Doppler Radar: New Look into Violent Weather

The tornado began its 8-mile path of destruction outside Oklahoma City at about suppertime one evening last spring. No ordinary tornado, this "maxi" funnel was one in a hundred, bulging to as much as 800 meters in width as it roared through the edge of suburban Piedmont and into the surrounding countryside.

By chance, Oklahoma City escaped damage, but the Piedmont tornado destroyed 25 homes and caused damage estimated at $5 million. The tornado did not kill anyone and no one was injured, but that was not a matter of chance. Residents had 30 minutes to hear a warning issued by the U.S. Weather Service and take shelter before the tornado even touched down. In the past, forecasters could not issue a warning until someone sighted the descending funnel cloud, usually only moments before it reached the ground. Now, researchers can peer into the heart of a violent storm and anticipate a tornado's formation, making it unnecessary to simply wait for a sighting report.

The key to this new view of the weather is Doppler radar, a form of radar that, by measuring shifts in the frequency of the reflected signals, can directly detect the motion of raindrops, ice particles, and even clear air itself. Rather than simply showing how heavy the precipitation is within a storm, as conventional radar does, Doppler radar can also provide a picture of the winds that feed energy to a storm and give a storm its typical form (Fig. 1). This capability is being used in a variety of meteorological studies, not only of tornadoes and thunderstorms, but also of turbulent winds over airport runways.

A characteristic wind pattern, revealed only by Doppler radar, suggested to researchers who organized the Joint Doppler Operational Project (JDOP)* that an individual tornado could be predicted. During the first 2 years of JDOP, all strong tornadoes have been preceded by larger, less intense vortexes called mesocyclones. These are typically about 6 kilometers across and have wind speeds of about 70 kilometers per hour, compared to the 50- to 100-meter diameter and the 200- to 400-kilometer-per-hour winds of a tornado. Conventional radar cannot reliably detect mesocyclones before they spawn tornadoes because the mesocyclone's wind pattern dos not produce a unique precipitation pattern.

Doppler radar's ability to detect motion directly is based on the same phenomenon exemplified by the familiar change in pitch of a passing train's whistle, the Doppler effect. Conventional radar simply measures the distance to an object, such as a raindrop or an ice particle, by timing the round trip of a reflected microwave signal. The strength of the reflected signal also indicates the intensity of the precipitation. Doppler radar in addition compares the frequency of the reflected pulse to that of the original pulse. Motion of raindrops toward the radar increases the frequency of the reflected signal and motion away from the radar decreases it, both changes being in proportion to the speed of the raindrops. This change in frequency, on the order of 1 part in 100 million, is then interpreted in terms of a speed toward or away from the radar.

The demands of manipulating and interpreting the hundreds of thousands of frequency changes detected each minute by Doppler radar had impeded its use for 15 years, but its popularity has mushroomed in the last 5 years with the development of greater data handling capabilities. The advent of color display units, in which motion toward and away from the radar are color-coded and shown on the same screen, has made possible the visual presentation of quantitative information without confusion. The discovery about 10 years ago of mathematical shortcuts for converting frequency changes into velocities made rapid data calculations possible. Finally, the sharply decreasing cost of electronic components made the necessary equipment accessible to most laboratories.

JDOP investigators used two Doppler radars, operated independently, to detect the development of tornado-generating mesocyclones in the heart of the tornado belt near Oklahoma City. Within a practical limit of about 230 kilometers, a unit can detect the initial formation of the swirling mesocyclone within storm clouds at a height of about 6000 meters and follow its subsequent growth both upward and downward. Only 50 percent of these mesocyclones produce tornadoes, but 96 percent of them produce damaging hail, severe winds, or tornadoes, according to Donald Burgess of the National Severe Storms Laboratory. Likely tornado generators can be identified, he notes, by their higher wind speeds and their sharper gradients of wind speed.

Results from two complete seasons of JDOP show that the use of Doppler radar can dramatically improve tornado warnings, according to David Holmes of the U.S. Weather Service. Without Doppler radar, the warning system must depend on visual sightings by a few trained observers and members of the general public. Such a system is prone to incomplete coverage and error, especially at night, when funnel clouds can go unnoticed or harmless clouds may be mistaken for a twister.

Typically, more than half of the advisories issued by the Weather Service turn out to be false alarms, according to Holmes. Only about one-third are followed by an actual tornado. In contrast, predictions based on Doppler radar were right 75 percent of the time. More important, perhaps, the average warning time before the tornadoes touched down was 21 minutes compared with the less than 2 minutes provided by visual observation. In addition, Doppler radar can usually track the tornado itself when it moves within 100 kilometers of the radar site. This capability proved to be a lifesaving one last spring when researchers watched a tornado make a sudden unexpected change of direction. Several families heard the resulting warning in time to take shelter before the swerving tornado destroyed their homes.

Thunderstorm Research

Doppler radar's ability to perceive motion directly is also being applied to the study of thunderstorms, particularly as generators of lightning. Researchers participating in a major cooperative project, the Thunderstorm Research International Program (TRIP), are attempting to associate the pattern of thunderstorm winds, as detected by Doppler radar, with the electrical generating processes that eventually produce the storm's lightning. Preliminary analyses of results from the last three summers' observa-

*A cooperative project of the National Severe Storms Laboratory, Norman, Oklahoma; National Weather Service; U.S. Air Force's Air Weather Service; Federal Aviation Administration; and the Air Force Geophysics Laboratory, Bedford, Mass.

tions at Kennedy Space Center suggest that lightning originates in the vicinity of strong updrafts, which cannot be detected by conventional radar, and not necessarily near areas of the most intense precipitation, according to Roger Lhermitte of the University of Miami.

Exactly how opposite electrical charges are generated and then separated before they are discharged as lightning has remained a mystery. According to a number of theories, smaller precipitation particles, by one means or another, take on a net positive charge and larger ones become negatively charged. These charges may come about through collisions of ice particles, splitting of liquid drops, or, perhaps, the freezing of raindrops. Once charged, sorting of these particles by gravity or winds on the basis of size leaves the cloud top positively charged and the middle levels negatively charged. The sudden release of these charges within the cloud, to another cloud, or to the ground produces lightning.

Doppler radar plays an important role in the TRIP studies, along with other remote sensing devices, because it can provide three-dimensional pictures of wind and particle movement throughout a storm's development. Although a storm may encompass several thousand cubic kilometers, a set of three Doppler radars can scan it once every 2 to 3 minutes and provide the speed and direction of particles at more than 60,000 different points. From information on particle size, it is possible to calculate wind speeds and directions.

With this information plus the locations of lightning within the cloud, Lhermitte believes that a tentative association can be made between strong updrafts and the electrification process. In the case of one storm, lightning occurred near a particular updraft even though that updraft did not have the heaviest precipitation in the storm. But that updraft had reached a possibly critical speed of about 70 kilometers per hour and an altitude of about 8 kilometers. It may be, Lhermitte suggests, that these conditions produce enough collisions between small and large ice particles to separate the required charges. According to calculations of particle behavior based on Doppler radar data, the lightning in this particular updraft only originated near where small and large particles would be separated, the small particles continuing to be carried toward the cloud top and the larger ones being carried over into downdrafts. Confirmation of such a scheme will require information on the composition and charge of individual particles.

A less obvious but still hazardous weather phenomenon being studied with Doppler radar is strong wind shear, the abrupt change in wind speed over a short distance that can send low-flying aircraft out of control, and crashing into the ground. Earl Gossard and his group at the National Oceanic and Atmospheric Agency's Wave Propagation Laboratory in Boulder have detected wind shear across a runway during operational tests of a special form of Doppler radar, a frequency-modulated, continuous-wave (FM-CW) Doppler radar. One antenna of this radar emits a continuous signal that sweeps up and down a range of frequencies. A second antenna receives the signal reflected from boundaries between air of different temperatures or humidities. Raindrops or ice particles need not be present to reflect the signal. Thus, a sharp variation in wind speed across a runway can be measured directly without even a cloud in the sky.

This wide range of objects for Doppler radar studies, from thunderstorms to

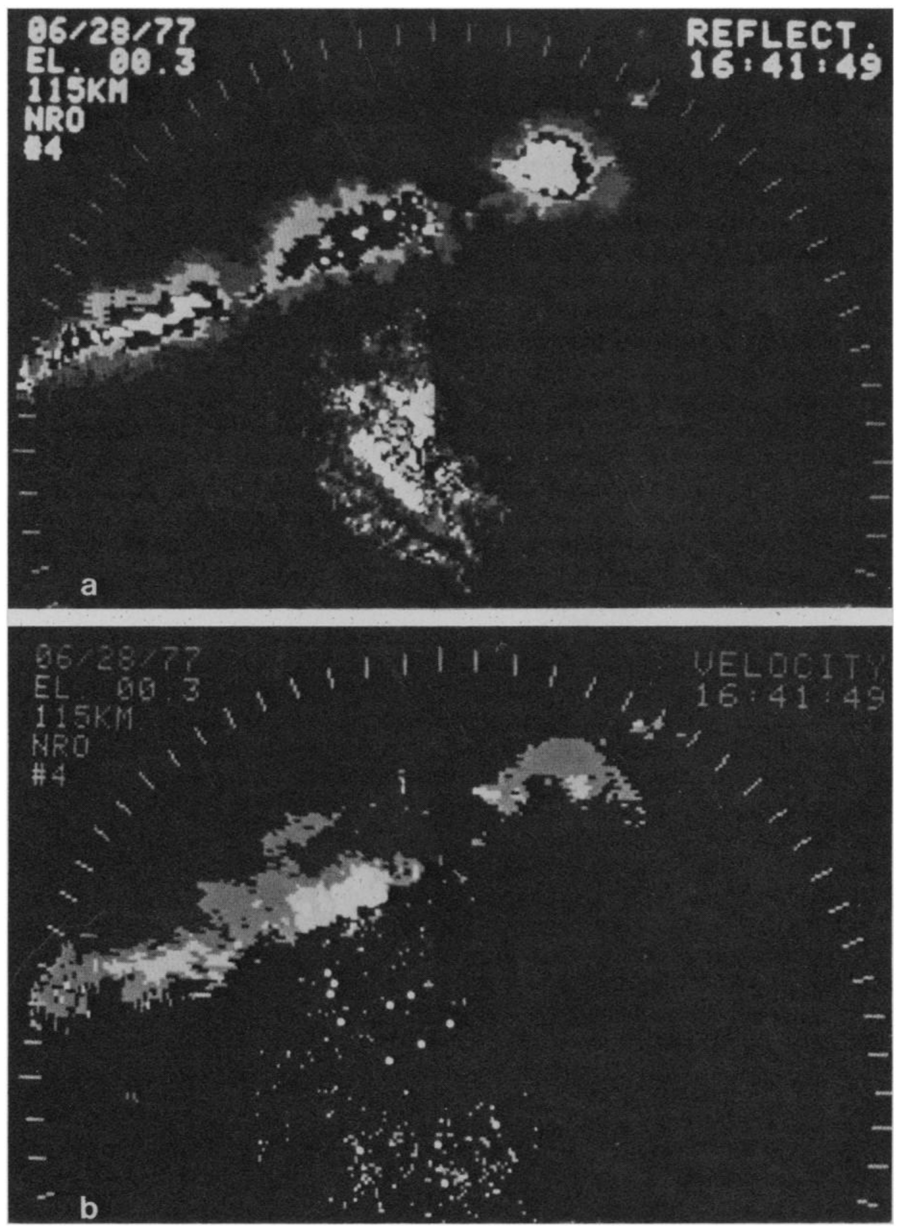

Fig. 1. Radar displays of a squall line approaching Oklahoma City as seen with Doppler radar: (a) Conventional display showing contours of radar reflectivity, which indicate varying rainfall intensities. Lightest rainfall was in the dark gray areas, and the heaviest was in the white areas, as in the heavy thunderstorm in the right-hand portion of the squall line. (b) Doppler display showing contours of wind velocity toward the radar within the same squall line. The lighter the shading, the higher the wind speed. The highest wind speeds, which exceeded 120 kilometers per hour, were not associated with the heaviest rainfall. The area covered by the displays is 230 kilometers across. [Source: National Severe Storms Laboratory, Norman, Oklahoma]

winds in clear air, is achieved largely by the use of improved signal processing techniques and by varying the frequency of the broadcasted signal. Thus, researchers have looked at snow storms, a hurricane, turbulence in clear air near the ground, and clear air winds at altitudes up to 15 kilometers. At much lower frequencies than those used to probe the atmosphere, oceanographers have even been able to measure the motion of waves and ocean currents up to 70 kilometers from the shore.

Doppler radar is rapidly becoming a popular research tool. Some data handling problems, including the rapid processing of three-dimensional data, have not yet been tackled. But larger Doppler networks (seven or more radars) are planned for the immediate future, and some researchers envision an operational network spanning the country to provide warnings of violent weather.

—RICHARD A. KERR

The 1978 Nobel Prize in Chemistry

Award of the Nobel Prize in Chemistry to Peter Mitchell honors the achievements of a strikingly original mind. A quarter of a century ago, Mitchell recognized that biochemical reactions associated with membranes may have a direction in space, and he set out, virtually alone, to explore the implications of this insight. The result was nothing less than a scientific revolution, in Thomas Kuhn's sense. During the past decade the paradigms of bioenergetics have been transformed under the impact of Mitchell's chemiosmotic theory; in time it may transmute our perception of how living cells function.

How do organisms generate energy and harness it to the performance of such useful work as movement, transport, and biosynthesis? By 1955, Fritz Lipmann's concept that adenosine triphosphate (ATP) serves as the universal energy currency had been assimilated. The function of the great metabolic highways—fermentation, respiration, and photosynthesis—was seen to be the production of ATP, which, in turn, supports various work functions by virtue of its energy-rich phosphoryl bonds. In outline, at least, bioenergetics seemed comprehensible, and what remained to be done was to work out the molecular details.

That proved to be a major undertaking, for the enzymes of oxidative and photosynthetic phosphorylation are firmly associated with the lipoprotein membranes of mitochondria and chloroplasts, respectively, and could not be satisfactorily studied in solution. Some of the most illustrious biochemists of a generation—P. D. Boyer, B. Chance, L. Ernster, D. E. Green, H. A. Lardy, A. L. Lehninger, E. Racker, E. C. Slater, and many others—devoted their efforts to the task of delineating the basic features of oxidative phosphorylation. In the upshot it was recognized that respiration is mediated by a cascade of enzymes and coenzymes that transport electrons from various reduced substrates to oxygen. The synthesis of ATP itself is catalyzed by a distinct enzyme complex, referred to as an ATPase (adenosinetriphosphatase) because its activity is usually assayed in the hydrolytic direction. In chloroplasts, likewise, electrons ejected when light is absorbed by chlorophyll travel along a series of carriers to the ultimate acceptor, water; ATP synthesis is mediated by an ATPase complex whose molecular structure closely resembles that of mitochondrial membranes. The issue of "energy coupling" was now sharply focused: how does the free energy released during electron transport drive the ATPase "uphill," in the direction of ATP synthesis? The search for molecular mechanisms was guided by the postulate that the respiratory chain and ATPase are linked by high energy intermediates, analogous to those discovered in reactions catalyzed by soluble enzymes. For a decade, one putative intermediate after another was proposed, examined, and rejected, with mounting frustration. Something had gone wrong, but what?

Peter Mitchell was not, to begin with, a properly licensed mitochondriologist. His intellectual roots lay in the study of metabolite transport across the cytoplasmic membrane of bacteria, a subject he had taken up while a student in Ernest Gale's laboratory in Cambridge. Transport, also, was bedeviled by a major conceptual difficulty: How can the scalar reactions of metabolism generate vectorial transport of substances into or out of cells? In 1958, Mitchell, together with former fellow student Jennifer Moyle, pointed out that enzymic reactions are intrinsically vectorial. Their direction in space is masked in solution but may become manifest when enzymes are incorporated into membranes. An enzyme complex may be so embedded within a membrane that the reaction pathway traverses the barrier, catalyzing at once a chemical reaction and the translocation of a chemical group: vectorial metabolism.

Pondering the implications of this principle led Mitchell, between 1961 and 1966, to formulate what he called the chemiosmotic hypothesis, a radical solution to the problem of energy coupling in oxidative and photosynthetic phosphorylation. Briefly, he proposed that the respiratory chain is an alternating sequence of carriers for hydrogen and electrons, so arrayed within the inner mitochondrial membrane as to transport protons across it. Since the mitochondrial membrane is essentially impermeable to the passive flow of protons, respiration generates an electrochemical potential gradient for H^+ with the matrix electrically negative and alkaline relative to the outside. Protons at the outer surface will seek to move back into the matrix, down the potential gradient; this proton current, analogous to the electron current produced by a battery, can be drawn upon to do work. The ATPase is a second, independent proton-translocating system that also spans the membrane; movement of protons through a channel within the ATPase complex, down the electrochemical gradient generated by respiration, drives the synthesis of ATP. The chemiosmotic hypothesis denied the existence of chemical links between the respiratory chain and the ATPase; they need not even be physically contiguous. What is required is that both complexes be localized in a single, topologically closed vesicle tight enough to sustain the proton gradient that effects their coupling.

It must be said that the chemiosmotic hypothesis found little welcome among biochemists. Mitchell had invoked strange principles with an almost mystical flavor; besides, there seemed at first to be good grounds for doubting the validity of some of his proposals. It was probably the open-minded skepticism of Efraim Racker that persuaded Mitchell that he must buttress his argument with solid data. But hard evidence was not easily come by, for it required the invention of methods with which to ask nature quite novel questions. Jointly, Mitchell

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