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Clear Air Turbulence: A Mystery May Be Unfolding

High altitude turbulence poses serious problems for aviation and atmospheric science.

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The advent of the jet age, with sleek airplanes that could cruise above clouds and storms, led aviation to hope that its troubles with weather would be confined to takeoffs and landings. But a new danger appeared—a form of turbulence that occurs in clear air and thus can neither be seen nor avoided by pilots.

This clear air turbulence was first encountered in World War II by high-flying aircraft with supercharged piston engines; jet airplanes reach with ease the altitudes at which this turbulence occurs most frequently. The increasing use of jet aircraft has emphasized the necessity of learning about these apparently rare outbreaks of atmospheric motions in clear air, which are sometimes violent enough to injure passengers with unfastened seat belts and, in severe cases, to damage the giant airplanes themselves.

In addition to the impact on aviation, clear air turbulence plays a fundamental part in the atmospheric processes that must be fully comprehended if significant improvements in long-range weather forecasting, and perhaps control, are to be made.

The importance of such turbulence to aviation is revealed by statistics compiled by the National Committee for Clear Air Turbulence (*1*). Damage to aircraft is estimated to have cost the Department of Defense \$30 million for the period 1963 to 1965; no economic cost figure can be placed on injury to aircrews or on the effect of turbulence in reducing combat effectiveness. The committee reported a study that showed the cost to commercial aviation in 1964 to have exceeded \$18 million, of which a major portion was the increased expense caused by diversions around areas in which turbulence was forecast or had occurred.

Not all sudden vertical motions experienced by airplanes outside of clouds are due to clear air turbulence, however. There are severe but solitary bumps whose cause is not now understood. Or, aircraft may encounter internal waves, quasiperiodic disturbances in the atmosphere which are much like ocean waves. These gravity waves have smaller amplitudes at a given wavelength than clear air turbulence has, and are not a serious hazard to flight at present aircraft speeds.

Most ominous of all, however, aircraft may encounter very severe vertical currents that are part of the convection patterns of large-scale phenomena such as squall lines. Such motions usually occur close to thunderstorm clouds. Early in the jet age, aircraft were hurtled into surprising attitudes, and the continuing effects of the convection led to disastrous situations not previously experienced. On several such occasions pilots lost control and the airplanes ended up in steep, high-speed dives toward the earth's surface. Pullout from such a dive is both dangerous and tricky. If done too slowly, the airplane will hit the ground before leveling out; if done too rapidly, the immense forces that result may destroy the aircraft. Procedures have now been worked out which allow pilots to retain control under these conditions and which prevent the aeronautical forces resulting from penetration of these currents from reaching overwhelming proportions.

The name "clear air turbulence" specifically refers to turbulence occurring several kilometers above the earth's surface in air that is free of clouds and strong convective currents. It generally implies turbulence severe enough to produce noticeable motions of aircraft flying through it.

Despite the fact that clear air turbulence has not led to any fatal accidents in the United States, passengers and cabin attendants have been injured and aircraft have suffered structural damage. Thus such turbulence is to be avoided whenever possible.

The investigations of the structure and physics of clear air turbulence instigated by the requirements of aviation and the aeronautical sciences have revealed some of the basic properties of the phenomenon. These results demonstrate that such turbulence controls an important valve in the atmospheric engine, and that any attempt to develop computerized models of atmospheric flow which will make it possible to predict atmospheric conditions weeks in advance will require that the flows of energy through this valve be modeled correctly.

In this article we attempt to survey the present knowledge of clear air turbulence, to demonstrate that the available empirical data are in agreement with basic theories of atmospheric motion, and to comment on the implica-

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tions of these results for the future course of research into the properties of such turbulence and the possibility of predicting its occurrence. We make no attempt to provide a complete bibliography; rather, our aim is to suggest that the developments cited here provide a framework for further investigations which should yield definitive answers.

It is certain that complete understanding of clear air turbulence will not lead to its extinction, but perhaps methods can be perfected that will permit pilots to avoid most of it. We can, at least, hope to learn what to expect when aircraft encounter it, or when we try to capture its characteristics in a computer model for numerical weather prediction.

Properties of Turbulent Motion

Clear air turbulence is one of several forms of motion in the atmosphere. To understand its precise nature, it is useful to review the fundamental properties of turbulence.

The details of a turbulent flow appear to be random, and repetition of experiments leads to flows that differ from each other, although certain average properties may be the same. Thus, turbulent motion appears chaotic, and its apparent randomness distinguishes it from the smooth (or laminar) nonturbulent flows.

Many of the properties of atmospheric turbulence are revealed by consideration of its energy budget. Under simplifying assumptions, this budget may be written in the following form:

$$dE/dt = M + B - \epsilon + T \qquad (1)$$

In this equation, E is the mean kinetic energy of the turbulence per unit mass, dE/dt is its rate of change; M is the rate of production of turbulent energy by the wind shear (rate of change of wind with elevation); B is the rate of production of energy by buoyancy; T is a transport term; and ε is the rate of frictional dissipation of turbulent kinetic energy into heat.

The term M, which in its analytical form shows how wind shear and the turbulent motion interact to produce turbulent energy, is almost always positive because it is usually proportional to the square of the wind shear in the vertical. Both change of wind speed and change of wind direction with height can contribute to this term, and if the only energy source is through M, we refer to the resulting chaotic motion as mechanical turbulence.

The term B depends on the vertical distribution of temperature and moisture. The effect of moisture is usually small and is disregarded here. When the temperature decreases more rapidly with height than 1°C per 100 meters, B is positive. If B is responsible for the turbulence, the motion is referred to as heat convection or convective turbulence. Unlike M, the term B is frequently negative; in fact, only in clouds of the cumulus type and near the ground on sunny days is B consistently positive. When B is negative it acts as an energy sink which diminishes or damps out mechanical turbulence.

The rate of dissipation, ε, is always positive and thus dissipation is always an energy sink. In general, M or B, or both, create rather large-scale turbulence. The resulting eddies decay into smaller and smaller eddies, until the energy is finally dissipated by viscosity. Because air has a small coefficient of viscosity, dissipation is important only when there are very small eddies to give very large velocity gradients.

The transport term T allows for the possibility that energy produced in a given air parcel is not necessarily dissipated there but may instead be exported and dissipated elsewhere.

Because clear air turbulence occurs in regions in which B is negative (that is, occurs under hydrostatically stable conditions), it must be produced by M; it is thus mechanical turbulence damped somewhat by the temperature stratification. Of course, for turbulence to occur in stable air, the rate of production M must be large enough to counteract the rate of drainage of energy by B and ε.

In order to judge quantitatively whether mechanical production is sufficiently large to overcome the energy sinks, the flux Richardson number $R_f(= -B/M)$ is used. By this definition, R_f measures the ratio of the rate of withdrawal of energy by the stable stratification to the rate of production of energy by the wind shear. Let us assume that transport of energy is not important, and rewrite Eq. 1 as follows:

$$\frac{dE}{dt} = M(1 - R_f) - \epsilon \qquad (2)$$

Thus, if R_f is negative, both B and M are feeding energy, and the turbulence probably will be intense. If R_f is large

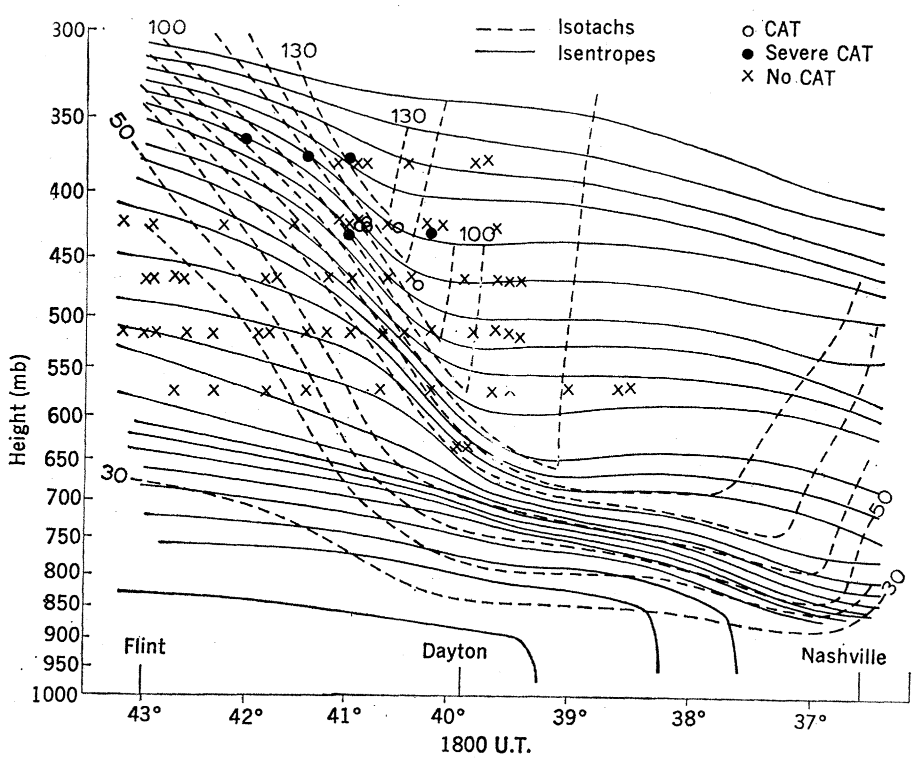

Fig. 1. Cross section showing the relationship of the occurrence of clear air turbulence (CAT) to the location of the internal front. The region shown extends from Flint, Michigan, to Nashville, Tennessee; the data were obtained 23 April 1963 at 1800 hours GMT. (Dashed lines) Isotachs at intervals of 10 knots; (solid lines) isentropes at intervals of 2°K; (open circles) turbulence; (solid circles) severe turbulence; (crosses) no turbulence.

and positive, energy is withdrawn so rapidly by the buoyancy term B that turbulence does not develop. If R_f is zero, only mechanical turbulence is possible. It is generally assumed that there is some positive, critical Richardson number, R_c, such that turbulence will persist only if $R_f < R_c$. From Eq. 2 we have

$$R_c = 1 - \epsilon/M \qquad (3)$$

but the ratio ϵ/M is not known well enough to establish R_c. We discuss the problem of determining R_c below.

Where Clear Air Turbulence Occurs

The usual acronym for clear air turbulence—CAT—encourages a possibly overused play on words in which feline characteristics are attributed to the physical phenomenon. However, there is a useful parallel between the essential ingredients of a scientific study of CAT and the steps that are necessary in a biological investigation of any animal and its interactions with its environment (*2*).

As the result of a variety of measurement programs and collections of data, the anatomy of CAT is fairly well understood; our main concern in this article, however, is with the ecology, physiology, and life cycle of CAT.

The relevant facts concerning the regions where clear air turbulence occurs have been collected in statistical form through analysis of the reports of U.S. (*3*) and Soviet (*4*) aircraft pilots. The conclusions drawn from these statistics and supported by measurements made by means of specially instrumented airplanes flown into turbulence for research purposes may be summarized as follows.

1) The probability that clear air turbulence will occur is largest in regions of strong vertical wind shear and strong horizontal temperature gradients. (These two factors are closely related to each other, because the wind tends to change in the vertical most rapidly when there are strong horizontal temperature gradients.)

2) In middle latitudes, clear air turbulence is most frequent and most severe in January and February, because in these months horizontal temperature gradients in the upper atmosphere are the largest.

3) The probability of an airplane encountering clear air turbulence increases with increasing altitude, reaching a maximum at the general region of the boundary between the lower atmosphere and the stratosphere. This boundary, called the tropopause, is associated in middle latitudes and in the subtropics with the atmospheric jet stream, a region of strong winds which circles the globe in a sinuous pattern. Clear air turbulence also occurs in the stratosphere, above this region of maximum winds, but less frequently.

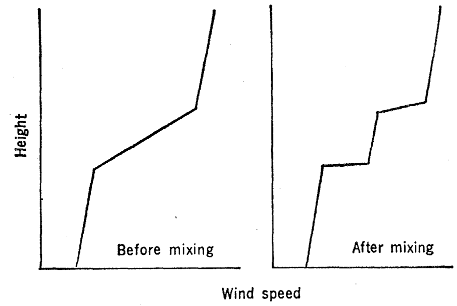

Fig. 2. Schematic illustration of a hypothesis concerning the way in which turbulent mixing affects an internal front. The situation at left represents the frontal structure before mixing, that at right shows the postulated concentration of the shear in the boundaries of the front after the center of the region is mixed by turbulent motion.

4) Clear air turbulence is more frequent and more intense over land than over the oceans, and over mountains and hilly terrain than over the plains.

5) Clear air turbulence is likely to occur in regions in which the Richardson number R_f is small.

Even though the five statistical relations enumerated above are quite significant, it is impossible to determine with certainty from ordinary weather charts whether or not turbulence will occur. The difficulty is that both the spatial and temporal resolution of ordinary upper-air data is poor. Observations are usually made every 12 hours at stations a few hundred kilometers apart, and data points are obtained only every 700 meters or so in the vertical. This resolution is too coarse for locating the regions of turbulence exactly, or for giving much detail on the flows of energy to and from the turbulent motion.

Thus, even though we know the characteristics of the regions in which clear air turbulence occurs, the atmosphere is not sufficiently well sampled for us to find the turbulence easily. Special field studies and special equipment are needed for studying the interactions of clear air turbulence with its environment.

A Model of Turbulence Occurrence

On several occasions detailed studies have been made of simultaneous distributions of wind, of temperature, of the intensity of turbulence, and of other variables by combining reports from specially instrumented aircraft with data from radiosonde balloons.

A vertical cross section obtained during such a study (*5*) is shown in Fig. 1. Lines of constant wind speed (isotachs) and lines of constant potential temperature (isentropes) have been drawn in Fig. 1. The potential temperature θ is defined as the temperature the air would have if it were brought down to the ground (more exactly, to a pressure of 1000 millibars) without exchange of heat. Because this adiabatic process would require compression of the air parcel, the potential temperature of the parcel is larger than its ordinary temperature. When the potential temperature increases with height, as it does in most regions of the atmosphere, then the region is hydrostatically stable (*6*), and buoyant forces will inhibit the growth of turbulence. The closer together isentropes are, the greater is the stability.

Note that at the top of Fig. 1 there is a zone where both isotachs and isentropes are crowded together; this crowding indicates that both the stability and the wind shear are large. Such a region is called a baroclinic zone or an internal front, because it separates masses of air with different characteristic wind speeds and temperature.

Now we must consider another Richardson number, this one called the gradient form, which is given by

$$R_i = \frac{g\partial\theta}{\theta\partial z} \Big/ \left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right] \qquad (4)$$

where θ is the potential temperature, g is the acceleration of gravity, and U and V are the wind components in two orthogonal horizontal directions. This number R_i and the flux version R_f are proportional if the ability of the turbulence to transport heat vertically is proportional to its ability to transport momentum. Meteorologists often assume this is the case, but, viewed rigorously, R_f arises from the energy budget whereas R_i arises in the theory of wave stability. But computation of R_f is difficult and often impossible, so that R_i is generally used as an approximation in observational studies of turbulence.

Hence we have assumed in Eq. 4 that the generation of mechanical turbulence depends essentially on the square of the wind shear which may arise from a change of wind speed, of wind direction, or of both, while the destruction of turbulence by the stable stratification depends on the first power of the gradient of potential temperature. Therefore, the larger the contrasts are across the front, the more likely it is that M in the denominator of R_i will overcome the stabilizing effect of $-B$ in the numerator; thus, the more pronounced the front is, the lower the Richardson number is likely to be.

In Fig. 1 the Richardson numbers are less than unity in the frontal zone, but considerably larger outside that zone. Figure 1 shows also that effectively all the turbulence occurred within the frontal layer, with the most severe turbulence at the edges of that layer. Many other case studies have shown that clear air turbulence tends to be concentrated in these internal fronts where the Richardson numbers are small.

There is a convenient way to relate the Richardson number to the properties of internal fronts by introducing approximate forms of some of the dynamic equations governing atmospheric motion. The result is

$$R_i = \text{const}/[s^2(g\partial\theta/\theta\partial z)] \qquad (5)$$

where s is the slope of the internal front. To derive Eq. 5 we have used the fact that the wind shear is approximately given by the horizontal gradient of potential temperature. Thus the square of the wind shear becomes proportional to $s^2(g\partial\theta/\theta\partial z)^2$. The point is that, because of the relation between horizontal and vertical gradients of potential temperature, the numerator and denominator of Eq. 4 are not really independent quantities, and neither are the two factors in the denominator of Eq. 5. With this version of R_i, however, we are led to the surprising result that clear air turbulence is most likely to occur in regions of hydrostatic stability, provided the slope of the front is large enough. As discussed below, these hydrostatically stable layers may be dynamically unstable.

Thus the application of Eq. 5 to weather charts should make it relatively easy to find regions in which turbulence is likely to occur. The trouble is that these layers are quite thin and cannot be located through use of the ordinary weather data available every day. But the association of clear air turbulence with internal fronts explains the correlations that have been found with ordinary meteorological variables, and the thinness of the layers explains why the correlations are not perfect.

In addition, there is evidence that the turbulence in the internal fronts varies considerably in intensity and may thus be considered to be patchy in structure.

We have, therefore, tentatively identified the kind of environment that is hospitable to clear air turbulence. Before discussing the agreement of this identification with theory and other empirical data, we now turn to consideration of the effects of the turbulence on its environment.

As an internal front is formed by external forces compressing the layer, both the isotachs and the isentropes will move closer together. Finally, the Richardson number is small enough so that turbulence begins in the layer. Thus turbulence causes mixing, and the air in the center will be thoroughly stirred, so that there is very little wind shear left in the middle. Thus, all the change in the wind across the thin layer must now be concentrated at the edges, as illustrated in Fig. 2.

But this strong shear at the edges would provide very rapid feeding of energy to the turbulence near the boundaries of the front, and so the most intense turbulence would occur at the edges of the original front, with only light turbulence left in the center. This process would thus explain the observations shown in Fig. 1, and other case studies (*7*) illustrate the same tendency.

The important thing to notice is that these studies provide an empirical model for the life cycle of clear air turbulence which involves internal fronts that are not generally detected in regular weather data processing. If the fronts are not found in these data after they have formed, it is not surprising that their occurrence has not been forecast by regular procedures, and that the apparently sudden appearance of clear air turbulence has seemed to defy the prognostic capabilities of both man and computer.

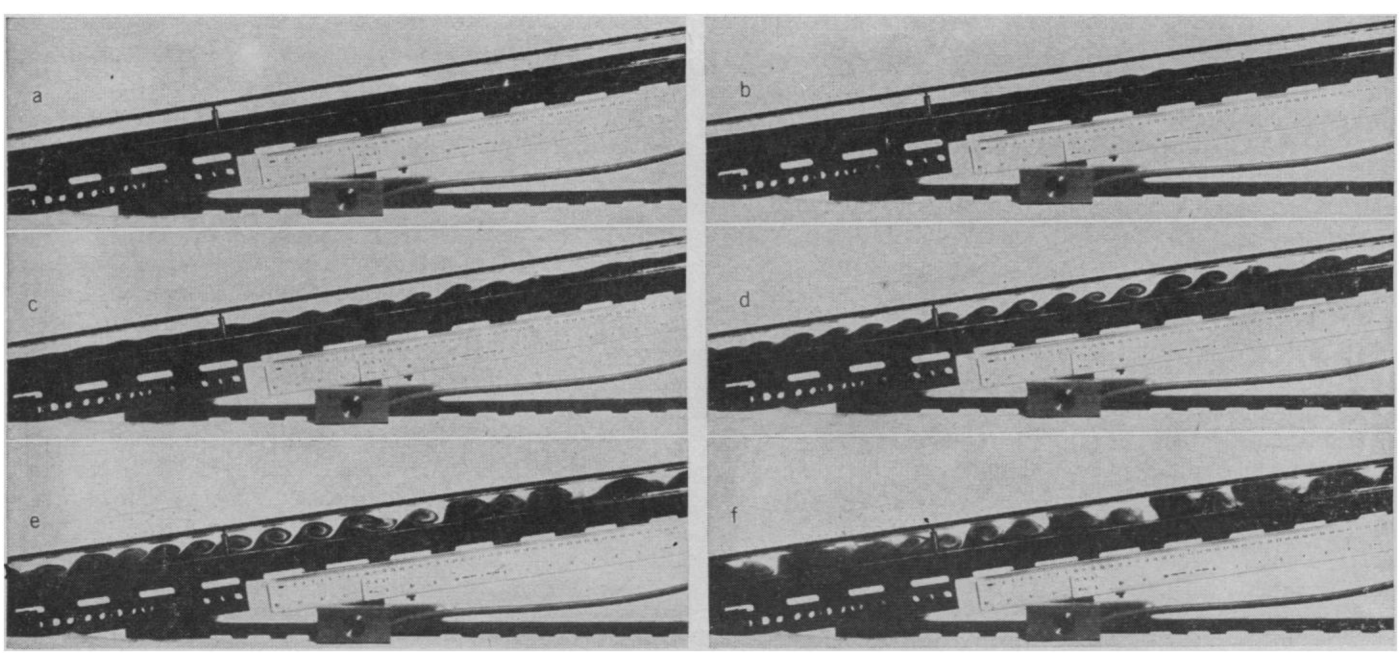

Fig. 3. Development of the Kelvin-Helmholtz instability as revealed by the laboratory experiments of Thorpe (*12*). Time interval between (a) and (b) is 7 seconds; remaining photographs in the sequence were taken at approximately 5-second intervals.

Mechanisms of Development

It appears today that the secret of clear air turbulence may have been discovered—in what seems to be a sudden convergence of almost classical theory and new empirical data from the laboratory, the ocean, and the atmosphere.

The hypothesis that such turbulence occurs in internal fronts with strong shear and stability is difficult to test in the atmosphere because the motions of the air are not visible and the turbulence remains unseen. If the same phenomenon were modeled with liquids rather than air, we might expect that the processes could be made more easily visible.

The question naturally is whether the turbulence can be correctly reproduced in a liquid environment. It is useful to consider one of the basic models of a situation in which small perturbations of a laminar flow lead to instability and rapid growth of the perturbations in the fluid motions.

Suppose that we have two fluids of different density and that we arrange them in a stable stratification with the lighter one on top. Then we set the fluids in motion, with one of the two moving more rapidly than the other, or in the direction opposite to the other. If the density change across the interface is strong enough and the shear is not too great, smaller perturbations will be damped out and the interface will come back to rest. But when the shear is strong relative to the density gradient, the situation is unstable and the perturbations will grow rapidly with time; vortices are created, as though a tumbleweed were being rolled between two streams of air.

This rapid growth of perturbations on an internal front in a fluid, called the Kelvin-Helmholtz instability, has recently been under intensive study. Miles (*8*) and Howard (*9*) have confirmed by recent theoretical analysis Taylor's result (*10*) that the critical Richardson number, R_i, for instability is ¼. More precisely, $R_i > 1/4$ is sufficient for stability, and $R_i \leq 1/4$ is necessary, but not sufficient, for instability. It has also been shown that these results, which apply to an incompressible fluid, are valid for the compressible motions of the atmosphere (*11*). These linear theoretical studies predict the conditions under which instability may occur but do not provide a detailed forecast of precisely what will occur. It can be expected that, as the unstable wave grows, nonlinear processes will become important, the wave will break, and turbulence will result.

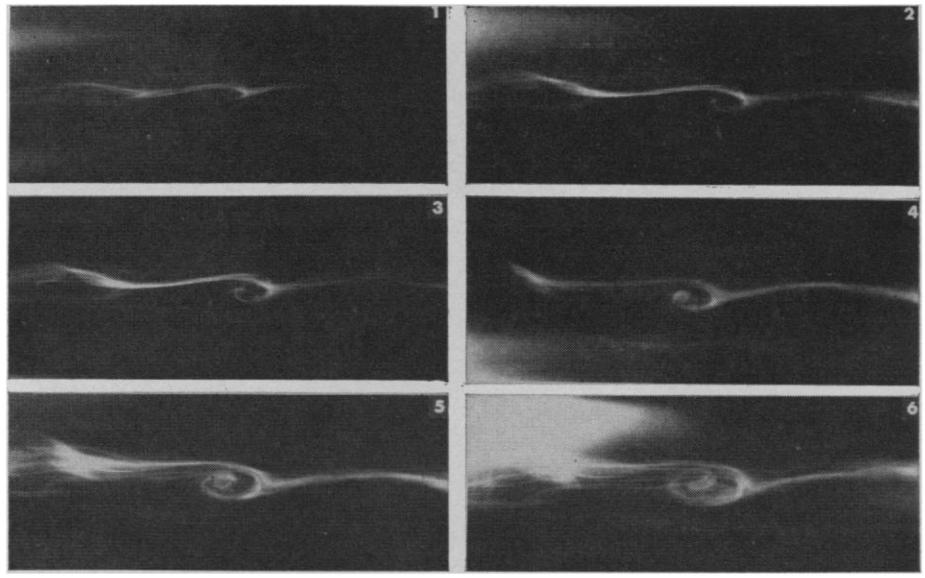

Fig. 4. Stages in the growth of a large undersea breaker with wavelength of 250 centimeters, as shown by Woods (*13*). [Photographs reproduced by permission of the Director-General, Meteorological Office, England. Copyright, Controller of Her Majesty's Stationery Office]

The mechanisms of the entire process have been demonstrated recently by some revealing experiments conducted by Thorpe (*12*). He places a lighter fluid on top of a heavier one in a long tube. When one end of the tube is raised, the heavy liquid flows downhill, the light liquid flows uphill, and shear across the interface is created. Under the right conditions, waves form on the interface, grow rapidly, curl over like a breaker on a beach, and finally disintegrate into turbulent motion. The process is illustrated in Fig. 3, which shows the sequence of events in Thorpe's experiments.

This same pattern of turbulence is found at sea too and has been studied under water by Woods (*13*) in the summer Mediterranean. The general decrease in the temperature of the seawater with depth is punctuated by more rapid changes which occur across

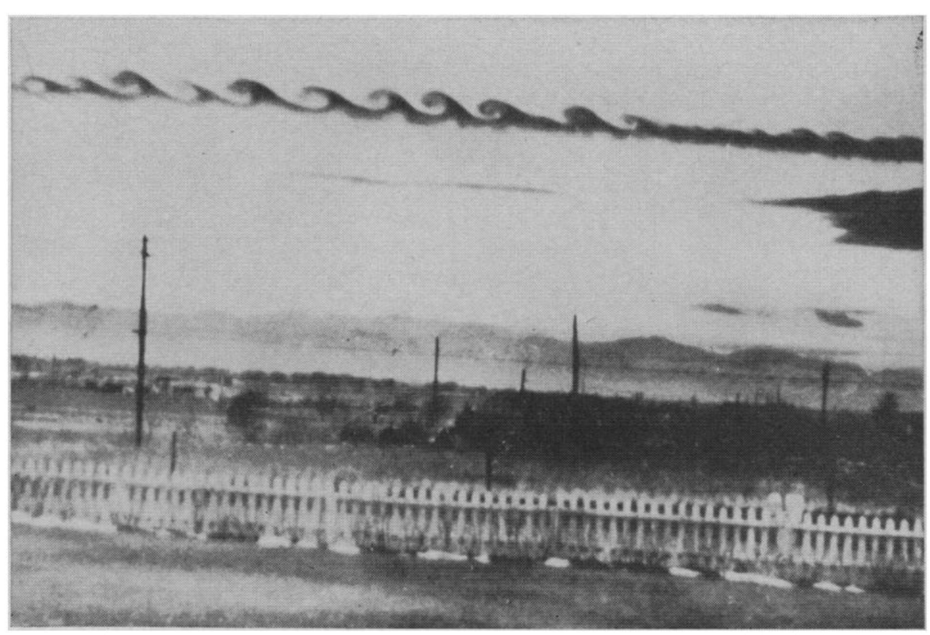

Fig. 5. Photograph of a wave-cloud formation which shows the typical vortices that develop in the Kelvin-Helmholtz instability. [Photograph taken near Denver, Colorado, by Paul E. Branstein on 14 February 1953 and published in *Weatherwise*, April 1953, in an article by DeVer Colson; reproduced with permission]

sheets (similar to the internal fronts in the atmosphere) which are hydrostatically very stable and are characterized by strong shears. Some of the features of these sheets are revealed by staining them with dye.

Originally, these sheets may be thin regions of laminar flow, and the larger regions in between manifest weakly turbulent motions. But, again under the right conditions, waves may form on the internal fronts, increase in amplitude, break, and leave behind a patch of turbulence which feeds on the shear created by the large waves. Woods and his co-workers have observed that the velocity patterns in the waves contribute to regions of especially large shear at the wave crest and trough and that the internal front may thus become unstable in discrete patches. This type of behavior was analyzed theoretically by Phillips (*14*). A sequence of photographs showing the growth and disintegration of a particularly large breaker studied by Woods is shown in Fig. 4.

Whether this turbulence is of the same kind as the atmospheric turbulence is the all-important question. Figure 5 is a remarkable photograph in which a cloud band, illuminated by a fortuitous combination of circumstances, shows the typical patterns of the Kelvin-Helmholtz instability in the atmosphere. The evidence of this photograph is confirmed by evidence from the special radars at Wallops Island, Virginia. Figure 6 is a photograph of a range-height radar picture of a braided structure some 15 miles long at altitude of about 10 kilometers. An analysis by Hicks and Angell (*15*) shows that the patterns of radar reflectivity which would develop in a breaking wave of the type shown in Fig. 5 would give the braided structure shown in the radar picture.

It is of considerable interest to compare the radar picture with the analysis by Hardy (*16*) of the associated meteorological situation shown in Fig. 7. The graph shows quite clearly that the braided pattern is occurring along an internal front where the combination of variables leads to a small value of the Richardson number (note the pronounced shear and the rapid increase in temperature, which implies strong stability).

The combination of evidence from the laboratory, from the ocean, and from photographic and radar analysis of atmospheric motion suggests strongly that the same mechanisms are present in the formation of the Kelvin-Helmholtz instability and the resulting turbulence in all three cases.

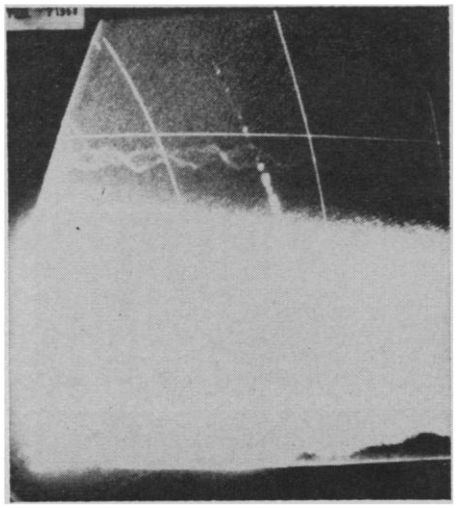

Fig. 6. Photograph of a (range-height) radar image of a braided structure observed 7 February 1968 at Wallops Island, Virginia, by Hardy, Glover, and Ottersten (*16*). The range marks are at intervals of 5 nautical miles, the height marker is 12.2 kilometers (40,000 feet). The extensive white region below 10 kilometers is due to cloud and precipitation; the braided structure occurs at about 11.3 kilometers. For the meteorological situation, see Fig. 7. [Photograph courtesy of the U.S. Air Force Cambridge Research Laboratory]

The next question is whether atmospheric data reveal that the critical Richardson number is indeed ¼. There is overwhelming evidence that, as shown in Fig. 1, the clear air turbulence is associated with Richardson numbers of less than unity, but actually there is a serious problem involved in computing this parameter from atmospheric data. First, it is almost always determined from standard balloon ascent data, which, because of poor resolution, do not give accurate values, and the measured Richardson numbers are consequently too large (*17*). Second, the theoretical value for the critical number is derived on the basis of the assumption that the instability arises from the growth of small perturbations. Actually, atmospheric turbulence may be initiated by large perturbations (for example, in the lee of mountains), and, as pointed out by Phillips (*18*), the theoretical value would then exceed ¼. This probably accounts in part for the increased frequency and severity of turbulence in mountainous regions.

In summary, because of the inadequacies of the available data, we cannot verify the conclusion that turbulence arising from small perturbations always results from instabilities occurring at gradient Richardson numbers of less than ¼. Furthermore, as shown above, the turbulence will modify the region of instability quite rapidly once it sets in, and the Richardson number at the onset of the process cannot be computed from data obtained subsequently.

Although small Richardson numbers are known to be associated statistically with the occurrence of clear air turbulence, the correlation between the intensity of turbulence and the Richardson number is not good. There exist, for example, some very well-mixed layers in which the Richardson numbers are essentially zero; turbulence exists in such layers but is quite weak.

Apparently the actual intensity of turbulence depends on the wind contrast across the turbulent layers, whereas the critical gradient number R_c acts as threshold to the occurrence of turbulence. The wind contrast will be large across internal fronts at the initial stages of turbulence formation but small across well-mixed layers.

The combination of evidence from theory and diverse empirical sources gives considerable confidence that the Kelvin-Helmholtz instability is the correct theoretical model for the origin of clear air turbulence, and thus that an apparently complex phenomenon has been explained in quite simple terms.

The task now is to determine whether all clear air turbulence is a consequence of the processes of this particular model; if there are cases to which the model is not applicable, an explanation for them must be found, one that will make clear the difference between the mechanism in question and the Kelvin-Helmholtz model.

Relation between Wavelength and the Energy of Turbulence

Because of the randomness of turbulent motion, atmospheric scientists rarely study the properties of clear air turbulence in direct form but generally seek statistical quantities which reveal the average structure. In the most useful procedure at present, it is supposed that the motion is composed of the sum of many sinusoidal functions, each having a different amplitude. The turbulence which affects airplanes has sinusoidal components ranging in length from a few kilometers to the wavelengths, only fractions of a centimeter long, at which the frictional dissipation is occurring. Airplanes, of course, are affected only by wavelengths greater than about the width of the wing.

It was predicted theoretically in the 1940's (*19*) that there should exist a range of wavelengths, in an idealized form of turbulence, in which the amplitudes A are related to the wavelength L according to the relation

$$A = \text{const}\,(\epsilon L)^{1/3} \qquad (6)$$

Despite the fact that atmospheric turbulence does not strictly satisfy the assumptions used in the theory, when the turbulence is sufficiently intense it is almost always found that the ⅓ power law is obeyed over a range of wavelengths from a kilometer or so to a few meters.

The behavior of the amplitudes and thus the distribution of the energy of turbulence at wavelengths greater than a few kilometers is an important area of present research. It appears that the amplitudes decrease with increasing L from values of L of a few kilometers to about 20 kilometers and then begin to increase again as the energy of large-scale motion is encountered.

An important consequence of the relation (*6*) is that observations of the distribution of turbulence energy with respect to wavelength make it possible to estimate the dissipation ϵ. With this technique it has been found that 20 to 30 percent of the total dissipation of atmospheric energy is due to clear air turbulence (*20*).

Problems and Solutions

There are two problems associated with clear air turbulence. First, such turbulence is a hindrance and a hazard to aviation; second, it appears to have important effects on atmospheric dynamics.

There must be a combination solution to the turbulence problem for aviation. Methods must be developed for avoiding as much of it as possible, but aircraft must be designed to cope with it when avoidance techniques fail. Accurate forecasts of the regions in which turbulence is likely to occur are an obvious answer, but, as noted above, the data that are regularly available are not sufficiently accurate to reveal the internal fronts where most turbulence occurs, or to permit accurate estimation of the telltale Richardson numbers. There is, however, some hope that data processing methods can be designed to utilize the hypothesis of the occurrence of turbulence presented here in order to produce better forecasts.

Considerable interest has centered on the possibility of remote detection of clear air turbulence by electronic or optical devices, possibly airborne. The hopes are modeled, apparently, on the aid radar has given aviation with respect to convective phenomena. The detection problem should be approached in a scientific manner, with empirical and theoretical determination of the electronic or optical signatures that can be expected from clear air turbulence. When these are known, it will then remain to be ascertained whether it is indeed possible to detect these signatures from high-speed aircraft in sufficient time for avoidance maneuvers to be successful. A review of direct sensing techniques from airplanes by Atlas (*21*) has shown that none of the techniques suggested so far—radar, pulsed lasers, or infrared temperature detection devices—appears at all promising at present. In contrast, some success has been demonstrated [see, for example, (*16*)] at finding clear air turbulence with ground-based electronic equipment.

The second problem stems from the mounting evidence that the dissipation of kinetic energy by clear air turbulence and the mixing, by turbulence, of air with different properties affects the dynamics of the atmosphere. These effects must be accounted for in numerical weather prediction schemes which attempt to make forecasts for periods longer than a few days in advance. Considerably more needs to be known about the physical structure of the regions of turbulence and their dependence upon the large-scale variables, to permit incorporation of the effects of turbulence in such a computer model of the atmosphere.

In order, then, to reduce the hazards to aviation by better forecasts of clear air turbulence or by development of remote detection devices, and to improve weather prediction, much more needs to be known about such turbulence. Major observational programs are now under consideration, and, if they are conducted carefully and with physical insight, they may provide the

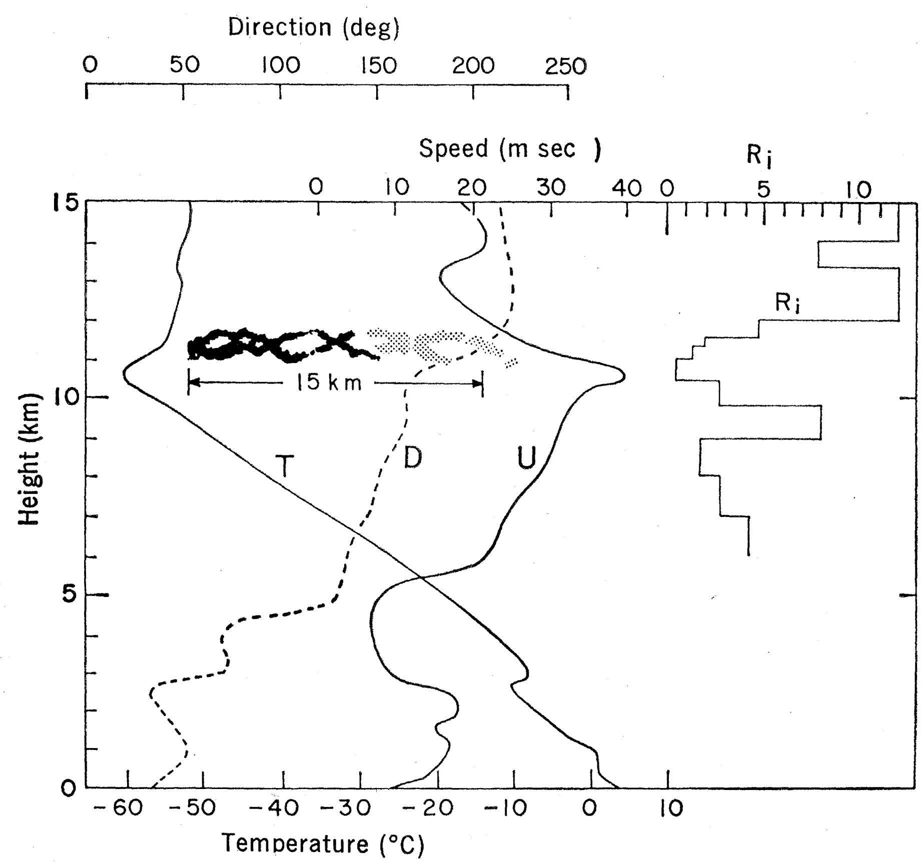

Fig. 7. Meteorological situation associated with the radar image of the braided structure shown in Fig. 6. The curve marked T is the temperature; U, the wind speed; D, the wind direction R_i, the Richardson number. Note that the braided structure occurs in a region of strong stability and strong shear, with a low value of the Richardson number. [Analysis made available by K. R. Hardy of the U.S. Air Force Cambridge Research Laboratories]

scientific knowledge needed for solving these problems. However, even at present, improved communications between pilots and meteorologists on the ground can improve the situation.

Conclusion

It has been shown that clear air turbulence is an important problem for both aviation and atmospheric science, and that the difficulties it raises can be attacked only when we have a thorough knowledge of the details of its formation and evolution.

The available empirical knowledge appears to be in agreement with the hypothesis that at least some of the clear air turbulence results from the hydrodynamic instability of internal fronts in accord with the Kelvin-Helmholtz model; the investigation of this hypothesis seems to provide an important new vista for research into the processes of the turbulence.

An important consequence of the establishment of a physical model of clear air turbulence would be the ability to determine what resolution and spacing of observations are necessary for accurate prediction of the likelihood of turbulence.

However, our main point is that clear air turbulence is neither capricious nor mysterious; it obeys the laws of physics, and careful measurements and intelligent data processing should reveal its secrets.

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Molecular Approach to Breadmaking

Biochemistry of components that control breadmaking is described.

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The functional (breadmaking) properties of wheat flour depend on several factors including wheat variety, environmental and soil conditions under which the wheat was grown, the process used to mill the wheat into flour, and the chemical composition of the flour. Wheat varies widely in chemical composition. Percentages of proteins, lipids, minerals, vitamins, pigments, and enzymes show up to a fivefold range among cargoes of wheat. Such differences in composition have far-reaching effects on processing and on the best way of use. The problem of relating the chemical composition and structure of wheat components to functional properties has kept more cereal chemists at work than any other single problem in the field.

Over 200 years ago (in 1745) Becari reported separating gluten from wheat flour, the first plant protein to be isolated. Approximately 150 years ago, it was found that about half of the gluten proteins is soluble in 70 percent ethanol. A century ago, Ritthausen laid the foundations of seed protein chemistry so ably expanded by Osborne half a century or so later (*1*). However, biochemical methods only recently have been applied to studying breadmaking quality of wheat. This article summarizes some studies on the relation between chemical composition and breadmaking potentialities of wheat flour.

Performance Test

Relating chemical composition and structure of wheat flour components to functional properties in breadmaking requires: (i) knowledge or analytical data of the components present; (ii) methods to extract, fractionate, and characterize flour components; (iii) techniques to reconstitute the isolated moieties; and (iv) tools to ascertain that neither the fractionation nor the reconstitution procedures impair functional properties of the components.

Historically, the last requirement was met first. Investigations of Finney and Barmore (*2*) led to an optimized baking test. In that test, five factors—mixing time, oxidation level, yeast activity, fer-

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