

The Nature of Clear Air Turbulence and its Detection

By
Elmar R. Reiter

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado



**Department of
Atmospheric Science**

Paper No. 146

THE NATURE OF CLEAR AIR TURBULENCE: A REVIEW

Elmar R. Reiter

Colorado State University

Fort Collins, Colorado

1. DEFINITION OF CAT

The National Committee for Clear Air Turbulence in a 1966 resolution (U. S. Department of Commerce, 1966), has adopted the following definition of clear air turbulence:

CAT comprises "all turbulence in the free atmosphere of interest in aerospace operations that is not in, or adjacent to, visible convective activity. This includes turbulence found in cirrus clouds not in, or adjacent to, visible convective activity".

CAT thus defined considers all bumpy flight conditions away from convective clouds as they affect airplanes, rockets, VSTOLs, etc. We will not go wrong in assuming that CAT in different types of aerospace vehicles may have different atmospheric causes. So, for instance, will CAT in vertically launched vehicles depend to a certain degree on atmospheric layers with varying wind shears (Fig. 1), and on the response of the missile guidance system to these shears. A horizontally-flying airplane may experience no CAT at all in the same region, and vice versa.

As is evident from the various "gust equations" and response functions, used by aeronautical engineers, airplanes of different design will also show different sensitivity to CAT. Since the involvement of an aerospace vehicle in the experience of CAT comprises airplane design factors,

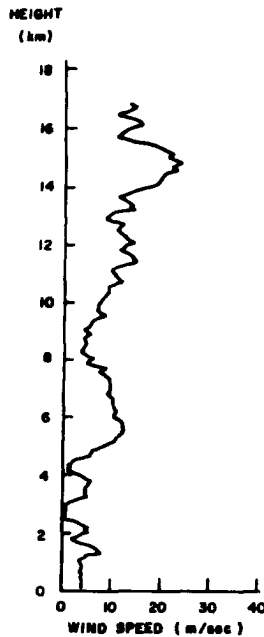


Figure 1. Detailed scalar vertical wind profile measured by FPS-16 Radar on 29 December 1964, 1731 GMT. Regions of positive and negative vertical wind shear will affect vertically rising vehicles (see e.g. Smith 1963). Spectra of these wind fluctuations (see e.g. Scoggins 1963) may be compared to response frequencies of the rising vehicle.

flight aspects and meteorological aspects, the problem of CAT detection, forecasting, and/or forewarning becomes quite complex. In the subsequent discussion we will restrict ourselves to meteorological aspects only. But, as we shall see, even such a restriction will not yield an unambiguous combination of meteorological parameters that may be held responsible for CAT.

2. DIMENSIONS OF CAT

Jet aircraft of present design respond to atmospheric eddies of dimensions 20 to 200 m with bumpy flight conditions, if the kinetic energy in this range of eddy sizes is of sufficient magnitude. Eddies smaller than this scale will be integrated by the surface of the aircraft; eddies larger

than 200 m usually will not cause accelerations large enough to be felt as (severe) bumps. (Asymmetric waves of a wavelength greater than 200 m, of course, may contain larger-than-normal accelerations. As an extreme case we may think of a "step-function" distribution of up- and down-drafts. In a spectrum analysis such a step function will, however, show itself as the superposition of many waves of smaller wavelengths.) For supersonic aircraft this eddy range will have to be increased by about one order of magnitude.

3. OCCURRENCE OF CAT

From subjective and objective CAT observations with jet aircraft we may draw the following conclusions:

(a) Turbulent flight conditions are nearly always present in the planetary boundary layer. Frictionally induced turbulence, dependent on wind speed near the ground, and convective motions depending on lapse rate and depth of the mixing layer, will influence the intensity of CAT. This low-level turbulence may critically affect landing and take-off operations of conventional planes as well as of VSTOLs.

(b) Most CAT experienced by jet aircraft of conventional design is of a patchy nature. Most of these patches seem to have horizontal dimensions of < 20 miles (Cunningham, 1958) (Fig. 2). From this we may conclude that the atmospheric meso-structure (ca. 10-100 km horizontal dimension) plays a decisive role in the immediate generation of CAT, more so than the macro-structure, for instance at synoptic scale.

(c) CAT occurs more frequently near the jet stream than away from it. (Figs. 3 and 4.) In the vicinity of jet streams it appears to have an affinity for stable layers with vertical wind shears. (The work of many authors has been reviewed, for instance, by Reiter, 1960, 1963, 1968.) From U-2 measurements over both hemispheres and from Jindivik (drone plane) observations over Australia, it appears that CAT may also be expected at flight levels of a supersonic transport aircraft (45 to 55,000 ft).

(d) CAT occurs more frequently over mountains and continents than over flat terrain and oceans (Clodman et al.,

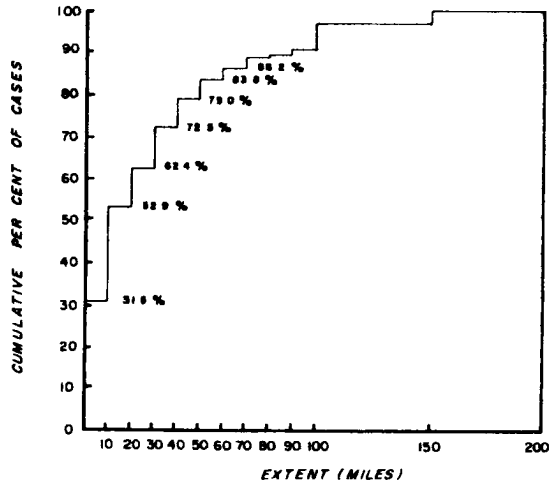


Figure 2. Horizontal extent of clear air turbulence encountered in project Jet Stream (after Cunningham 1958).

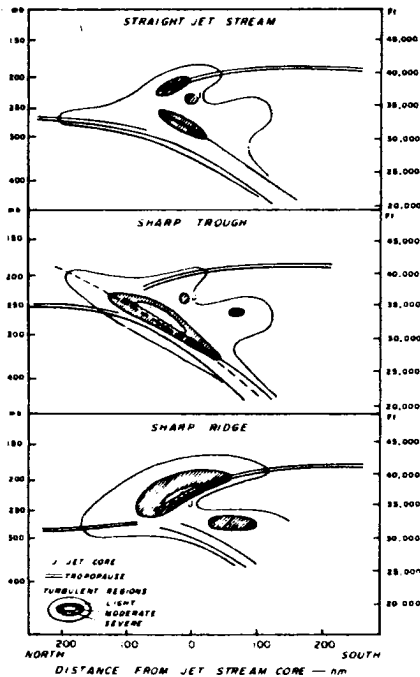


Figure 3. Idealized models of turbulent regions in the vicinity of the jet stream (after Endlich 1963).

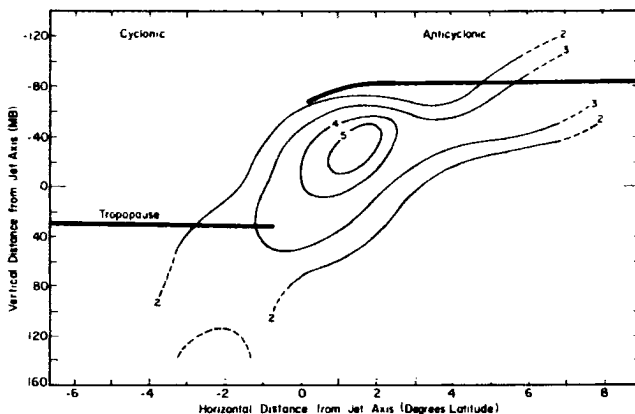


Figure 4. Occurrence of high-level turbulence near the jet stream over the North Atlantic Ocean in vertical "boxes" of 40 mb x 120 n. mi. Isopleths indicate number of CAT observations in each block. (After Clodman et al., 1961).

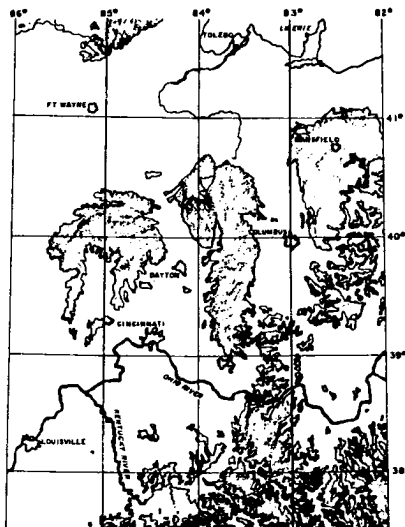


Figure 5. Topography in vicinity of Patterson AFB. Unshaded areas 0-1000 ft above msl; shaded areas 1000-2000 ft above msl (after Clodman et al., 1961).

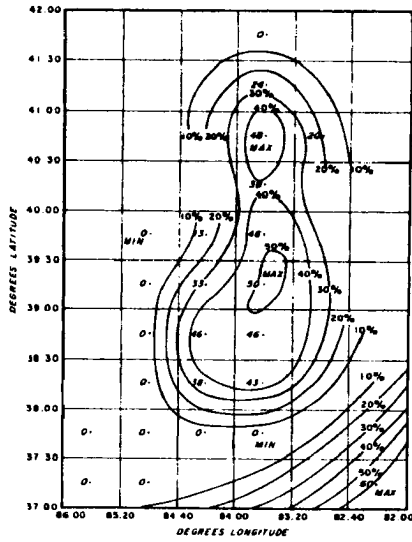


Figure 6. Percentage of turbulence occurrences in the Patterson area with the 850 mb central wind direction $(085-265^{\circ} \pm 30^{\circ})$ normal to the central ridge (after Clodman et al., 1961).

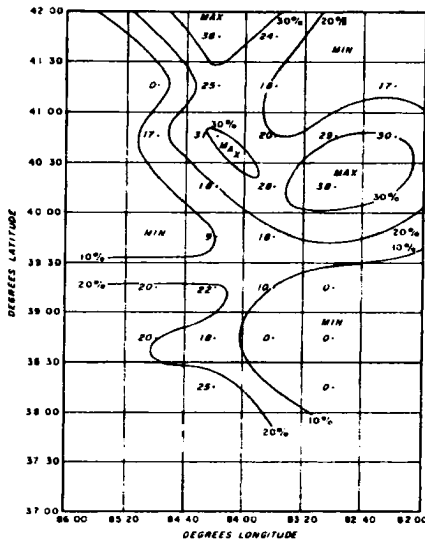


Figure 7. Percentage of turbulence occurrences in the Patterson area with the 850 mb central wind direction $(175-355^{\circ} \pm 59^{\circ})$ parallel to the central ridge (after Clodman et al., 1961).

1961) (Figs. 5, 6, 7). This suggests that the input of finite amounts of perturbation energy into the atmospheric flow by the terrain configuration, or by enhanced convective activity, plays a role at least in certain incidences of CAT.

4. NATURE OF CAT

The eddy sizes involved in CAT -- 20 to 200 m -- suggest that the turbulence laws derived for the inertial subrange, and expressed as

$$E(k) = ac^{2/3} k^{-5/3} \quad (1)$$

in a one-dimensional spectral form, may not be strictly applicable to CAT. From the measurements of atmospheric gusts in CAT over Australia (Burns and Rider, 1965; Reiter and Burns, 1965, 1966), it appears that the inertial subrange of turbulence extends to slightly larger eddy sizes in the free atmosphere than near the ground (ca. 100 to 200 m, as compared to ca. 30 m) (Figs. 8, 9, 10). Beyond this subrange

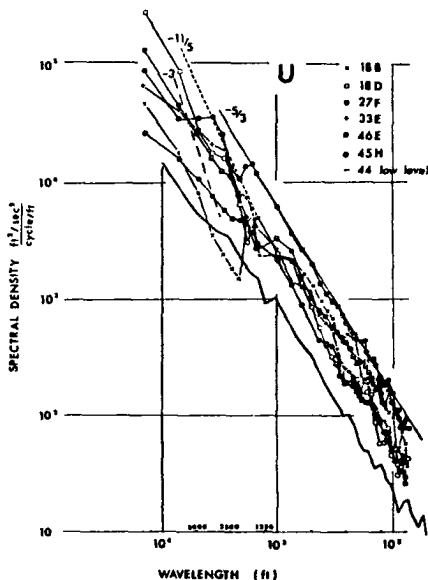


Figure 8. Spectra of gustiness of u component (along flight direction) measured by Project Topcat research aircraft over Australia (after Reiter and Burns 1965).

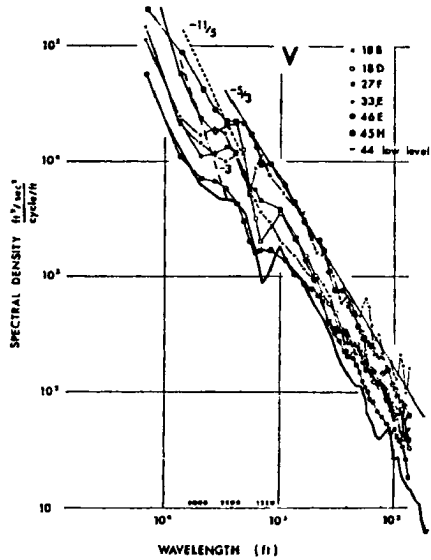


Figure 9. Same as Figure 8, except v component (across flight direction)(after Reiter and Burns 1965).

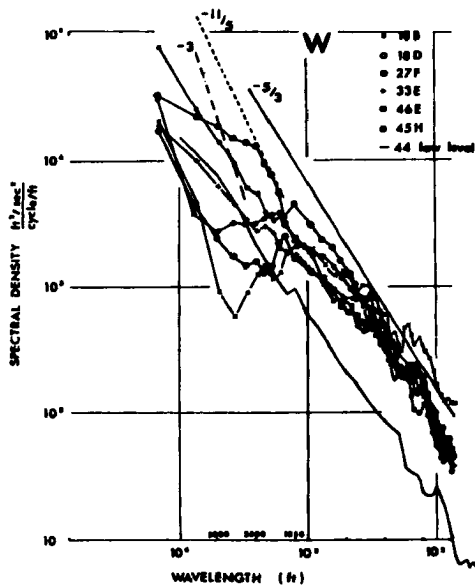


Figure 10. Same as Figure 8, except w component (vertical component)(after Reiter and Burns 1965).

of turbulence, where not only the re-distribution of kinetic energy, but also the generation and/or dissipation of kinetic energy by various physical processes becomes important, a variety of conditions may occur:

(a) The turbulence energy within the isotropic sub-range may be "fed" by the kinetic energy of the flow over rough terrain in a near-neutral stratification. This could be the case for low level turbulence. The "spectrum" of the terrain configuration may have an influence on eddy sizes beyond the inertial subrange. (See, for instance, the "wake effect" of islands, and the resulting Kármán eddies, as revealed from cloud photographs. Effects of a smaller scale should also be expected to be felt.) Such flow processes have been poorly explored as yet.

(b) In the free atmosphere eddy sizes beyond the isotropic inertial subrange may be influenced by positive and negative buoyant forces. The former would occur under free convection and -- if they are of appreciable magnitude -- would most likely be associated with clouds. Negative buoyant forces, and the dissipation of kinetic energy by them, have been postulated by Bolgiano (1959, 1962), and also by Shur (1962) and Vinnichenko et al. (1965) (see Pinus, Reiter, et al., 1967). Under such conditions, as they should occur in this "buoyant subrange" of turbulence, the spectral density $E(k)$ is expected to be proportional to k^{-n} , where $n > 5/3$.

(c) In the presence of vertical wind shears in a thermally stable layer CAT may be generated by eddies produced in the shearing layer. This seems to be the case with most of CAT experienced in the vicinity of the jet stream and in the stratosphere. Australian and Russian spectrum measurements suggest that turbulent energy may be generated in such a shearing layer, possibly through the formation of unstable waves.

5. "MODELS" OF CAT FORMATION

The distribution of kinetic energy as a function of wave number within the inertial subrange of turbulence has been the subject of numerous investigations. In the planetary boundary layer we will have to assume that turbulent flow conditions will be greatly influenced by the meso- and micro-

scale roughness of the terrain. This is, among other things, evident from the fact that the macro-scale of turbulence

$$L = \int_0^{\infty} R(\xi) d\xi \quad (2)$$

(ξ is a distance measured along the direction of flow, R is the auto-correlation function) is a function of the distance from the boundary surface.

In the free atmosphere such a "rough" boundary surface is not present. Turbulence, if present, will have to be generated spontaneously from "supercritical" flow conditions (as, for instance, expressed by a critical Richardson number of certain magnitude) which prevail over a region of meso-scale extent. The patchiness of the CAT phenomenon is an indicator of such confined regions in which the eddies at CAT wavelengths have been provided with enough energy to be felt as bumpiness by the aircraft crew. The aforementioned observation, that the inertial subrange of turbulence seems to extend to greater wavelengths in CAT near the tropopause than near the ground, also may be taken as characteristic for this "spontaneous" or internal turbulence away from a rough boundary surface.

The energy may be provided to the eddies of the inertial subrange by the action of buoyant forces in thermally unstable layers, or by the work of shearing stresses in a vertically shearing and thermally stable current. The latter mechanism appears to dominate in CAT near the jet stream and in the stratosphere. The input of energy may occur at various scales. Australian CAT measurements, for instance, appear to indicate an effect of gravity waves with a wavelength of > 300 m. These short gravitational shearing waves themselves will probably be generated by the meso-structure of wind shear and thermal stability (Reiter and Burns, 1966).

Although in the above discussion terrain roughness has been assumed to have no effect on the turbulence in the inertial subrange of the free atmosphere, it will have a pronounced effect on the atmospheric meso-structure. This is easily demonstrated by the leewave phenomenon that frequently occurs over mountains. Since CAT occurs frequently near mountain ranges, one has to suspect that orogenic leewaves

may provide an input of perturbation energy into the atmospheric flow, which ultimately also effects small eddies of CAT dimensions.

It will be difficult, if not impossible, to formulate mathematically in a tractable fashion the energy transfer mechanisms between meso-scale waves in the atmospheric flow, and random turbulence in the isotropic subrange. Since such energy transfers will be essentially governed by non-linear processes, the mathematical problem becomes hopelessly complex. One may attempt, however, to parameterize the kinetic energies at various scales of atmospheric motions, and -- even without an explicit knowledge of the physical processes involved -- attempt to study the interaction between small-, meso-, and possibly large-scale eddy flow characteristics. One such attempt has been made by Reiter and Foltz (1967), by estimating the energy in lee waves (wavelength ca. 10 km) and correlating it with observed CAT over the mountains (Fig. 11). Systematic measurements, using similar but im-

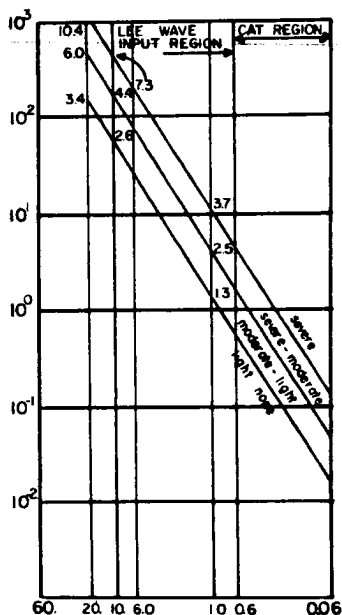


Figure 11. Spectra for various intensity levels of CAT, extrapolated with "-5/3 slope" to leewave lengths. Numerical values entered along the spectrum lines are maximum vertical velocities w_0 required to yield the necessary spectral densities at the appropriate wave lengths (after Foltz 1966).

proved approaches should yield considerable insight into the complicated processes that govern the atmospheric meso- and micro-scale. It is the author's conviction that the "problem of CAT" will not be solved satisfactorily before these interactions are better understood.

6. EFFECTS OF TURBULENCE ON ATMOSPHERIC STRUCTURE

It has been stated above that CAT frequently occurs in thermally stable layers with vertical wind shear. The very presence of turbulence, however, should destroy such a stratification and such shears. The eddy transports of heat and momentum in the turbulent medium should lead to the formation of an adiabatic lapse rate, and to a uniform wind speed within this adiabatic layer. Shear and stability should become concentrated near the bottom and the top of such a layer, leading to even more turbulent conditions there (Fig. 12). Thus, a turbulent layer should be increasing in thickness once it has formed, unless the increased stability near its upper and lower boundaries offsets the increase in shear. The latter should be expected if $\partial Ri/\partial L > 0$ in the region in which the turbulent layer is forming (L is the layer thickness). It has been observed that "stable" layers in the atmosphere frequently reveal a small-scale structure (usually not detected by conventional sounding instrumentation) in the form of a succession of thin stable and thin adiabatic layers (see e.g. Danielsen, 1959). Accurately measured vertical and horizontal wind profiles also reveal a considerable meso-structure of atmospheric flow (see e.g. Reiter and Lester, 1968; Reiter, 1963). To the author's knowledge it has never been investigated if such details may be cause and/or effect of atmospheric turbulence. Reports that CAT appears to favor the edges of stable layers in the atmosphere lend some support to the above speculations.

7. DETECTION OF CAT

The report by the National Committee on Clear Air Turbulence (U.S. Department of Commerce, 1966), as well as the Proceedings of the National Meeting on Clear Air Turbulence (Society of Automotive Engineers, 1966) contain many a hint on the possibilities of the remote sensing of CAT. It would lead too far afield if all such attempts of ground-based and air-borne sensing were reviewed here in detail. Instead, a

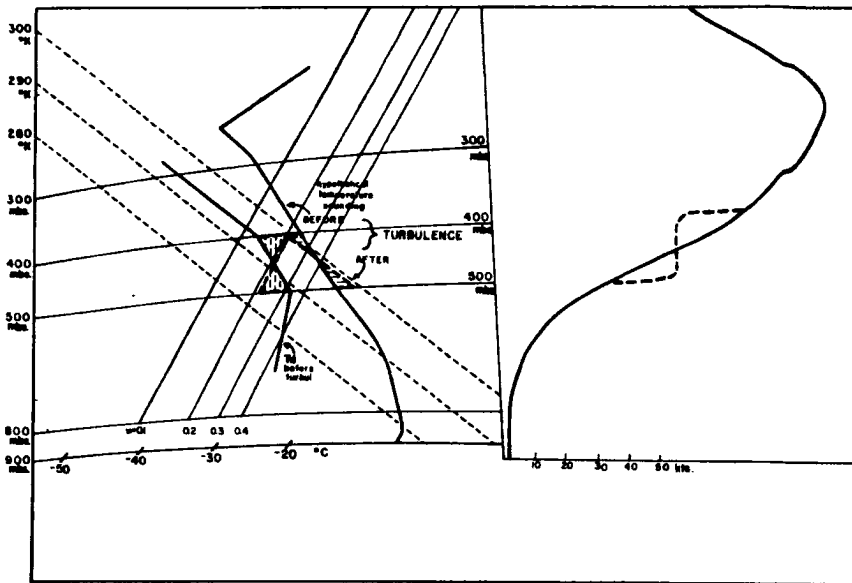


Figure 12. Schematic view of effects of turbulence on vertical wind, temperature and humidity profiles: A stable lapse rate will change into an adiabatic layer bounded by two inversions; at the same time the momentum exchange within the adiabatic layer will cause the formation of a "nose" on the vertical wind profile. (Similar "noses" are frequently observed in FPS-16 wind soundings.) Vertical wind shears will be concentrated at the top and bottom of the adiabatic layer. Vertical mixing in this layer will also equalize the water vapor mixing ratio in the adiabatic layer. If there was a vertical gradient in the mixing ratio to start with, strong gradients of the quantity will result at the top and the bottom of the adiabatic layer. Turbulence elements of a certain size will now generate larger fluctuations in atmospheric refractivity "n" at the bottom and top of this layer, than they did before turbulence started under moderately stable conditions. Solid lines indicate conditions before the onset of turbulence, dashed lines after the establishment of a turbulent layer. Note that under favorable conditions a haze layer may develop on top of the turbulent region.

few general remarks will be provided as a basis for discussion.

(a) Forward-and/or backscatter of electromagnetic waves by refractive-index discontinuities will provide useful means at (electromagnetic) wavelengths which are influenced by atmospheric eddies larger than those of the frictional dissipation range (i.e. $>$ ca. 1 cm). Long-wave radar, therefore, appears to be more promising than 3 cm radar or laser (Atlas, Hardy and Naito, 1966; Stephens and Reiter, 1966). In view of the fact that vertical gradients in radio refractivity should be enhanced at the top and bottom of a turbulent layer (for the same reasons that should cause an adiabatic layer to form), it might be possible that turbulence is "seen" by such devices only after it has been active for some time (Fig. 12). More systematic studies will be needed in which remote sensing equipment operates simultaneously with detailed (radiosonde and aircraft) measurements of atmospheric structure.

(b) Aerosol dispersions may provide measurable returns from a turbulent medium to give an indication of turbulence intensity. "Schlieren" effects will also influence beams of incoherent light causing intensity fluctuations in the received light. Such "crossed-beam" experiments are presently conducted at Colorado State University. Preliminary descriptions of this experiment have been given by Drs. F. Krause (NASA, Huntsville), Fisher and Montgomery (IITRI, Chicago) in internal reports. These studies, promising as they are, will also have to be correlated with direct measurements of atmospheric structure.

(c) The systematic measurement and interpretation of atmospheric meso-structure is still in its infancy stages. Although we know about the existence of such a meso-structure we know nearly nothing about its life history and its interplay with macro- and micro-scale. A systematic attack on the atmospheric meso-structure would, in the author's opinion, yield the largest return in the understanding of CAT. Physical models of CAT, based upon such an understanding, together with ground-based, air-and/or satellite-borne remote sensing devices will truly "tame the CAT".

8. APPENDIX SPECTRAL ANALYSIS OF A BREAKING WAVE

Elmar R. Reiter, P. F. Lester and G. Wooldridge

Photogrammetric studies of cloud patterns in the Fort Collins area revealed the presence of "breaking waves" on the upper boundary surface of lenticular cloud sheets. Such clouds are indicative of orogenic lee-wave formation. From various theoretical and experimental studies of these lee waves it is apparent that shallow layers with strong vertical wind shears may exist especially near the tropopause where wave amplitudes usually are large. Since large vertical excursions of streamlines are conducive to the formation of lenticular clouds, it is not surprising that the upper surfaces of these clouds every so often reveal conditions of unstable flow. This is shown schematically in Fig. 13.

Figs. 14a, 14b, and 14c show a sequence of cloud photographs taken at 1830, 1835 and 1845 GMT, respectively, November 9, 1967. The view is toward the south from the roof of the Colorado State University Atmospheric Science Building west of Fort Collins, Colorado. The reader can observe the breaking billows on the top surface of the cloud stream at the bottom center of the 1830 GMT photograph (Fig. 14a). The billows were reformed by 1835 GMT (Fig. 14b) and breaking again by 1845 GMT (Fig. 14c). The generation of unstable billows on similar time scales (a few minutes) has been observed on several occasions under the same weather conditions on lenticular clouds in this region.

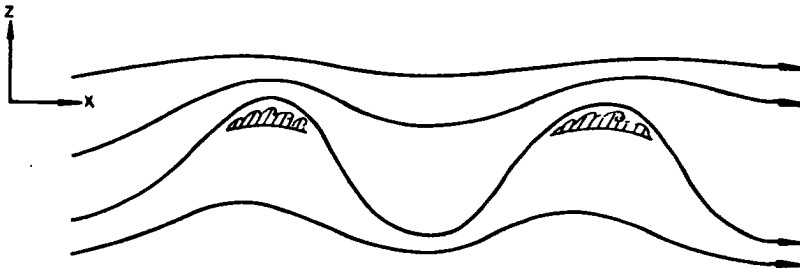


Figure 13. Formation of unstable billows on the upper surface of lenticular clouds in regions of strong vertical wind shears (expressed by the vertical gradient in the spacing of stream lines).

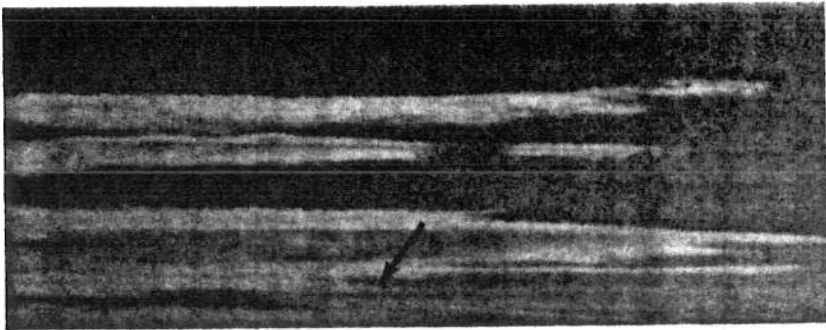
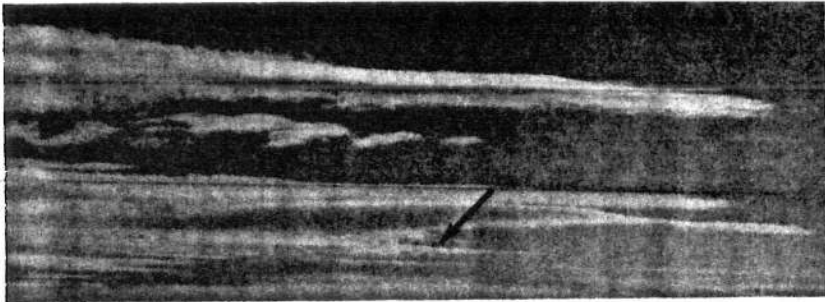


Figure 14. Unstable billows observed in a lenticular cloud layer south of Fort Collins on November 9, 1967. a, b, c Picture-taking times are: Fig. 14a, 1830 GMT; Fig. 14b, 1835 GMT; Fig. 14c, 1845 GMT.

As has been pointed out in the preceding section, the occurrence of CAT, at least in a number of documented instances (see TOPCAT measurements over Australia, Figs. 8, 9, and 10, and Mr. G. Mather's measurements published in this volume), is linked to a breaking-wave phenomenon. At the same time a spectral density distribution of eddy kinetic energy with a "-5/3 slope" in a log-log presentation seems to approximate well the functional relationship between $E(k)$ and k [see eqn. (1)]. The purpose of the present study was to deduce the behavior of spectra of wave motions which -- at least in a qualitative way -- resemble the motions observed in billows of the kind shown in Figs. 14a, 14b and 14c.

For the purpose of this analysis the total time, T , in which the waves became unstable was assumed to be 300 sec. Photogrammetric evaluation of the billows shown in Fig. 14b yielded a wave length of $\lambda \approx 50$ m and an amplitude of $A \approx 15$ m. Inspection of other pictures obtained during this field study indicated a ratio of $A:\lambda \approx 1:4$ for a breaking-wave phenomenon. The assumption on dimensions made above, therefore, appear to be reasonable. A wind sounding made at Ault, Colorado, close to the time at which the wave phenomenon of Fig. 14b appeared (1135 local standard time) showed winds of 10 to 13 mps in the altitude range under consideration. For the subsequent computations the wind speed u was taken as 10 mps. Assuming that the billows were standing waves (which they were not), a period of $\tau = 5$ sec would result for air parcels moving through the breaking wave. A wave speed $c \neq u$, which was not measured in the present instance, would not have a major effect on the following computations. It would uniformly decrease the kinetic energy at all wave lengths, i.e. the rate of dissipation of kinetic energy ϵ , would be less than that appearing in the subsequent calculations. The slope of the computed spectra, however, would not be altered.

As a first approximation it was assumed that a pure sine-wave was amplifying exponentially according to

$$z = \exp \frac{\alpha t}{T} \sin \frac{2\pi t}{\tau} \quad (3)$$

where z , the vertical excursion of the streamline from its equilibrium position, was taken to be equivalent (with a phase shift of $\pi/2$) to the vertical velocity w . The latter, of course, will depend on the magnitude of $(u - c)$. As

stated above, c was assumed to be zero for the present case study. The following values were substituted into eqn. (3): $T = 300$ sec; $\tau = 5$ sec; $\alpha = 2.7$. Results of the computations under the above assumptions (Case 1) are shown in Fig. 15. The abscissae on the left side of this diagram contain the number of data points (5 points per wave). (Only portions of the total record are shown here.) Normalized spectral densities are plotted as a function of frequency intervals on the right side of this figure. As should be expected from the Fourier transform of an exponentially increasing sine wave (Bendat and Piersol, 1966, p. 86), the spectrum essentially shows a "spike" at the frequency of the characteristic wave phenomenon, with an (almost) exponential slope on both sides. It appears that, unless wave amplitudes are made to increase very rapidly (large values of α), a flow configuration as given by eqn. (3) will not produce spectra similar to the ones observed in CAT. From Figs. 14a, 14b, and 14c it appears that a drastic increase in the exponential rate of growth of the breaking waves, however, is not justified. From this we may conclude that turbulent flow characteristic of CAT is not associated with a simple increase in wave amplitude.

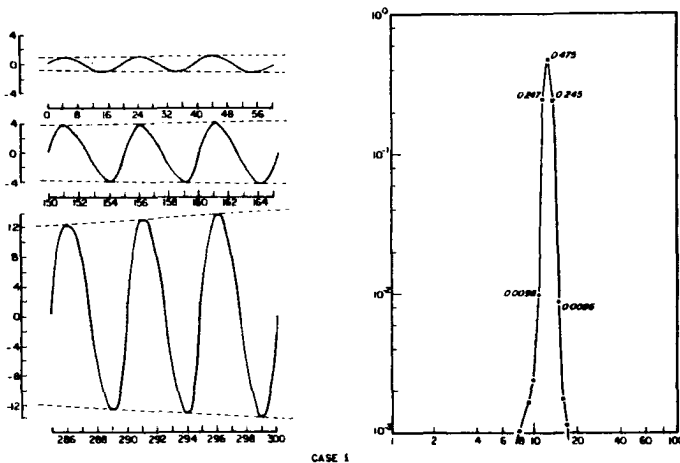


Figure 15. Exponentially increasing waves [left side of diagram, ordinate: meters, abscissa: data points (1 data point = 1 sec); right side: power spectrum as a function of logarithm of wave number].

As a next step, a rather artificial and formalistic "breaking wave" was spectrum-analyzed. A truly breaking wave, as is evident from the appearance of "curling" billows, was not considered because "z" would have multiple values along the t-axis wherever such curls occur.

In Case 2 it was assumed that the first 30 waves of the 60-wave record showed a simple exponential increase in wave amplitude, identical to Case 1. In the last 30 waves, however, a "breaking" mechanism was introduced by extending the wave maxima along the lines of the exponential slope, $e^{2.7t/T}$, until they were located above the inflection points of the waves. The point thus obtained was then connected by a straight line with the subsequent wave minimum (Fig. 16). Results of the computations are shown in Fig. 17. The left side, again, shows portions of the assumed breaking wave train. Dashed lines indicate the approximation of the assumed wave by the computer program. The spectrum given on the right side of this diagram indicates a "dumping" of kinetic energy into a higher-frequency wave mode. A relatively small amount of energy also appears at low wave numbers:

In Case 3 the slopes of the "breaking waves" were steepened further by extending the maximum points of the waves No. 31 through 60 along the exponential amplification lines, until they were located directly over the minimum points (Fig. 18). Fig. 19 shows the computational results. The steepening of the wave fronts obviously produces a faster dumping of energy into higher wave number, indicated by a less steep slope of the envelope of the peaks in the spectrum curve.

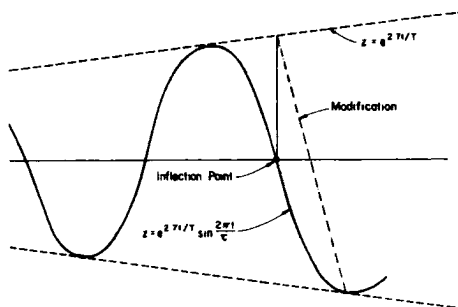


Figure 16. Schematic presentation of "breaking wave". For explanation, see text.

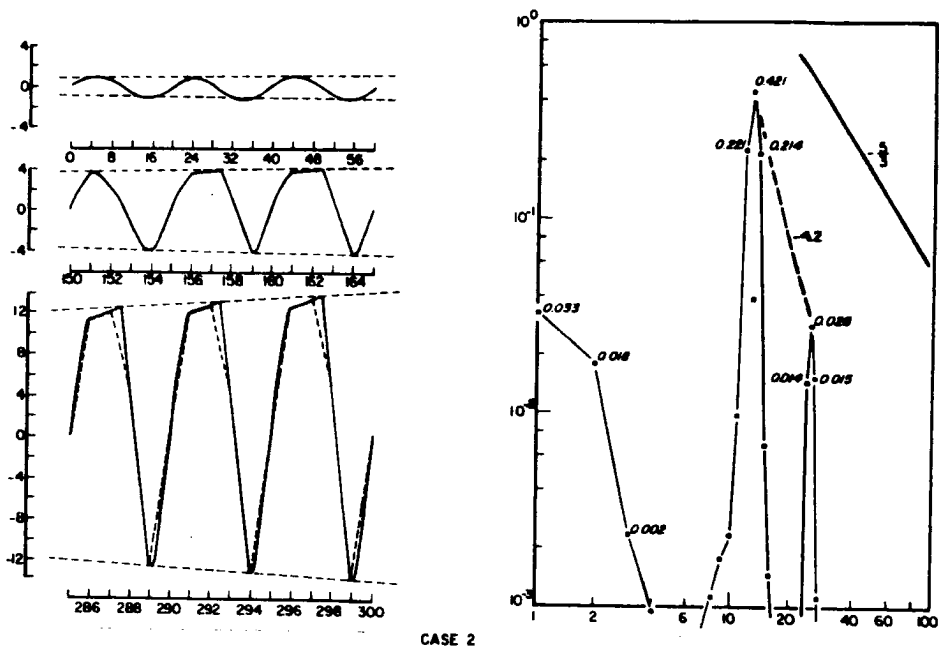


Figure 17. Same as Fig. 15, except for exponentially increasing "breaking wave".

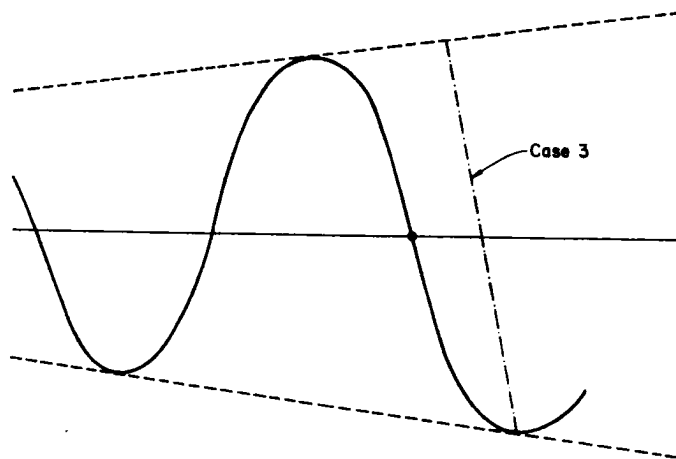


Figure 18. Schematic presentation of "breaking wave". For explanation, see text.

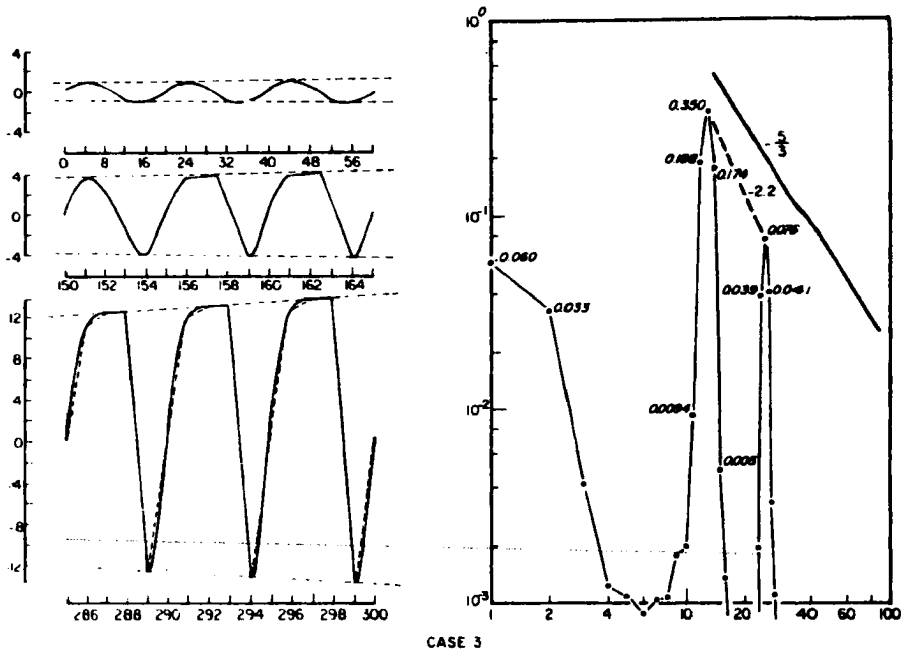


Figure 19. Same as Fig. 15, except for "breaking wave" defined in Fig. 18. For explanation, see text.

In the preceding cases, five data points were used to model the shape of each wave. As may be seen from the dashed lines on the left side of Figs. 17 and 19, the resolution of the actual wave by such a limited number of data points is only moderate. Much better resolution was achieved by allowing 20 data points for each wave. In Case 4, again, an exponential increase of a pure sine wave was assumed to hold for the first 30 waves. From thereon the wave fronts were assumed to "break" by leading the maximum point of each wave along the line of exponential amplitude increase directly over the inflection point of the wave. Then, for each succeeding two waves this maximum point was advanced further along the exponential-increase line until, at wave No. 39, this point was only one data point behind the location of the minimum points of the wave. From thereon through wave No. 60 the maximum point was kept one data point (≈ 0.25 sec) behind the minimum point. Results of the computations are shown in Fig. 20.

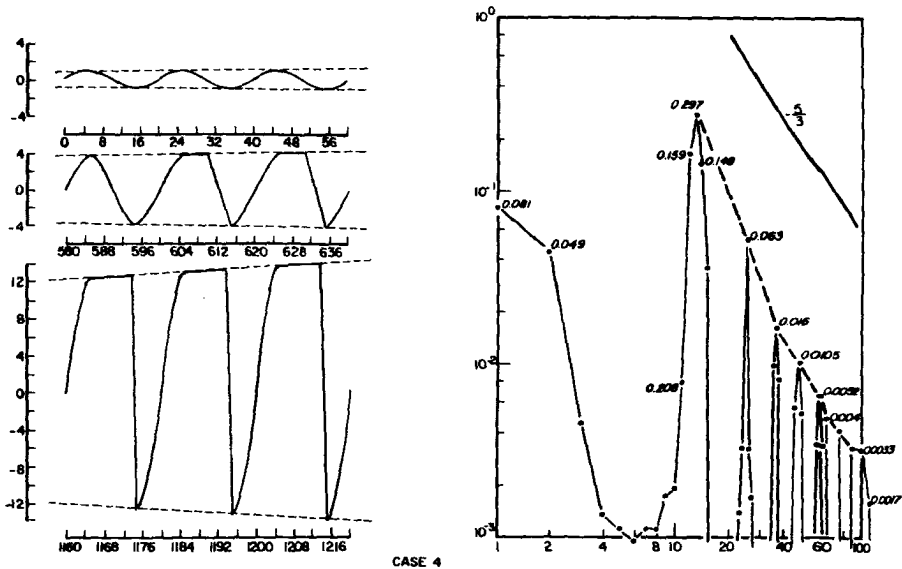


Figure 20. Same as Fig. 17, except for finer resolution in data points. For explanation, see text.

The finer resolution of 20 data points per wave permits the calculation of eddy kinetic energy at larger wave numbers than was possible in the previous cases under consideration. The existence of "spikes" rather than of a smooth spectrum curve has to be ascribed to the computational scheme and to the introduction of a well specified curve which has been spectrum-analyzed. Such conditions, of course, would not exist in the real atmosphere. The line connecting these "spikes" in the spectrum has a slope of approximately -2.4 .

Case 5 is similar to Case 4, except that the waves were steepened more gradually now: The maximum point of each wave, beginning with wave No. 31 was advanced by one data point from the location above the inflection point towards the location above the minimum point only for every sixth wave. Maximum steepness was reached for the last six waves. As may be seen from Fig. 21, the more gradual "breaking process" of the wave causes a steeper slope of the envelope of the "spikes" in the spectrum curve (slope = -2.8 in this case) than with the more rapid "breaking" shown in Case 4. This confirms the evident conclusion that with a sudden breaking of waves energy will be transferred more readily into smaller eddies than with a slowly breaking process.

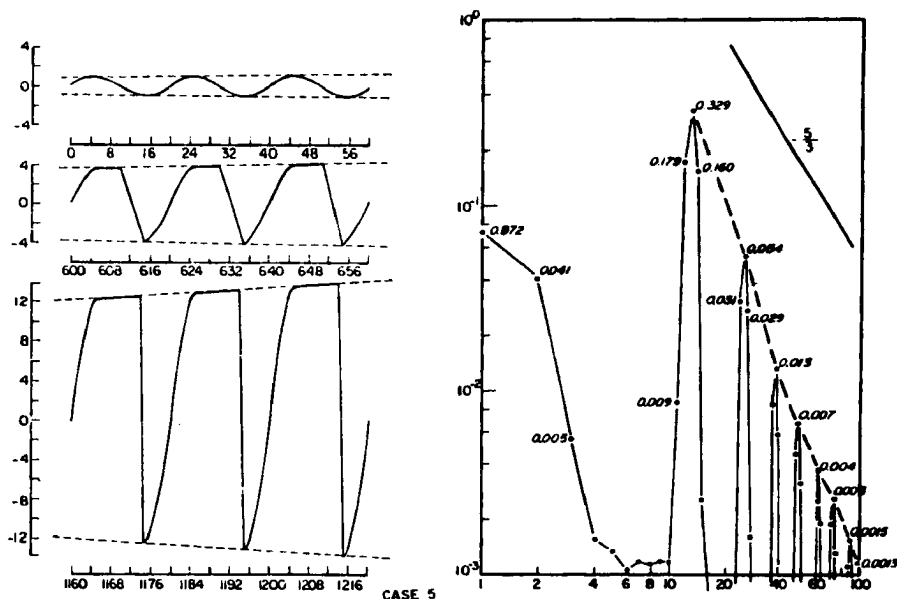


Figure 21. Same as Fig. 19, except for finer resolution in data points. For explanation, see text.

From the foregoing it is quite evident that the processes of steepening wave fronts and of ultimate "breaking" of these waves produce spectra of eddy kinetic energy which are surprisingly similar to those observed with CAT. Spectral slopes computed for Cases 4 and 5 are -2.4 and -2.8 respectively. Even though the assumptions which were made in the above computations were rather artificial, these values come close to the $-11/5$ and -3 slopes assumed for the buoyant subrange by Bolgiano (1959) and by Vinnichenko, Pinus, and Shur (1967). As has been stated before, the waves considered in the present computations were not really breaking but only steepening their leading edges. In a true breaking mechanism energy would be transferred even more rapidly into higher wave numbers than indicated by Figs. 18 and 19 of the present case study. Thus, it would seem that a combination of wave-front steepening and of final breaking of the waves might simulate quite satisfactorily the CAT spectra obtained by various authors. This would hold for the spectral slopes, as well as for the "humps" observed by Reiter and Burns (1966) and by Mather (see elsewhere in this volume).

9. ACKNOWLEDGEMENT

The cloud photographs shown in this study were obtained during a field measurement program supported by ESSA Grant No. E-10-68G.

10. REFERENCES

1. Atlas, D., Hardy, K. R., and Naito, K. (1966). Optimizing the radar detection of clear air turbulence. Proceedings, Clear Air Turbulence Meeting, Washington, D. C., Feb. 23-24, 97-106.
2. Bendat, J. S. and Piersol, A. G. (1966). Measurement and analysis of random data. (John Wiley & Sons, New York).
3. Bolgiano, R. Jr. (1959). Turbulent spectra in a stably stratified atmosphere. J. Geophys. Res., 64, 2226.
4. Bolgiano, R., Jr. (1962). Structure of turbulence in stratified media. J. Geophys. Res., 67, 3015-3023.
5. Burns, A., and Rider, C. K. (1965). Project TOPCAT, power spectral measurements of clear air turbulence associated with jet streams. Royal Aircraft Establishment, Technical Report No. 65210.
6. Clodman, J., Morgan, G. M., Jr., and Ball, J. T. (1960). High level turbulence. Air Weather Service Technical Report 158, Contract No. AF 19(604)-5208, New York University.
7. Cunningham, N. W. (1958). A study of the duration of clear air turbulence near the jet stream and its relation to horizontal temperature gradient. Texas A and M College, Dept. of Oceanography and Meteorology, Final Report "Wind field near the tropopause", Contract No. AF 19(604)-1565, 75-85.
8. Danielsen, E. F. (1959). The laminar structure of the atmosphere and its relation to the concept of a tropopause. Archiv. Meteor. Geophys. Bioklim. Sec. A, 11(3): 293-332.

9. Endlich, R. M. (1963). The detailed structure of the atmosphere in regions of clear air turbulence. Final report, SRI Project No. 4055, Contract Cwb-10324.
10. Foltz, H. P. (1966). Prediction of clear-air turbulence. Department of Atmospheric Science, Colorado State University, Atmospheric Science Paper No. 106.
11. Pinus, N. Z., Reiter, E. R., Shur, G. N., and Vinnichenko, N. K. (1967). Power spectra of turbulence in the free atmosphere. *Tellus* 19(2):206-213.
12. Reiter, E. R. (1960). Turbulenz im wolkenfreien Raum (Clear air Turbulence). *Berichte D. Deutschen Wetterdienstes*, No. 61.
13. Reiter, E. R. (1963). Nature and observations of high-level turbulence, especially in clear air. U. S. Navy Weather Research Facility, Norfolk, Virginia, Report NWRP 15-1262-071, 28 pages.
14. Reiter, E. R. (1963). Jet stream meteorology. (Univ. of Chicago Press, Chicago).
15. Reiter, E. R. and Burns, A. (1965). Atmospheric structure and clear air turbulence. Colorado State University Atmospheric Science Technical Paper No. 65.
16. Reiter, E. R. and Burns, A. (1966). The structure of clear air turbulence derived from "TOPCAT" aircraft measurements. *J. Atmosph. Sci.* 23(2):206-212.
17. Reiter, E. R. and Foltz, H. P. (1967). The prediction of clear air turbulence over mountainous terrain. *J. Applied Meteorol.* 6(3):549-556.
18. Reiter, E. R. and Lester, P. F. (1968). Richardson's number in the free atmosphere. *Archiv. Meteor. Geophys. Bioklim. Sec. A*, 17(1):1-7.
19. Reiter, E. R. (1968). Recent advances in the study of clear air turbulence (CAT). U. S. Navy Weather Research Facility, Norfolk, Virginia, NWRP 15-0468-136.

20. Scoggins, J. R. (1963). Preliminary study of atmospheric turbulence above Cape Canaveral, Fla. NASA, George C. Marshall Space Center, Huntsville, Ala., MTP-AERO-63-10.
21. Shur, G. N. (1962). Experimental investigation of the energy spectrum of atmospheric turbulence. Trudy Ts AO, No. 43.
22. Smith, J. W. (1963). Atmospheric environment for the flight of Saturn (SA-3), NASA, George C. Marshall Space Flight Center, Huntsville, Ala., MTP-AERO-63-20.
23. Society of Automotive Engineers (1966). Conference Proceedings, Clear Air Turbulence Meeting, Washington, D. C., Feb. 23-24, 198 pp.
24. Stephens, J. J. and Reiter, E. R. (1966). Estimating refractive index spectra in regions of clear air turbulence. Antennas and Propagation Div., Electrical Engineering Research Lab., Univ. of Texas, Austin, Texas, Report No. P-12, 44 pages.
25. U.S. Department of Commerce, (1966). Report of the National Committee for Clear Air Turbulence.
26. Vinnichenko, N. K., Pinus, N. Z., and Shur, G. N. (1967). Some results of experimental turbulence investigations in the troposphere. (In Russian). In: Atmospheric Turbulence and Radio Wave Propagation. Nauka, Moscow, 65-75.

DISCUSSION

Robert R. Long: Gap in the energy spectrum may be explained as dumping of energy in wavebreaking to smaller-scale waves.

Elmar R. Reiter: I agree with Dr. Long's interpretation of a gap in the energy spectra of atmospheric turbulence. I doubt, however that in the free atmosphere a gap as large as the one observed by Van der Hoven should be expected. Frictional dissipation near the ground would act even on a uniform and stationary mean flow by virtue of the observed (logarithmic) vertical wind profiles. Thus one might

postulate conditions in which kinetic energy would exist only in infinitely large wavenumbers and in small-scale isotropic turbulence, with the synoptic-scale eddies missing, too, from the spectrum. Such conditions would demonstrate quite effectively Dr. Long's "dumping" mechanism. I do not think, however, that the free atmosphere and its internal turbulence is capable of bridging such a wide gap in the spectrum of motions without the assistance of a pronounced meso-scale.

David Atlas: I wonder if we should continue to accept the Project Jet Stream statistics on the horizontal extent of CAT since we now know that many CAT layers are tilted and are not adequately sampled by horizontal flights.

Elmar R. Reiter: A tilting of CAT layers may indeed occur, however the synoptic-scale slope of isentropic surfaces may turn out to be a poor indicator of such a tilt, especially if the meso-structure of the atmosphere plays the dominant role in generating CAT. Since most of the present air space users fly isobaric rather than isentropic patterns, data acquired from quasi-horizontal flight tracks appear to be quite appropriate to characterize CAT for present and possible future needs.

George H. Fichtl: In Van der Hoven's paper the spectra were plotted in $(kS(k), \ln k)$ coordinates. These coordinates amplify the gap. Perhaps a plot of your spectra in these coordinates would amplify or reveal a gap.

Elmar R. Reiter: Such a widening of the gap would, indeed, occur in the coordinate system proposed by Dr. Fichtl, however not to the degree suggested by Van der Hoven's spectra.