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CURRENT PROBLEMS IN RESEARCH

The Atmosphere in Motion

Research in geophysical fluid mechanics shows how density variation and rotation affect air motions.

Robert R. Long

The atmosphere is a fluid; it is a gas, pressed against the spinning earth by the force of gravity, heated by the sun and, as its moisture in gaseous form is turned into cloud and mist, by the latent heat of condensation. If the heating process is looked upon as known, study of its motion is a branch of fluid mechanics—physics in 1860, engineering science in 1960.

Until recently, research in meteorology was dominated, even oppressed, by the needs of weather forecasting. An understanding of the simplest effects of rotation and of density and temperature variations must surely precede an understanding of atmospheric phenomena containing these and a host of other features, but the relationship of such basic research to forecasting was considered too remote. Meteorologists hoped, rather, to find their prediction tools by studying the drift and development of the isobars on their weather maps, or by a variety of careful or casual statistical approaches.

But, it can be argued that all progress in forecasting since 1920—and it has been very modest—has come from looking more closely and more frequently at our atmosphere—that is, from improved observations rather than from research efforts. If the meteorologist will not accept this proposition, at least he will acknowledge that the returns from the vast amount of empirical synoptic and statistical research of the past 40 years have been astonishingly small. In other words, we are on a plateau and have been on it for many years. The situation is not changed, incidentally, by the advent in the past decade of numerical weather forecasting; the Weather Bureau forecaster now adds the output of the routine numerical integration to his other, older forecasting tools, but the improvement is too slight for much optimism.

Clearly, future progress demands fundamental research. Some basic work in what might be called geophysical fluid mechanics is now going on. I mean by this term, motion of fluids whose elements have spin, for example those disturbed in some way from a basic state of solid rotation, and motion of fluids in which density variations are present and important. A reservoir of knowledge is lacking in this field. True, fluid mechanics is an old subject, but classical work of the 19th century (*1*) was limited precisely to fluids in which rotation and density differences are absent. More recent work (*2*) has stemmed from the needs of aerodynamics, to a large extent, and these differ fundamentally from the needs of meteorology, oceanography, or astrophysics.

Geophysical Fluid Mechanics

Ruthlessly simplified, two simple items form the backbone of geophysical fluid mechanics. The first has to do with the motion of a particle as it appears to an observer on a rotating platform (*3*). To illustrate, suppose a particle is projected straight out from the center of rotation. If it is under no forces, the *resting* observer sees its path as a straight line, the dashed line in Fig. 1. He sees the platform turn underneath the moving particle, but this does not influence his measurement of the particle's path. The observer on the platform sees the particle curve to the right, however; to preserve the form of Newton's second law, "force equals mass times acceleration," he imagines that a force is acting, pushing the particle to the right. This is the Coriolis force; its presence, arising from the earth's rotation, is responsible for the fascination and the difficulty of much of geophysical fluid mechanics.

We mentioned a second feature; this is the typical variation of density of geophysical fluid systems. An example is ocean water, cold and therefore heavy near the ocean floor, warm and therefore light near the surface. Such density stratification brings with it a great resistance to vertical motion (*4*). If a cold, heavy particle of water is forced to rise by some disturbance or other, it finds itself surrounded by warm, light material, and it tends to sink again. The particle will usually drop below its natural level on the way down; if it does so, it will then find itself embedded in colder and denser fluid, and it will be forced back up. Not only does this work in favor of horizontal motion, but the repeated overshooting, an answer to a disturbance, is a wave phenomenon of separate interest and importance.

Air, the material of the atmosphere, is compressible; as it rises or falls, its density decreases or increases as the surrounding air presses on it less heavily or more heavily. But the principle is the same. If forced to rise, a parcel of air will normally find its surroundings lighter, and it will begin to sink; if forced to drop below its level of origin, it will normally find its surroundings denser, and it will be pushed back up. I will refer to these restoring forces as buoyancy forces.

The science of fluid mechanics is unusual in one respect; we have precise

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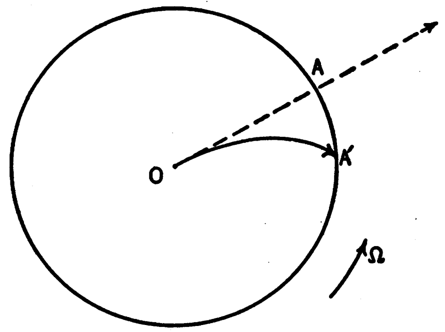


Fig. 1. Paths of a particle shot out from the axis of a rotating disk. The fixed observer sees the path as the straight, dashed line. However, the point of the disk A' has moved to the fixed point A while the particle is traveling from the center to the edge of the disk; the moving observer sees the path as the curve OA'.

mathematical expressions for the laws governing the motion of fluids, and these laws have passed with flying colors nearly all tests of their accuracy (*5*). Even in the sister science, solid mechanics, the equations of motion are not known for any real material. In a sense the whole of fluid mechanics is reduced to finding solutions of a mathematically determinate set of differential equations, and, in fact, applied mathematicians have been especially attracted to this field. But two things spoil this neat picture: first, only a few solutions of the equations have ever been found, despite a century of searching (*6*); second, the natural state of fluid motions, especially geophysical motions, is so disordered or turbulent (*7*) that it is unreasonable to ask for a knowledge of the motion in all its detail. The second point suggests that what we really want to know is some kind of average values of speed, temperature, and so on. But as far as we have developed them to date, the equations governing these average motions do not determine the problem in a mathematical sense.

We find ourselves, then, in a situation not differing much from that of other scientists, and we respond to our limitations in similar ways: we resort to both simplification and experiment. Experiment, however, despite its prominent role in almost all forms of scientific inquiry, has not been used much in geophysics, because it was thought impossible to reduce such vast systems to the scale of the laboratory (*8*). Recent work has shown that this estimate is overly pessimistic; in any event, it is unnecessary to claim that a little whirlpool generated in a rotating vessel of water in the laboratory is identical to a tornado in order to justify a scientist's giving it the second look. These assertions are justified below.

Stratified Flows

Experimentally, we may study the interplay of density variations and gravity in many ways. I limit myself to one, described in some detail. The geophysical motivation becomes obvious as the picture unfolds.

The experimental set-up is a glass-walled channel, 20 feet long, 2 feet deep, and 6 inches wide (*9*). We fill it with salt and water, so mixed that the saltiness, and therefore the density, decreases uniformly from bottom to top. Now we have a stratified fluid like the water in the ocean or the air in the atmosphere, although, in both of these fluids, density variations stem from temperature rather than salinity. Suppose now we put a small obstacle of some "easy" shape in the channel and pull it along the bottom at a fixed speed. The disturbance it causes would fascinate any person curious about the ways of nature. The geophysicist too is intrigued, but he prefers to look at the motion as he (actually, as a camera) sees it, moving along with the obstacle on a track parallel to the channel walls. In this way, he sees a current of fluid, with density decrease in the vertical, moving at a steady speed over a "fixed" barrier. Now we have something meteorological, because this reproduces the essentials of

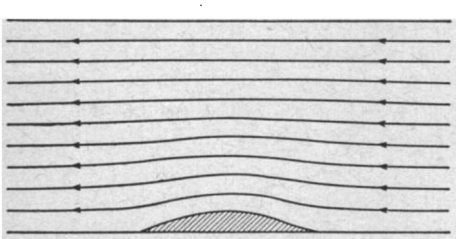
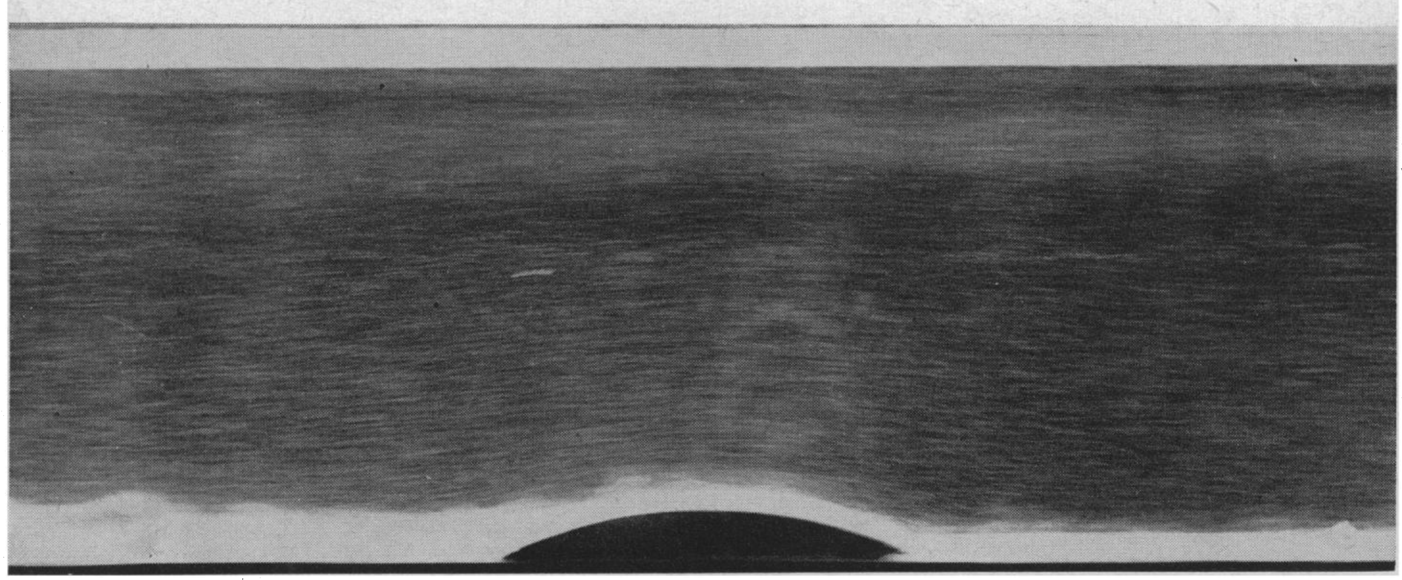
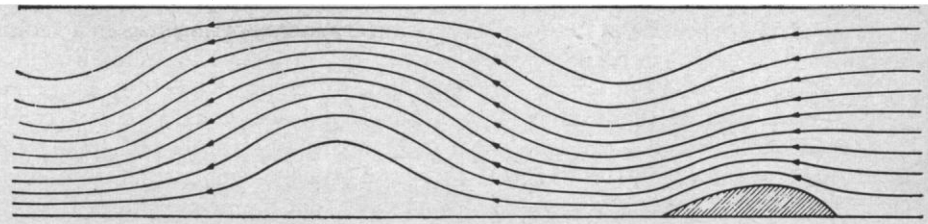


Fig. 2. Flow of pure water over an obstacle at the bottom of a channel. The flow is shown by putting an aluminum powder in the water and taking a photograph with a 1-second time exposure. Each streak is the path of a particle during this time period. The direction of the streak gives the direction of the motion; the length of the streak gives the speed.





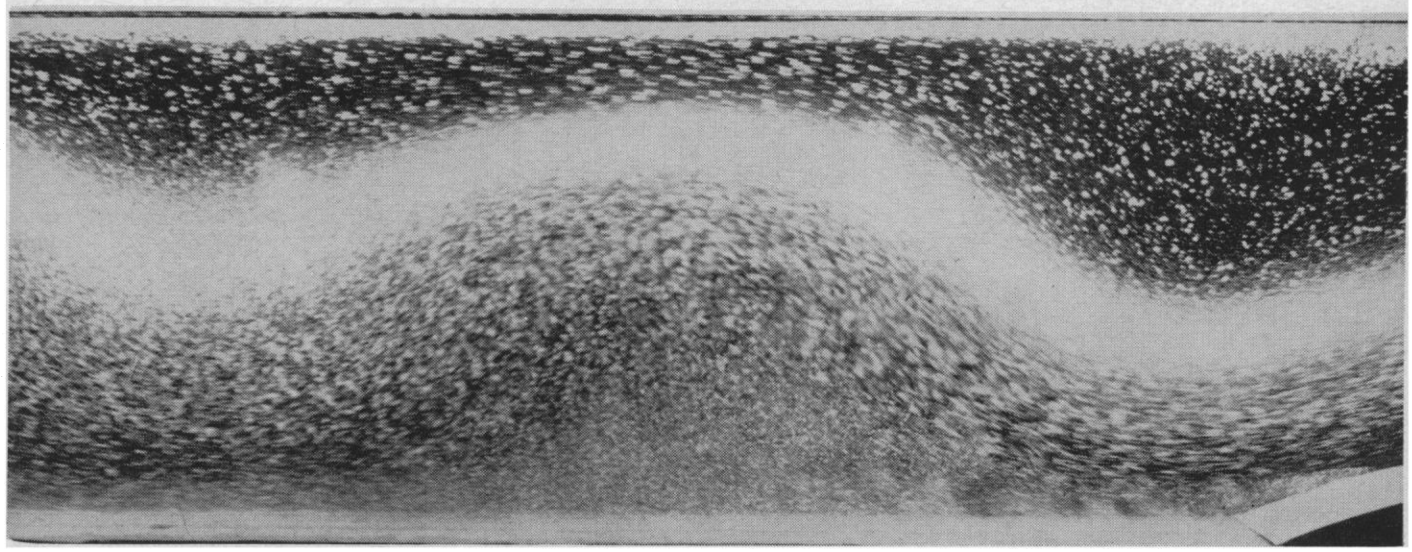


Fig. 3. Flow of a salt-water mixture over an obstacle. The undisturbed density variation in this experiment is a linear decrease with height. The line drawing is the plot of the flow obtained from a theoretical solution of the equations of motion.

air motion over mountain barriers on the ground.

As we have hinted, the density variation has a startling effect. If the fluid is pure water, the flow is like that in Fig. 2. But density variation produces an infinite variety of motion, depending on the speed of the basic current. If the current is very fast, the density variation has little or no influence, and the flow resembles Fig. 2 again. If the current is moderately slow, we have simple wave patterns, as in Fig. 3. The waves are explainable in a general way by the action of the buoyancy force that we have already discussed, but specific patterns can be very involved.

It was evident that the influence of internal friction on the flow patterns could be neglected, at least as a first approximation. With this and other minor simplifications, it was possible to find solutions for the flow. An example is the line drawing in Fig. 3, one of the myriad of flow patterns revealed by the theory. This particular pattern was chosen because the parameters which yield this theoretical flow pattern are the same as the parameters in this particular experiment. The agreement is excellent, as it is in all the comparisons of theory and experiment in this investigation.

But if theory and experiment are the same for a wide range of simple conditions, we are encouraged to rely solely on observations of the experiment if conditions (complicated obstacle forms) are so complicated that a theoretical solution is beyond our mathematical abilities. We might get even bolder than this and attempt to produce in our little channel a model of air flow over detailed terrain, or a model of the motion of tidal currents over a rough ocean bottom.

A particular case was chosen—air flow over the Sierra Nevadas in eastern California (*10*). Here we have a long ridge of mountains 12,000 to 14,000 feet high, running roughly north-south. The ground rises gradually from the Sacramento Valley to the west. East of the ridge it drops about 10,000 feet in a few miles, down to the Owens Valley. This valley is limited to the east by another very high ridge called the White Mountains. The Owens Valley is the scene of spectacular cloud forms and air motions. During days of strong activity a huge rotating cloud sits over the valley; motions in and around it are incredibly violent. Vertical velocities are so great that a light plane even in a full power dive may still be swept upward. World's altitude records for gliders are set here, and pilots could go still higher if cabins were pressurized.

The greatest activity comes when strong winds from the Pacific blow over the ridge. The air cascades down the lee and then rises in a series of standing waves. The motion has been studied carefully (*11*) in the Owens Valley near Bishop, California; the flow on a day of strong activity is pictured in Fig. 4. Compare this with the flow in the experimental model of Fig. 5. In the model an obstacle was made with a shape similar to the terrain in this area, and a certain number, called F_1, was chosen to be the same in the model as during this day in the region of the Sierras. (Equality of this number, which involves the basic speed of the current, gravity, and a measure of the density variation, is a necessary condition for similarity of the flow patterns.)

The agreement between the observed and the model flows is important. It is the first really definite indication, I think, that we can use in our geophysical studies this very powerful tool—modeling—which has proved so useful in engineering (in the design of aircraft, surface vessels, dams, and so on). In our case, all possible patterns of flow over the ridge could be found by a methodical variation of conditions of the experiment. A comparison of this catalog of findings with the forecast of "upstream" wind and temperature conditions on a given day would lead directly to a forecast of weather conditions in the Owens Valley. The same approach could be used for any locality in the world whose weather is substantially influenced by local terrain. This discussion of stratified flow shows how a piece of basic research can lead naturally, almost inevitably, to the solution of a practical problem.

The Tornado Vortex

A second example of the interplay of theory and experiment is in a recent study of vortices. The atmosphere has vortices of many scales, from the extratropical cyclone covering half a continent to the tiny dust whirls that form over a patch of hot ground on a summer day. But the investigations I report on here bear most directly on the tornado (*12*). The tornado is perhaps the most spectacular and dreadful display of nature. Its winds must reach speeds of several hundreds of miles per hour, but they are so dangerous and destructive that we cannot enter the tornado to measure them. Nor is high wind the only danger; the pressure at the center drops so low so quickly that build-

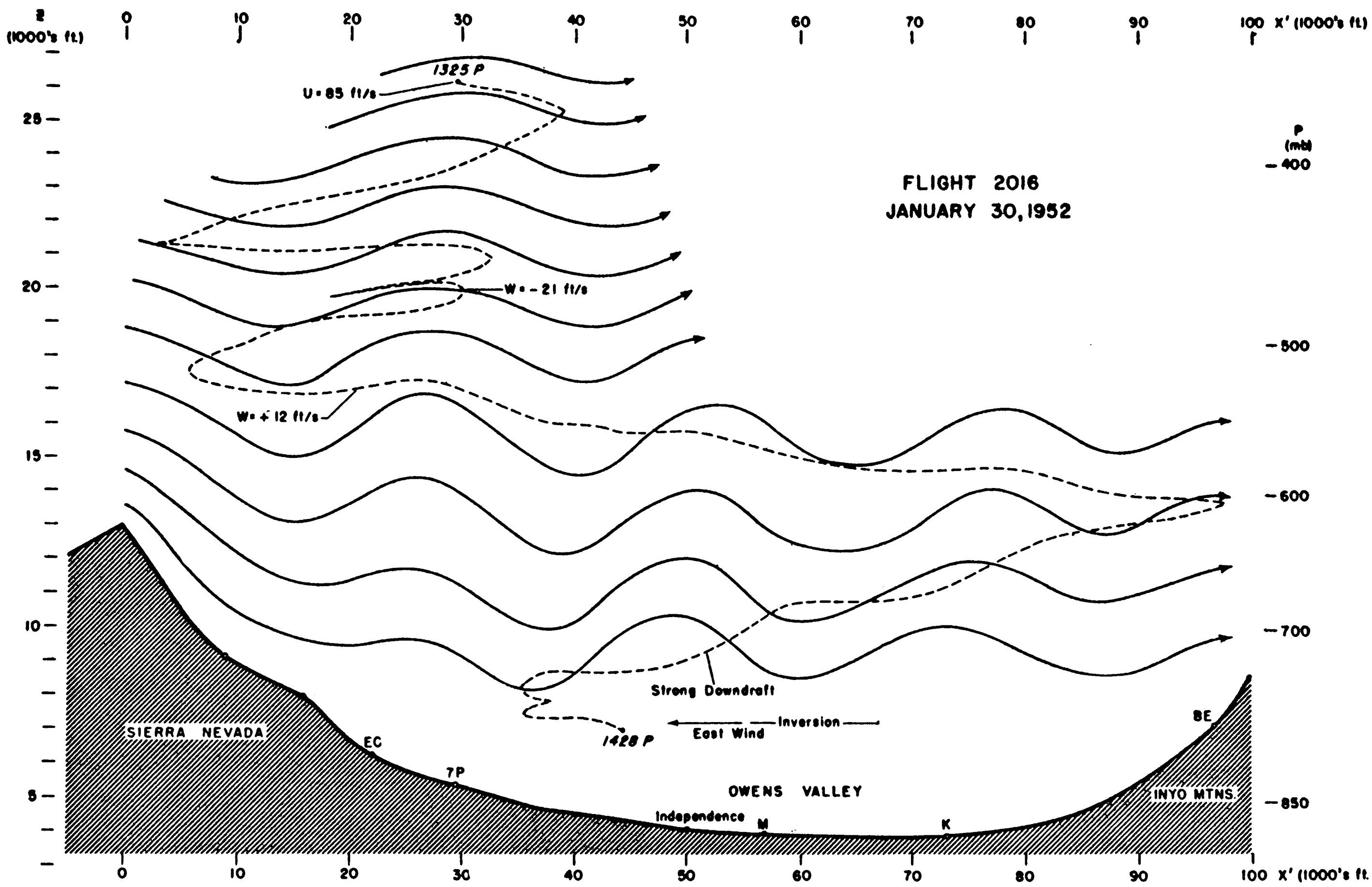


Fig. 4. Streamlines of air flow over the Sierra Nevada mountains on the afternoon of 30 January 1952, as determined by members of the department of meteorology, University of California, Los Angeles. The vertical dimensions of the atmosphere are greatly exaggerated in this drawing.

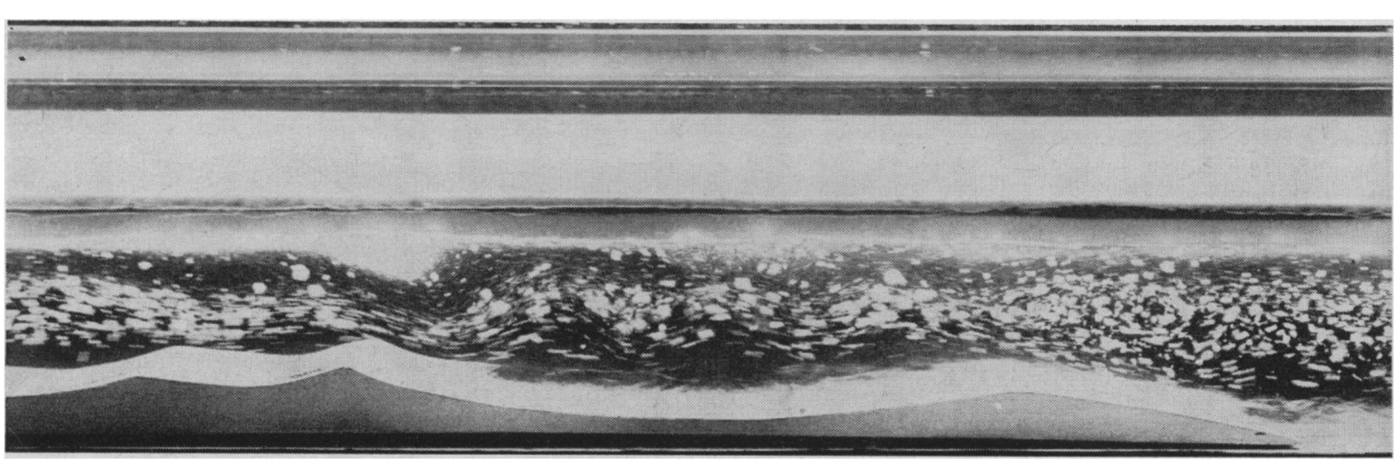


Fig. 5. Experimental model of air flow over the Sierra Nevadas. "Upstream" conditions were chosen to be as close as possible to those of Fig. 4. Layers of fluid on top are immiscible liquids lighter than salt water. They reproduce the very stable stratosphere.

ings explode outward as the vortex passes by. The practical importance of a study of tornadoes is obvious. They are now so unpredictable that the Weather Bureau can rarely provide even minimum warning.

The vortex study was begun with quite another end in mind. The original intention was to extend to a fluid in rotation a classical hydrodynamic study of the way in which fluid in a container moves toward a small hole in the wall of the container. This is a hydrodynamic *sink,* and although it may seem at first glance to be a trivial and uninteresting form of motion, it turns out to be of the greatest possible importance in fluid mechanics. This granted, a valuable study in rotating fluids might well be how water in a cylinder mounted on a rotating turntable flows toward a hole in the bottom of the vessel. Although few problems in rotating fluids can be solved theoretically, this one can if the withdrawal rate is above a minimum value and if friction is unimportant. If we pull out fluid fast enough, the movement of the water toward the hole is largely unaffected by the rotation. Lower the rate, and the sink draws more and more strongly from along the axis, until finally the water approaches the hole in a jet just at the axis. Here we have already the beginnings of a vortex because the fluid in the jet near the axis originates some distance away, and as it moves in, conservation of angular momentum means a considerable increase in spin.

The mathematical solutions resembled very closely the corresponding experimental flow. Although the theory was limited by the requirement that the withdrawal rate be above a certain value, no such limitation existed for the experiment. When we withdrew fluid at a rate lower than the theoretical minimum, the vortex at the axis became more and more concentrated and more and more intense. Eventually we got a remarkably strong vortex in which the spin was hundreds or thousands of times greater than before withdrawal began. Some idea of the motion can be gained from Fig. 6.

For the first time in our discussion we must take into account internal friction in the fluid. Friction is fundamental in fluids whenever velocity variations get large enough. In this vortex, for example, we see (Fig. 6) that speeds are enormous in a small core and drop off precipitately as we go out from the center. It was easy to make a quantitative estimate that friction is essential in the intense vortex, and this set off an investigation that led to a new theory of vortices.

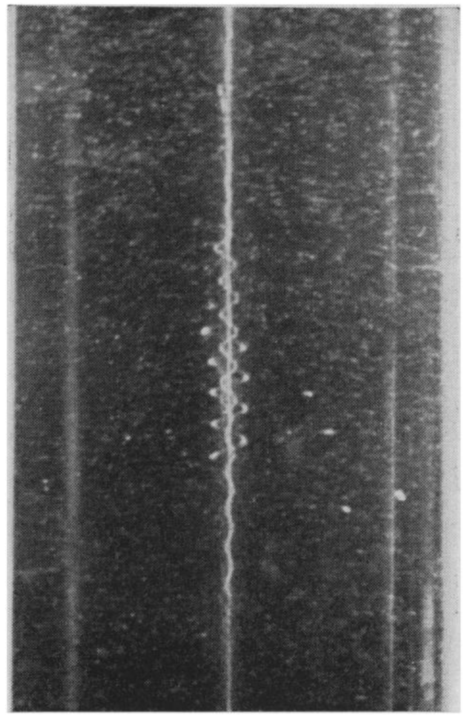


Fig. 6. Vortex at the axis of a rotating vessel of water. This 1/5-second time exposure shows that particles make several revolutions as they progress along the axis.

In a recent paper this theory was compared to the tornado phenomenon (*13*), with some remarkable conclusions about its form, its velocity field, and its causes. The most striking discovery is that the air must be rushing violently upward in the center of a tornado at speeds of several hundred miles an hour. Superimposed, of course, is the swirling velocity, which is also 200 or 300 miles an hour or so. The strong upward velocities were to some extent unexpected, although one observer once saw a tornado outrun the cloud in which it was embedded; while he watched it, the visible portion shot up to 35,000 feet in 1 minute (*12*). This implies a vertical velocity of about 400 miles per hour, as the theoretical model suggests.

The theory yields a picture of the funnel cloud of the tornado if we make the reasonable assumption that it is a surface of constant pressure in the lower layers. A particular case is shown in Fig. 7. If we take the funnel to be the 900-millibar surface, it has a diameter of several hundred feet as commonly observed, and its shape is very similar to the typical tornado funnel.

The theory permits an interesting speculation about the necessary conditions for the occurrence of a tornado. To get a theoretical vortex of the right intensity and size we must insert in the theory values of a number of atmospheric quantities—for example, density, ground pressure, and viscosity coefficient of the turbulent air. All of the

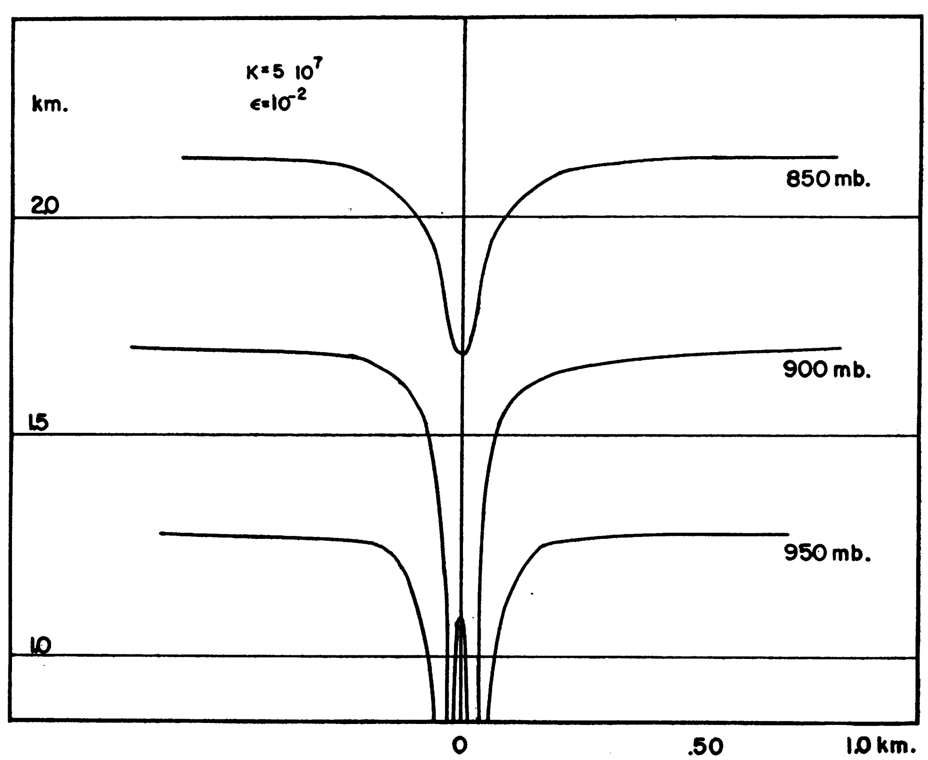


Fig. 7. Constant-pressure surfaces in a typical theoretical tornado. It is reasonable to take the 900-millibar surface as the outer surface of the tornado funnel.

parameters have values typical of, say, any warm, moist air mass found in spring and summer in the central United States, with a single exception, a quantity K called *circulation,* which is a measure of the general rotation of the air in which the tornado is imbedded. This quantity has been estimated with great accuracy for at least one tornado, and I think we know very closely its value in the typical case. It corresponds, however, to so great a rotation that it is obviously a very rare occurrence. This may explain the infrequency of tornadoes. It is possible that we could learn to predict this (parent) small-scale cyclone, and this in turn could lead to better forecasting of tornadoes.

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The Competitive Exclusion Principle

An idea that took a century to be born has implications in ecology, economics, and genetics.

Garrett Hardin

On 21 March 1944 the British Ecological Society devoted a symposium to the ecology of closely allied species. There were about 60 members and guests present. In the words of an anonymous reporter (*1*), "a lively discussion . . . centred about Gause's contention (1934) that two species with similar ecology cannot live together in the same place. . . . A distinct cleavage of opinion revealed itself on the question of the validity of Gause's concept. Of the main speakers, Mr. Lack, Mr. Elton and Dr. Varley supported the postulate. . . . Capt. Diver made a vigorous attack on Gause's concept, on the grounds that the mathematical and experimental approaches had been dangerously over simplified. . . . Pointing out the difficulty of defining 'similar ecology' he gave examples of many congruent species of both plants and animals apparently living and feeding together."

Thus was born what has since been called "Gause's principle." I say "born" rather than "conceived" in order to draw an analogy with the process of mammalian reproduction, where the moment of birth, of exposure to the external world, of becoming a fully legal entity, takes place long after the moment of conception. With respect to the principle here discussed, the length of the gestation period is a matter of controversy: 10 years, 12 years, 18 years, 40 years, or about 100 years, depending on whom one takes to be the father of the child.

Statement of the Principle

For reasons given below, I here refer to the principle by a name already introduced (*2*)—namely, the "competitive exclusion principle," or more briefly, the "exclusion principle." It may be briefly stated thus: *Complete competitors cannot coexist.* Many published discussions of the principle revolve around the ambiguity of the words used in stating it. The statement given above has been very carefully constructed: every one of the four words is ambiguous. This formulation has been chosen not out of perversity but because of a belief that it is best to use that wording which is least likely to hide the fact that we still do not comprehend the exact limits of the principle. For the present, I think the "threat of clarity" (*3*) is a serious one that is best minimized by using a formulation that is *admittedly* unclear; thus can we keep in the forefront of our minds the unfinished work before us. The wording given has, I think, another point of superiority in that it seems brutal and dogmatic. By emphasizing the very aspects that might result in our denial of them were they less plain we can keep the principle explicitly present in our minds until we see if its implications are, or are not, as unpleasant as our subconscious might suppose. The meaning of these somewhat cryptic remarks should become clear further on in the discussion.

What does the exclusion principle mean? Roughly this: that (i) if two noninterbreeding populations "do the same thing"—that is, occupy precisely the same ecological niche in Elton's sense (*4*)—and (ii) if they are "sympatric"—that is, if they occupy the same geographic territory—and (iii) if population A multiplies even the least bit faster than population B, then ultimately A will completely displace B, which will become extinct. This is the "weak form" of the principle. Always in practice a stronger form is used, based on the removal of the hypothetical character of condition (iii). We do this because we adhere to what may be called the axiom of inequality, which states that no two things or processes,

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