Thirty years of fluid dynamics

Physicists have made great progress both on fundamental problems, such as turbulence and statistical mechanics, and on many applications, including aerodynamics and the study of geophysical flows.

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Interest in fluid dynamics as a separate field of physics with its own set of problems came about largely as a result of experiences during World War II. Until that time, the various events occurring in fluids were usually thought of as problems in mathematics or engineering. During the war years, however, the relations among phenomena such as turbulence, explosions, shock waves and supersonic aerodynamics were recognized, and physicists began to consider them again from the point of view of their own science. In 1947, the Division of Fluid Dynamics was established within The American Physical Society.

In this brief review of the past thirty years or so of fluid dynamics, we shall look at two of the more fundamental subfields—turbulence and statistical mechanics—and at two of the applications—aerodynamics and geophysical flows. The two applied areas are also based, as we shall see, on an understanding of other fundamental disciplines, such as chemical thermodynamics, non-Newtonian flows in polymer solutions and magnetofluid dynamics.

Turbulence

By the late 1940's scientists already knew that turbulence in fluids is generated in boundary layers and through the motions induced by moving walls, fan blades, stirrers and jets. Statistical descriptions based on wind-tunnel measurements had grown out of the work in the late 1930's of Geoffrey Taylor, Theodore von Karman, Hugh Dryden, Joseph Kampé de Fériet, Johannes Burgers and Andrey Kolmogorov, working in European centers and, in the US, at the National Bureau of Standards and Caltech. In the following years, they built on this knowledge.

The intermittent character of "breakdown" in laminar boundary layers as water starts to flow over the edge of a plate was noted by Howard Emmons in a Harvard student laboratory and termed "spots." Galen Schubauer and Philip Klebanoff, working at NBS, produced these spots in air by setting off an electric spark, and watched the growth of their shapes. These spots are intriguing because they appear in the midst of regular laminar flow and grow by converting laminar flow to very irregular flow; irregular motions of fluid chunks smaller than 0.1 mm are "seen" by a hot-wire anemometer, which is sensitive to rapid velocity fluctuations. Oscillograms show a "spot" passing over the recording hot-wire anemometer, and smooth laminar flow is revealed right next to violent fluctuations; the flow returns to laminar again after the spot passes. Similar behavior occurs if pipe flow is made unstably laminar (by methods developed by Osborne Reynolds in the last century) and then injected with a tiny momentary jet of fluid from the wall. The perturbation grows into a spot traveling down the pipe.

The boundary between the wildly turbulent fluid in the spot and the smooth laminar fluid in which it is imbedded has been photographed by spark illumination as well as detected by hot wires. The mechanism by which laminar fluid is consumed as the boundary moves into it can, however, only be speculated on. The recent work of Donald Coles and Israel Wygnanski is evidence of renewed interest in the behavior of turbulent spots.

An alternative approach to the turbulence problem was developed by Kolmogorov and Alexander Obukhov, working in Moscow. Following the thinking of Taylor, they concentrated on the random kinetic energy of the fluid rather than on the molecular energy, proposing in 1941 that a certain amount of energy is introduced at a steady rate at large scales (the scale of a pipe, spoon or hole, for example). This energy cascades from large to intermediate to small scales, eventually disappearing at small scales (about one micron or so) where viscosity converts it to the internal energy of the fluid. At large and intermediate scales, where the inertial forces exceed the viscous forces (that is, at large Reynolds number), there is a statistical equilibrium of the turbulent-energy distribution among eddy sizes. These ideas were introduced to the fluid-dynamics community and further developed by George Batchelor (Cambridge) after World War II.

Considerable interest continues to this day in mathematical formulations of these ideas. Most formulations assume an isotropic turbulence and consider the variation of the amount of energy at a given eddy size with eddy size. This variation is termed the "spectral distribution" or the related shape of the "correlation function." However, it has become obvious that there is seldom a reasonable approximation to isotropic turbulence in actual flows. The best approximation occurs behind a grid in a steady wind-tunnel flow. A great deal of effort has been spent over the years in measuring turbulence behind grids, to

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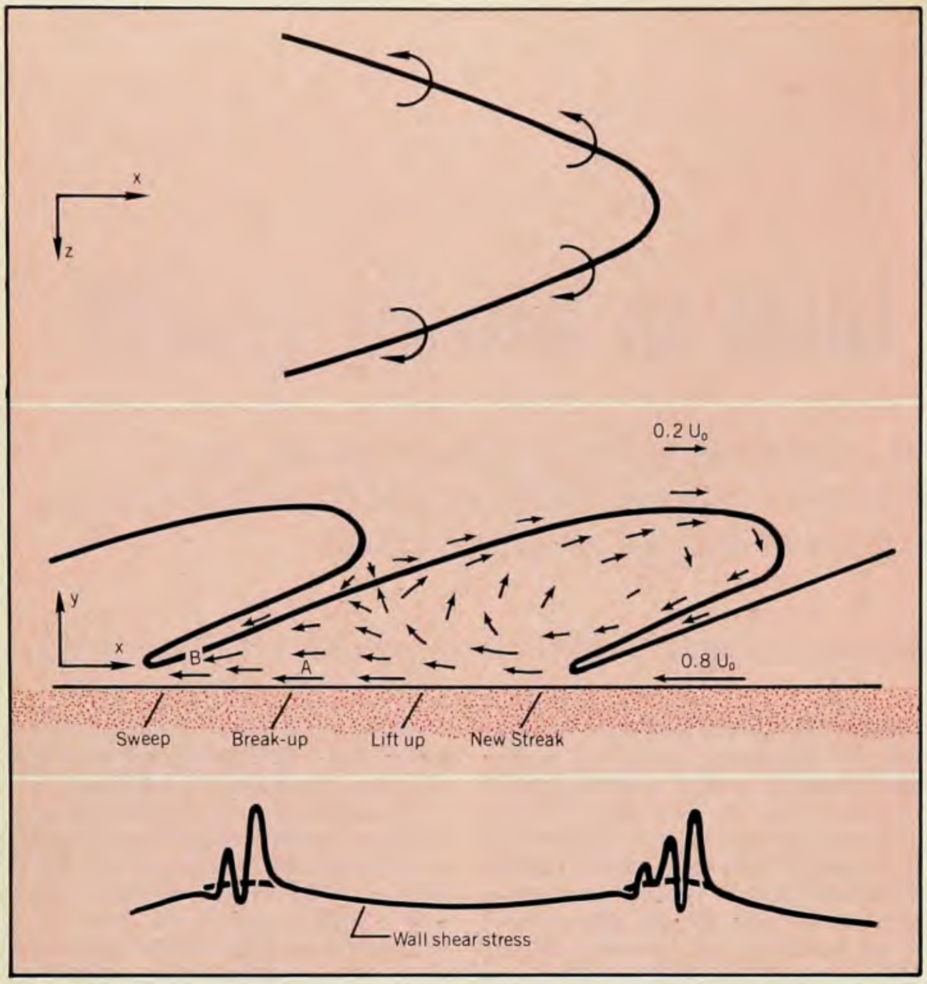
decide which theory predicts the proper distribution. As of now, it cannot be said that any turbulence theory has a greater likelihood of representing real phenomena than any other.

These parallel lines of investigation—detailed study of laminar flow breakdown and collection of spectral information behind grids in wind tunnels—were considered to be quite independent, the latter more general and therefore more basic. However A. A. Townsend in the UK pointed out early during these 30 years that study of steady turbulent wakes behind immersed bodies revealed a sharp fluctuating boundary between turbulent and laminar flow. Similar intermittent behavior was observed by Klebanoff and by Stanley Corrsin and Alan Kistler at Johns Hopkins, in the boundary layer growing beyond the leading edge of a plate. Extensive studies of turbulence in a boundary layer with hot-wire anemometers gave details of its very nonisotropic structure. Since the observations were of random phenomena, they were summarized as averages over long times and no regularity or large-scale structure were observed in these earlier measurements. In the meantime applications, concerned less with the details of the turbulent structures, made use of these time-averaged measurements and led to effective mathematical modeling of turbulent boundary layers.

Visualization techniques and high-speed computing techniques for both experimental measurements and theoretical computations have had a considerable influence in modifying the direction of turbulence research. About 1967 Steven Kline and others at Stanford studied the turbulence phenomena by photographing tracers of hydrogen bubbles in water and observed recurrent coherent patterns of events. They saw (figure 1) a streaky structure in the sublayer near the wall, followed by a gradual liftup and an ejection from near the wall of the fluid which moved in "bursts" away from the wall. This fruitful observation was followed up by John Laufer, Richard Kaplan, William Willmarth, Robert Brodkey and others who studied the average properties of these bursts by conditional sampling. Here the burst is detected by a hot wire or pressure gauge on the wall, and the velocity of the fluid at related times and distances is measured by hot wires.

As a result of work on these coherent structures in the boundary layer by Leslie Kovasznay, Ron Blackwelder, Garry Brown, Robert Falco, Helmut Eckelmann, Brodkey and many others, it is generally agreed that large-scale organized structures recur continually in all

Turbulent boundary layer in water. Electrolysis (see wire at top of photo) produces tiny hydrogen bubbles, which act as tracers for turbulence phenomena. Note that the interrupted ribbons of bubbles quickly lose their orderly pattern as the fluid streaks "burst." Photo seen here is from the work of Steven Kline and his colleagues at Stanford University. Figure 1



Model of a "horseshoe vortex," one of the large-scale organized structures believed to recur continually in turbulent boundary layers. Here is the proposed flow pattern as seen by an observer who is moving at 0.8 U_0 (where U_0 is the speed outside the boundary layer) and looking at the wall (top), and along the wall (center). Distribution of wall shear stress is below. Figure 2

turbulent boundary layers. The sketch in figure 2 is a model for such an organized structure, called a "horseshoe vortex." In this connection one remembers that in 1952 Theodore Theodorsen postulated the existence of horseshoe vortices extending to the edge of the boundary layer, and the generation of similar structures in the transition from laminar to turbulent boundary layers was observed by Klebanoff in 1962.

It is fascinating to imagine this recurrent bursting pattern and large-scale organized motion going on right under our noses in pipes, rivers, blood arteries and cooling breezes. How the detritus of these bursts arranges itself and mixes with the fluid outside the boundary layer remains a subject for continuing study. The hope is that Kolmogorov's idea of smaller-scale turbulence having a character rather unrelated to the large-scale structures may be valid. In this case the theories of isotropic turbulence may be applicable to the instantaneous distribution of energies at smaller scales during the rearrangement. The ubiquitous nature of boundary layers in generating turbulence gives hope that we are on the verge of understanding the mechanism of turbulence. There remains, however, that class of turbulence-generating flows not closely related to boundary layers: turbulence generated by flow separation behind obstacles and by mixing of streams (figure 3). Anatol Roshko, Brown, C. D. Winant and Fred Browand have observed large-scale structures in these flows.

In addition to the question of how turbulent fluid can coexist in the midst of laminar fluid, and of the mechanisms of conversion in the boundary of a growing "spot," serious doubts exist as to the one-way nature of turbulent energy cascade in the Kolmogorov picture of turbulence. In some cases, small-scale energy probably consolidates to produce a big eddy. There is also very little understanding of how a turbulent fluid left to itself comes to rest—if it ever does. Perhaps fluid at rest, and its concomitant by a Galilean transformation—uniform flow—is a nonexistent idealization.

Numerical simulation of fluid flow with computers has been developed during these 30 years. Marked progress is seen in the mathematical methodology, and in the capacity and speed of the computers on which the flow is simulated. The better understanding of turbulence phenomena, gained chiefly through visualization methods and computer-assisted analysis of data, can now be used to include details in the simulations of turbulent flows.

Despite the unexplained aspects of turbulence we still face today, we are certainly better informed than we were 30 years ago. The existence of new and more sensitive instruments—hot-wire and hot-film anemometers, and optical-tracer anemometers—and powerful data-handling techniques associated with digital computers give promise of continuing progress.

Statistical mechanics

One of the important scientific accomplishments of the late 19th and early 20th centuries was the discovery that the macroscopic properties of large systems of atoms or molecules can be determined by considering the average behavior of a large number of similarly prepared systems. This is, of course, the central idea of statistical mechanics. The founders of the field expected that the methods of statistical mechanics would lead to a derivation of the laws of thermodynamics together with expressions for the thermodynamic quantities in terms of the intermolecular forces, in the case that the system is macroscopically in a state of thermodynamic equilibrium. If the system was a fluid not in equilibrium, it was expected that statistical mechanics could provide a derivation of the equations of fluid dynamics, such as the Navier–Stokes equations, together with expressions for the transport coefficients in terms of the intermolecular forces. The success of statistical mechanics in predicting equilibrium properties is well known. We turn our attention here to recent progress on the derivation of the equations of fluid dynamics, and we consider a classical fluid composed of particles interacting with short-range forces.

James Clerk Maxwell, Ludwig Boltzmann and others made substantial progress in describing nonequilibrium phenomena in dilute gases. Of particular importance for the later developments was Boltzmann's transport equation for the single-particle distribution function F, defined such that $F\mathbf{drdv}$ is the number of particles in a region $\mathbf{drdv}$ about a point $(\mathbf{r},\mathbf{v})$ where $\mathbf{r}$ is the position and $\mathbf{v}$ the velocity of a particle. This distribution function is important because for a dilute gas, at least, the fluid dynamic variables—the local mass density, local velocity and local temperature—can be expressed as moments of F. Boltzmann's equation describes the time rate of change of F for the case where the gas is so dilute that only binary collisions need to be taken into account. The equation is

$$\frac{\partial F}{\partial t} = -\mathbf{v} \cdot \nabla_r F + J(F,F)$$

where $-\mathbf{v}\cdot\nabla_r F$ describes the change in F

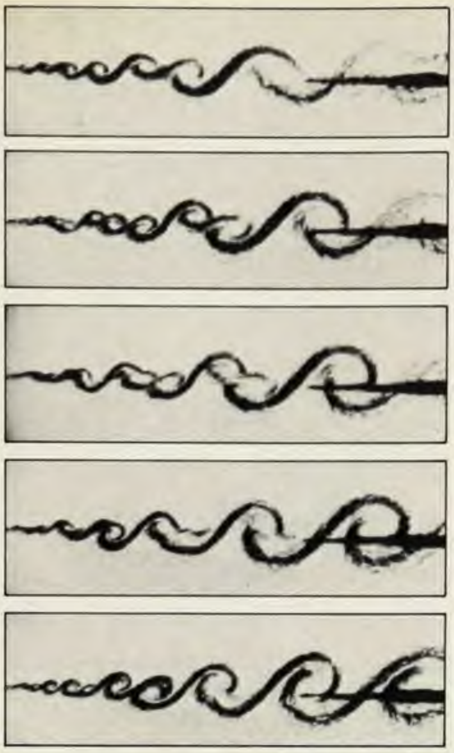
due to free motion of the particles, and $J(F,F)$ describes the change due to binary collisions.

Early in this century Sydney Chapman and David Enskog, independently, derived the equations of fluid dynamics from the Boltzmann equation by considering the case where the fluid variables change slowly over distances on the order of a mean free path l and expanding the distribution function in powers $\mu = l/L$ where L is the distance over which the fluid variables change. The zero order in the expansion of F leads to the Euler equations, the first order gives the Navier–Stokes equations, the second and higher orders give the Burnett and super-Burnett equations, and so on. This derivation of the fluid-dynamic equations also gives expressions for the transport coefficients—viscosity, diffusion, and thermal conductivity—in terms of the intermolecular forces, that are in superb agreement with experiment for dilute gases.

Nevertheless, the Boltzmann equation has two shortcomings that prevented it from being the basis of a general statistical-mechanical theory for the derivation of the equations of fluid dynamics. It is restricted to dilute gases, and the generalization of denser fluids is not obvious. The other, related difficulty is that Boltzmann's derivation was not based on statistical mechanics but was intuitive. It became clear that to extend the Boltzmann equation to higher densities one would have to reexamine the derivation of the Boltzmann equation itself.

This was the situation 30 years ago. It was necessary to derive from the basic equation of statistical mechanics, the Liouville equation, a generalized Boltzmann equation that would have, in addition to the two-body collision term $J(F,F)$, additional terms $K(F,F,F)$ + $L(F,F,F,F)$ + . . . to take 3-, 4-, . . . n-body collisions into account. The generalized Boltzmann equation would be expected to give corrections to the transport coefficient for gases in the form of an expansion in powers of the density. This was accomplished in 1947 by N. N. Bogoliubov, but nearly 15 years elapsed before George Uhlenbeck, S. T. Choh, M. S. Green and E. G. D. Cohen had analyzed the assumptions and clarified the method sufficiently to determine what dynamical events contribute to K, L, . . .

When the physical justifications for Bogoliubov's generalized Boltzmann equation were clarified, work began on studying the detailed properties of the collision integrals K, L, . . . , and on evaluating the density-dependent corrections to the Boltzmann transport coefficients. Uhlenbeck and Choh, and later Green and Jan Sengers, studied the three-body collision integral $K(F,F,F)$ for a gas of hard spheres, and Sengers evaluated the three-body contribution to the hard-sphere transport coefficients with the aid



Mixing of streams. The shadowgraph seen here shows the turbulent mixing layer between two streams of the same density, both flowing from left to right in each frame. The upper stream is flowing at 10 meters per second and the lower at 3.5 m/sec. Pressure is 8 atmospheres and the height of each frame is 5 cm. The frames seen here are from a sequence obtained with nitrogen and helium–argon at Caltech by L. Bernal, G. L. Brown and Anatol Roshko. Figure 3

of an extensive computer calculation. Study of the four-body integral $L(F,F,F,F)$ provided workers in this field with something of a shock, for L and all the higher terms diverge, and consequently all but the first two terms in the power series expansion of the transport coefficients in density are also divergent. Furthermore, for a two-dimensional gas, K, L, and higher terms diverge, so here too, an expansion of the transport coefficients as a power series in the density does not exist.

Physically, the divergences arise from "memory preserving events." Two particles, say 1 and 2, collide and move apart, but a third particle, 3, collides with 2 and knocks it back to 1 again; similar combinations of collisions occur among four bodies and so on. The divergence occurs because the phase-space regions associated with these sequences of correlated binary collisions can become arbitrarily large as the time between the first and last collision in the sequence increases. The error in the Bogoliubov theory resides in the assumption that the generalized collision integral as well as the expressions for the transport coefficients that result from it can be expanded as a power series in the density. As in the equilibrium theory, the coefficients in these power series or virial expansions are determined by the properties of small groups of particles considered in isolation from the rest of the gas. Thus, collective effects, such as a mean-free-path collision damping, cannot be properly treated by the Bogoliubov theory.

In spite of the divergence difficulties, Bogoliubov's approach to the kinetic theory of dense gases represents a major step forward in the attempt to derive the equations of fluid dynamics from the Liouville equation. Once we renormalize the virial expansion by resumming the most divergent terms, the hurdle of generalizing the Boltzmann equation to higher densities has been overcome, and we know a great deal about the macroscopic processes that are responsible for those features of the transport of particles, momentum and energy that are described macroscopically by the equations of fluid dynamics.

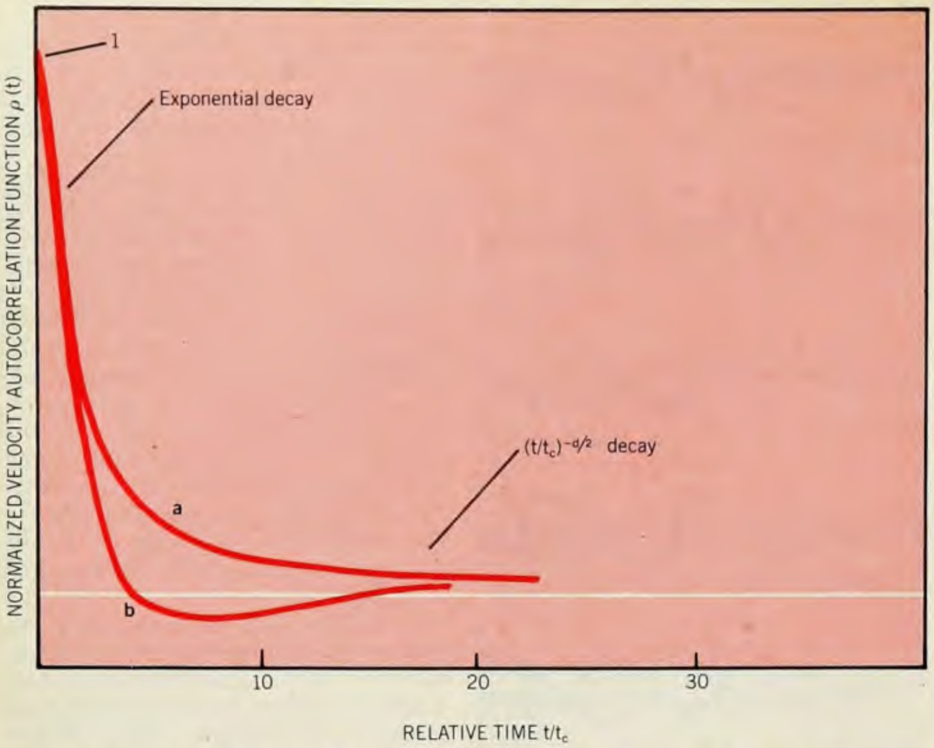
A second major development in understanding fluid dynamics from statistical mechanics is the time correlation function method developed by Green, Ryogo Kubo, Hazime Mori, Robert Zwanzig, Alan McLennan and others around 1955. This method has the advantage over the generalized Boltzmann equation that it applies to liquids as well as gases. In outline, the method consists of constructing "Chapman–Enskog like" solutions to the Liouville equation (not the Boltzmann equation) for the N-particle distribution function. The expansion is in powers of $\mu = l/L$, but now l is the mean free path or the molecular diameter, whichever is larger. As before, L is the scale on which the fluid-dynamic variables change. Until recently, the method has only been used to derive the linearized equations of fluid dynamics, where all but the first-order deviations of the fluid variables from their equilibrium values are neglected.

This method gives expressions for the transport coefficients appearing in the linearized Navier–Stokes equations that have the form of integrals over time of a quantity called the time correlation function. For example, the expression for the coefficient of shear viscosity, η, for a classical fluid is

$$\eta = \frac{1}{VkT}\int_0^\infty dt\,\langle J_\eta(0)J_\eta(t)\rangle$$

Here $\langle J_\eta(0)J_\eta(t)\rangle$ is the time correlation function of J_η, a microscopic current associated with the flow of momentum, $J_\eta(0)$ is its value at some initial time, and $J_\eta(t)$, its value after time t, and the angular brackets represent an equilibrium ensemble average. Time correlation functions are of special interest because they can be studied theoretically, experimentally (by light or neutron scattering) and by computer.

To determine the time correlation functions analytically, one must reduce N-body dynamics to few-body dynamics. When this is done for dilute or moderately



Computer results for a normalized velocity autocorrelation function $\rho(t)$, as a function of time for a system of hard spheres or hard disks. This rough sketch shows the main features at low densities (b) and high densities (a). In this sketch t_c is the mean free time between collisions and d is the number of dimensions of the system. Figure 4

dense gases, with methods similar to those used in deriving the generalized Boltzmann equation, the time correlation function method gives the same results as the generalized Boltzmann equation for the transport coefficients in the linearized fluid-dynamic equations.

Perhaps the most striking features of time correlation functions were first discovered by Berni Alder and Thomas Wainwright, who did a computer simulation of the diffusion of a tagged molecule in a system of mechanically similar molecules. If we define the normalized velocity autocorrelation function $\rho(t)$ by

$$\rho(t) = \frac{m}{kT} \langle v_x(0) v_x(t) \rangle$$

where m is the mass of the molecule, the variation of $\rho(t)$ with t/t_c as determined on the computer by Alder and Wainwright and by William Wood and Jerome Erpenbeck for a hard sphere or hard disk fluid, is seen in figure 4 for both high and low densities. Here t_c is the mean free time between collisions for a typical particle. For short times $t < 5\,t_c$ the correlation function decreases exponentially, which might be expected, but for intermediate times $5\,t_c < t < 20\,t_c$ at high densities the correlation is negative. This means that a molecule has a long memory and during this period its velocity is reversed on the average from what it was originally. The behavior of $\rho(t)$ for these times for low-density systems, although not negative, is clearly not an exponential decay either. The theory can satisfactorily account for the short-time exponential decay, but a careful theoretical explanation of the intermediate time behavior of $\rho(t)$ for high and low densities, expecially for the negative region, is yet to be given.

The computer results also show that $\rho(t)$ decreases slowly for long times because $\rho(t) \approx \alpha(t/t_c)^{-d/2}$ where d is the number of dimensions of the system. This slow decay (long time tail), which appears to be characteristic of many other time-correlation functions, can be accounted for theoretically, and is due to the memory-preserving events discussed earlier. There is a theoretical value for the coefficient α of $t^{-d/2}$, which is in excellent agreement with the computer results. The $t^{-d/2}$ decay of $\rho(t)$ implies that the diffusion coefficient D exists for three-dimensional systems, but not for two-dimensional systems. This feature appears to be general; that is, for two-dimensional systems one cannot show that the usual forms of the linearized hydrodynamical equations are correct.

The derivation of the linearized Navier–Stokes equations from the Liouville equation, then, by either the time-correlation function method for a general fluid or by the generalized Boltzmann equation for a gas, appears clear in outline for three-dimensional systems. Our understanding of fluid dynamics from a molecular point of view is much deeper than it was 30 years ago, but we still have much more work to do to calculate the values of the transport coefficients for realistic systems. Moreover, the structure of the fluid-dynamic equations beyond the Navier–Stokes order is not entirely clear.

There have been striking successes in approximate calculations. For example, the viscosity of argon can be calculated by a modified Enskog theory, even at densities beyond the critical density, to within a few percent. There has been success in the kinetic theory of boundary layers, and the subject of fluctuations in fluid dynamics variables—started by Lev Landau and E. M. Lifshitz and described in their 1959 book on fluid dynamics—is of considerable current interest.

Aerodynamics

Aerodynamics, an important area of applied fluid dynamics, also has its own separate fundamental problems. Perhaps three of these are generic, including all others within them: separation, boundary layers and shock waves. Aerodynamics, in one sense, is the combination of available fundamental knowledge of fluid flows with empirical methods for achieving practical ends such as the flight of vehicles and missiles, propulsion by blades and jets, prediction of blast-wave phenomena, conveyance of dust and fibers, and prediction of wind loads on structures. Heat transfer, flames and combustion are closely related practical subjects that often involve aerodynamic studies but, depending on chemistry as much as they do, usually are considered separately and equally within the province of chemical engineering.

Progress in aerodynamics in the past 30 years, so vividly illustrated by efficient large aircraft, supersonic flight, space vehicles launched by rockets, and V/STOL ("vertical or short take off and landing"), has been great. These developments were achieved without any great breakthrough in physical principles, but were accompanied by generation of powerful mathematical techniques, new instruments and better organization of ideas that were already known 30 years ago. The progress and status is perhaps best approached by a discussion of several problem areas of current interest.

Predicting and controlling where separation occurs in flow about bluff bodies is of continuing interest in the design of airfoils for helicopter rotors and engine compressor blades, as well as in flow about trucks (for air drag reduction) and tall buildings, for which such prediction forms the basis of criteria for attaching windows. For airfoils the problem of flow separation at large angles of attack is crucial to performance, stability and control. In turbulent flows we observe processes that are not understood in terms of physical principles, so that airfoil behavior cannot be systematically predicted. As an example, the steady lift and transient lift of a helicopter blade are seen in figure 5. The flow with changing angle of attack relative to the blade exhibits a hysteresis loop traversed at the rotor frequency, rarely giving the lift predicted from steady-state wind-tunnel data.

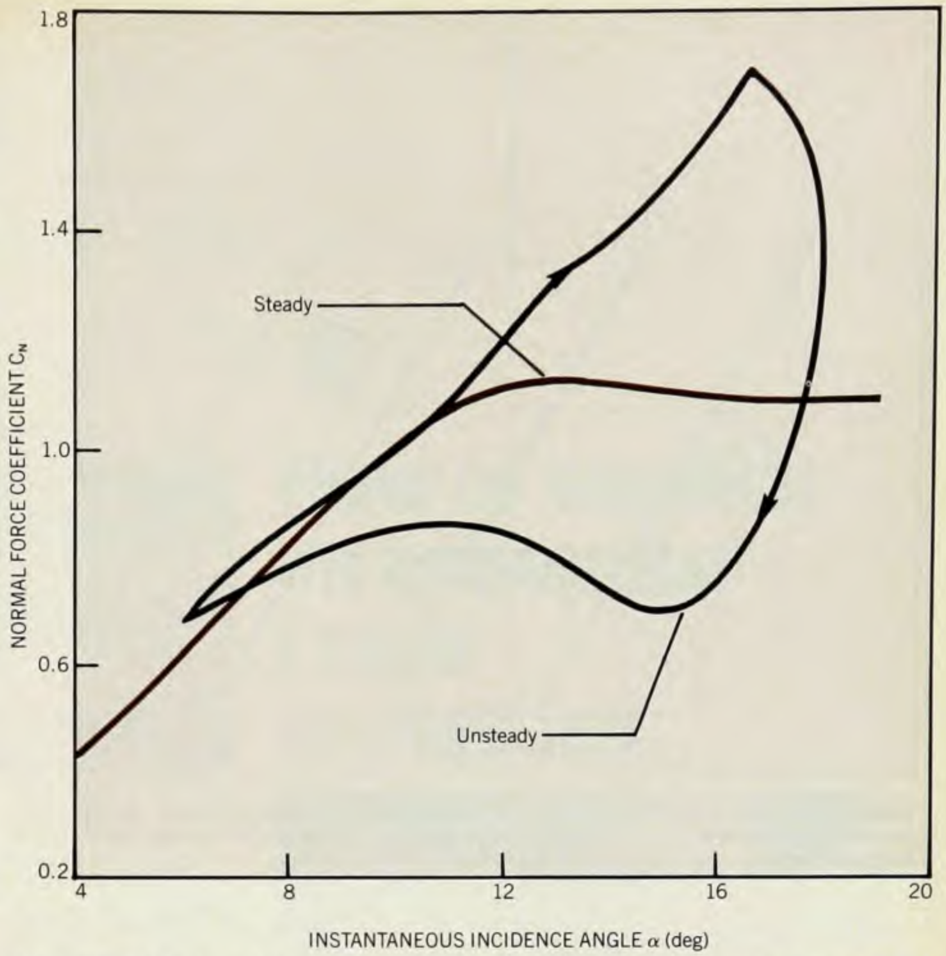
The separation of flow on one high-rise building in a wind produces unpredictable loads on another building downstream of the first, depending on the direction of the wind. Varying wind direction is analogous to changing the angle of attack of an airfoil in a moving stream.

To achieve maximum efficiency, a jet-engine compressor is operated near the boundary of flow separation conditions. An engine compressor is susceptible to variations in the incoming flow that may be spatial distortion if mounted in or near the fuselage, or temporal distortion from atmospheric gusts and aircraft maneuvers. Such distortions have the effect of varying the flow seen by the compressor blades and produce a hysteresis loop of the type shown in figure 5 for a helicopter blade. In a compressor row the blades interact strongly and produce a collective effect called rotating stall, which may blank out an appreciable fraction of the flow passages for many rotor revolutions.

Boundary layers are formed by friction on all surfaces adjacent to a moving fluid. An unanswered question involves transportation of particles within these layers. Although the aerodynamic transport of spherical and rodlike particles is understood in a stream flow, their behavior in boundary layers is not. Engineers would like to know how to design for transportation of pulverized coal in airstreams and to understand how a layer of combustible dust particles of roughly spherical shape is picked up. Furthermore, rodlike particles, such as cotton dust fibers and asbestos fibers, are believed to constitute health hazards when ingested into the lungs. The aerodynamic behavior of particulates when transported into the lungs and out again is poorly understood.

As aircraft speeds approached the speed of sound, shock waves were found to produce the large drag rise on airfoils once known as the sonic barrier. Shock waves produced by a supersonic aircraft also create the sonic boom of current interest. As the effects of shock waves on the flow about the wing were better understood, solutions in the form of the swept wing, transonic area rule and supercritical wing section have emerged as design concepts to sidestep the effects of shock waves. For supersonic and hypersonic flight the appearance of a mathematically elliptic flow region embedded in an otherwise hyperbolic region originally caused great difficulty in analysis. This difficulty has been surmounted by the combination of computers and clever analytical techniques such as the Chester–Chisnell–Whitham method and asymptotic matching.

Shock waves play a large role in understanding combustion and detonations,



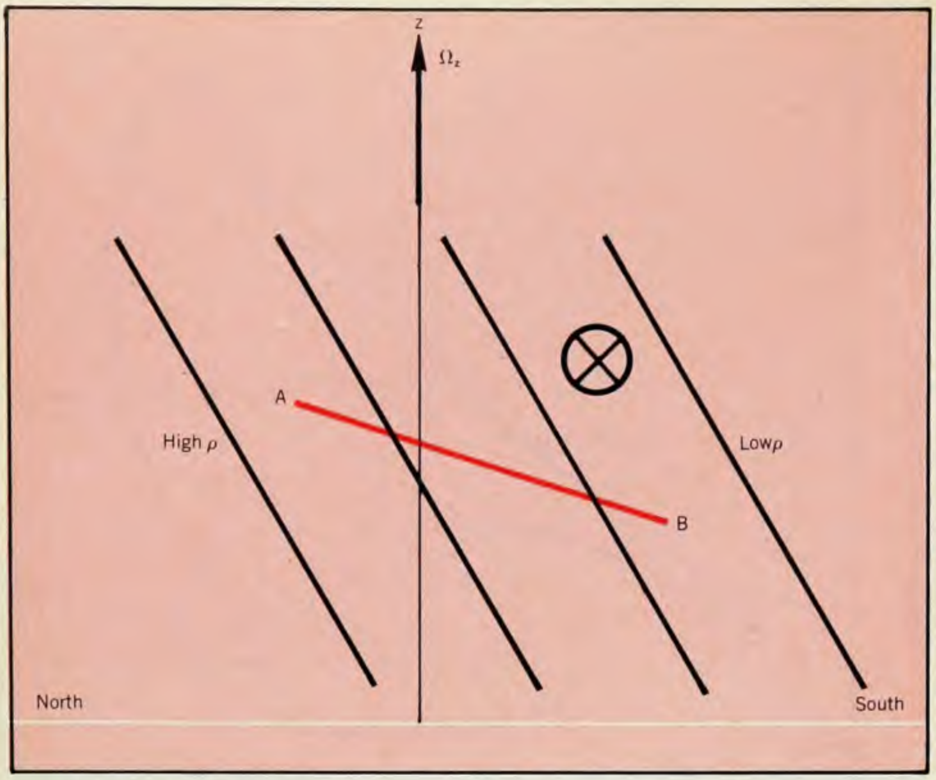
Transient lift of a helicopter blade, an example of how airfoil behavior cannot be systematically predicted. The flow exhibits a hysteresis loop at the rotor frequency (4 Hz here) as the angle of attack relative to the blade changes. Figure 5

which are important in the operation of internal combustion engines and in igniting flames in furnaces and rockets. An understanding of combustion and detonation has also been sought for many years for controlling explosions in dust-laden atmospheres in coal mines and grain elevators. As large-scale transportation of liquid and gaseous fuels becomes more common, there will be increased social pressures to understand the patterns of flame and shock propagation in combustible vapor clouds.

Facilities for aerodynamic testing, developed in the last 30 years, have been needed to test the behavior of vehicles and propulsion systems, which are the more obvious technical achievements. The conventional wind tunnel and the supersonic wind tunnel with a Laval nozzle were available in 1947. The shock tube was a new development in 1947 and has been used widely in studies at very high temperatures and pressures. Its role in chemistry rate studies has been crucial. A modification of the shock tube provides the hypersonic shock tunnel, where conditions simulating those of re-entry of space vehicles are achieved. In addition, wind tunnels have been built to operate at very low densities to simulate effects in the upper atmosphere; transonic tunnels with slotted walls permit experiments to be made at flows near Mach 1; helium hypersonic tunnels achieve high Mach numbers where oxygen and nitrogen would liquefy, and the rocket sled to carry instruments and even men reduces the expense and danger of preflight tests at very high speeds. Finally among achievements in facilities we may mention ballistic ranges where longer duration supersonic flows are established than is possible in shock tubes. Aerodynamics has produced many challenges to fluid dynamics and has used, and still needs, new knowledge in turbulence, nonequilibrium thermodynamics, separation, boundary layers and shock waves.

Geophysical flows

During the 1940's, one of the most important developments in the history of meteorology and oceanography occurred—the recognition of baroclinic instability and its role in the dynamics of oceans and atmospheres. Scale eddies in geophysical flows, caused primarily by baroclinic instability, may be thousands of kilometers in extent. These eddies are predominantly two-dimensional, however, in contrast to the three-dimensional eddies normally encountered in turbulence. This two-dimensionality is because of the relatively shallow depth of the atmosphere and oceans and also be-



Cross section of the atmosphere is seen here as by an observer looking eastward. Sloping parallel lines are constant-density contours, supporting a geostrophic flow directed into the figure. Denser fluid is on the left. The slopes are exaggerated here for emphasis. Figure 6

cause of their overall stable stratification.

By 1947 meteorological observations had provided convincing evidence of the importance of cyclones and anticyclones in the maintenance of the average circulation of the atmosphere. Victor Starr's analysis of meteorological data (1948) showed that the observed westerly winds in middle latitudes (that is, winds blowing from west to east) draw eastward momentum from nonlinear interactions of the "turbulent" eddies (storm systems). Subsequent theoretical developments, which have their roots in Jule Charney's analysis of baroclinic instability, have provided a firm dynamical foundation for our growing understanding of the physical processes that are involved in the eddy–mean-flow interactions in the atmosphere. Shortly after these major advances in atmospheric dynamics, Frederick Fuglister and L. V. Worthington reported the first definitive observations of an oceanographic "cyclone," a counterclockwise eddy formed by the meandering of the Gulf Stream. Since that time observations have indicated the nearly ubiquitous occurrence of these eddies, both anticyclones and cyclones.

The feature that distinguishes geophysical flows is the role played by the rotation of the Earth. Large-scale rotating flows are essentially hydrostatic. They are also approximately geostrophic; that is, the primary horizontal force balance is between the pressure gradient force and the Coriolis force. In figure 6 we see such an idealized geostrophic flow with the velocity vector directed into the figure (eastward) and with density increasing to the left (northward). Here we are considering a northern hemisphere example with a stably stratified, inviscid fluid and in which the northward directed pressure-gradient force is balanced by the southward directed Coriolis force, to the right of the velocity vector. In the illustrated case there is denser fluid on the left, and consequently the horizontal pressure gradient and the geostrophic wind speed increase with height. Also as a consequence of the density field, the basic configuration has potential energy (as well as kinetic energy) that is available to support perturbations of the basic flow. In the atmosphere such a density field is maintained by north–south differential heating of the Sun.

The method of the dynamical meteorologist or oceanographer in analyzing the large-scale eddies is to form a model of the global flow pattern and to study its stability. For the atmosphere, one can imagine a tropical band containing two counterrotating toroidal cells (Hadley cells) ringing the Earth from 30 deg North to 30 deg South. In a band stretching from 30 degrees latitude to 60 degrees latitude, four to six large horizontal cells are superposed on a continuous azimuthal flow (the prevailing westerlies). This region can be thought of as a system more or less separate from the polar section and the tropical regions. We are concerned here exclusively with this middle-latitude band, where the superposition of the cells and continuous flow constitutes a wavy flow extending around the Earth. This flow is modeled analytically by linearizing the fluid-dynamic equations and looking for solutions to the resulting wave equation. If we assume that the flow has a constant horizontal component at all heights ($d\mu/dz = 0$), we have barotropic flow, and certain types of perturbations may amplify: If so, this situation is called "barotropic instability." Of more interest are instabilities that arise when $d\mu/dz \neq 0$. Then the geostrophic equations show that the density depends on latitude, as in figure 6.

Baroclinic instability theory yields the conditions under which perturbations can grow at the expense of the basic potential energy. Unstable disturbances carry fluid parcels upward and northward (from B to A in figure 6) along a trajectory that has a slope less than that of the basic density field. Half a wavelength downstream, several hundred kilometers into the page in figure 6, fluid parcels are carried downward and southward from A to B. Thus, the net effect of the growing disturbance is to flatten the density field, so that basic available potential energy goes into perturbation kinetic energy.

The vertical motion of parcels is resisted by stratification, the intensity of which can be measured by the buoyancy frequency $N \equiv [(g/\rho)(\partial\rho/\partial z)]^{1/2}$ where g is gravitational acceleration, ρ is density and z is the vertical coordinate. The accompanying north–south excursion is enhanced by the effect of rotation (with frequency Ω_z), since only via rotation is a north–south flow generated by a downstream pressure gradient. With characteristic vertical and horizontal scales H and L, a nondimensional measure of instability is given by $L\Omega_z/NH$. When this parameter is of order one or larger, baroclinic instability occurs, with maximum growth of the perturbations for $L\Omega_z/NH \approx 1$. Hence, a characteristic horizontal scale of instability is given here by $L \approx H/\Omega_z[(g/\rho)(\partial\rho/\partial z)]^{1/2}$, which is called the "deformation length."

Analyses of the finite amplitude evolution of baroclinic instability by Norman Phillips, as well as subsequent fully nonlinear studies, have shown that the deformation length is the scale at which the disturbance penetrates the fluid vertically. In the atmosphere, a cyclone achieves maturity when upper and lower levels are locked in phase, and this occurs at the deformation length (about 1000 km for the atmosphere). Thus, although vertical structure—the so-called baroclinicity—is essential for the development of the disturbances, the evolution of the system is toward a barotropic (vertically uniform) state with relatively high kinetic energy. The trend toward barotropy may also be true for oceanic flows, although documentation is much more difficult to obtain in the ocean because of the scarcity of simultaneous observations of sufficient detail.

The situation just described can be extended to flows that have gradients of horizontal velocity components, where the added possibility of shear flow instability can occur. For parametric values appropriate to observed atmospheric and oceanic flows, the primary large-scale instability mechanism is baroclinic. Indeed, it has been shown by both theory and observation that the evolving disturbances have a structure that corresponds to barotropically stable modes.

In a series of informative numerical experiments Peter Rhines has demonstrated the pertinence of the basic physical mechanism of baroclinic instability to the evolution of large-scale oceanic flows. He has shown how initially turbulent flows with predominantly large or small scales will, through nonlinear interactions, feed energy into the deformation scale (about 70 km for the ocean) where baroclinic instability becomes operative. The system then tends toward a barotropic (occluded) state, although lateral boundaries and rough topography can detune the vertical phase-locking and inhibit the tendency toward barotropy. This type of numerical study, oriented toward an understanding of mechanisms, supplements other studies that are more phenomenologically oriented and serves to enhance our understanding of large-scale geophysical flows.

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