ONE POSSIBLE CAUSE OF CAT



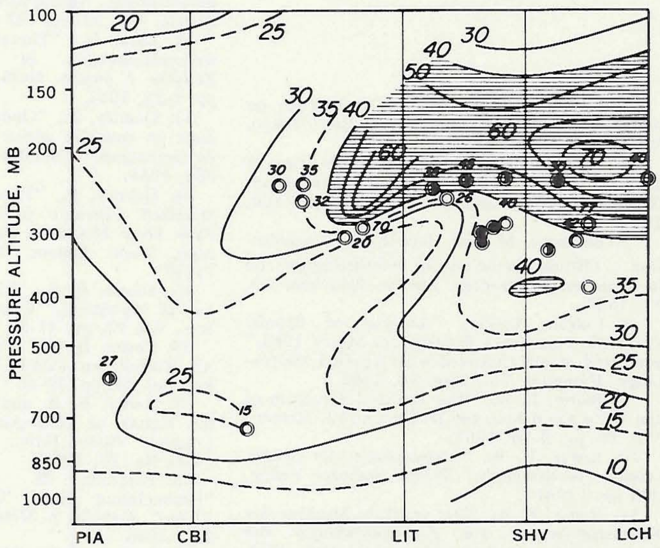
250-MB CHART SHOWING STRONG CAT AT MERGING JET-STREAM BRANCHES
Note: Strongest CAT is indicated by solid black circles.



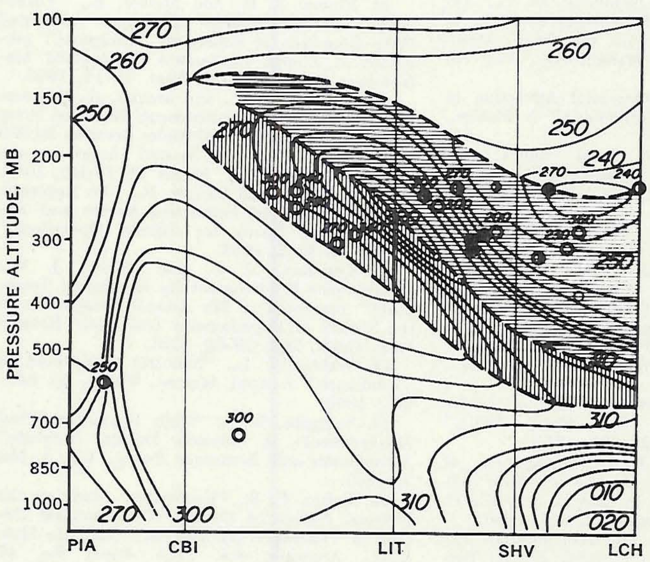
THREE PROFILES OF THE ATMOSPHERE AT 00 GCT, APRIL 13, 1962



A. Potential temperature (K).



B. Wind speed, m/sec.



C. Wind direction, deg.

Again, we may speculate that flow conditions favoring the development of such sharp temperature inversions may be found in the stratosphere, especially in the region of the polar night jet stream. A "washboard"-like warping of an interface into waves of approximately 2 km wavelengths may be suspected to occur especially over mountain ranges, but—as we have seen earlier—such oscillations may also be set off over level terrain.

Since under baroclinic conditions a vertical wind shear is usually associated with such sharp temperature inversions, a combination of both vertical and horizontal gusts in the classical action of CAT as well as of temperature effects upon the drag coefficient, may create quite complex response problems. With this, CAT research is moving into the dimensions of atmospheric acoustics, still unexplored yet challenging in its many engineering and scientific aspects. Thus, with the advent of supersonic commercial aviation, clear air "turbulence" may prove to be even more of a misnomer, since it may have even less to do with hydrodynamic "turbulence" than was the case in subsonic flight operations.

Important data on the situation are expected from continuing experiments. Among the most interesting is a recent effort at Cape Kennedy which may shed some light on how to identify CAT by means other than aircraft observations.

Sounding balloons were tracked by the new FPS-16 radar with an accuracy never achieved before. Winds along the balloon ascent were measured every 0.1 sec and combined into 3-sec averages. This averaging was essential because the FPS-16 is almost too accurate; for instance, it is able to detect the small erratic motions of the balloon up to about 10 km. (These motions are caused by the aerodynamic behavior of the balloon itself, and by the shedding of little eddies from its boundary layer as it rises through the atmosphere.) Stereophotography of smoke trails released from rockets also give evidence of small details in wind structure.[45,46]

With such refined measurement devices vertical wind shears of up to 20 knots in less than 50 meters height difference could be detected. Needless to say, such excessive wind shears are likely to initiate wave formations, thus causing turbulence to aircraft flying in the area.

Such strong shears also may cause havoc to missiles, especially when shearing layers are "stacked" atop each other at a critical frequency interval, possibly setting off vibrations within the missile or precipitating fuel sloshing. These eventualities, of course, are specific hazards to the mission.

Jet aviation in its early days really was a daring enterprise, probing into a strange environment and collecting meteorological data by its own means. The meteorologist as well as the aircraft designer had to learn as they went along, keeping their fingers crossed.

Now, as we stand but a small step from supersonic commercial flight, the question is whether we can afford once more to play it by ear. Encouragingly enough, there are indications that industry is responding with an emphatic "no!," for the inescapable facts are these:

1. The design and eventual operation of the SCAT involves a much larger national effort, financially as well as technically, than ever faced by commercial aviation; mistakes, if made, may be disastrous.

2. In contrast to the early days, we possess the capability of full exploration before the fact, and of anticipating potential problems.

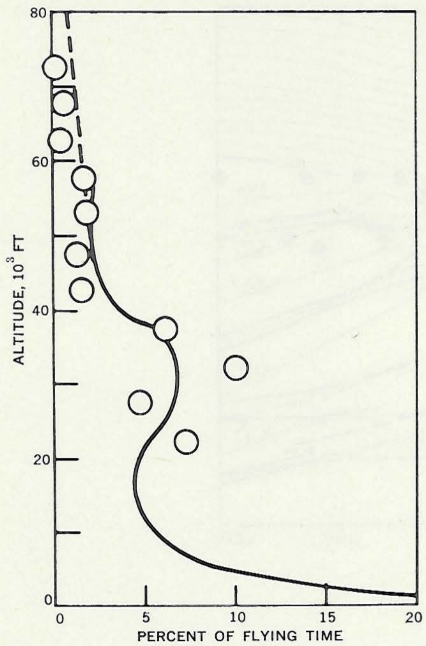
What remains to be done in clear-air turbulence research?

Primarily we need more accurate information on anything concerned with the small-scale structure of the stratosphere. New balloon techniques, such as the FPS-16, and properly equipped U-2 aircraft certainly could provide a wealth of data. Eventually we may also receive direct structural response data from aircraft such as the A-11. With such information our theories on CAT should be updated and put on a firm physical foundation.

Necessarily, forecasting techniques of CAT should be subjected to stringent tests: A forecast of CAT when *not* encountered should be counted as ineffective as unpredicted CAT occurrence.

Secondly, more effective channels of communication between industry and the various government and private agencies engaged in CAT research should be designed. For what good does it do if "the right hand does not know what the left hand is doing?"

TURBULENCE DATA ACQUIRED BY U-2



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