NCAR Quarterly
JULY, 1964

Migration of Thunderstorms

For a broad variety of human activities it is desirable to have detailed, short-period forecasts of thunderstorm occurrence. Such information is useful in planning many types of outdoor work and recreation. The increased density of air traffic and the costs involved in detouring hazardous storms make it essential for airway controllers to have accurate estimates of their locations and intensities.

Detailed forecasting of this kind is only feasible through the use of weather surveillance radar, which maps the locations and intensities of existing storms. The potential usefulness of radar observations has, however, been only partially realized because of our limited understanding of the ways in which storms typically move and develop.

The question of storm movement has recently been examined by Chester W. Newton of NCAR and James C. Fankhauser on temporary assignment to NCAR by the U. S. Weather Bureau. Having completed studies begun earlier at the Weather Bureau National Severe Storms Project in Kansas City, they reported their findings at the National Conference on Physics and Dynamics of Clouds at the University of Chicago on March 25, 1964.

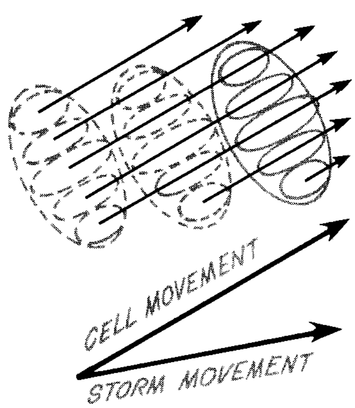
Thunderstorm Cells

What we know today about the inside structure of thunderstorms was derived in large part from ground-based and aircraft observations obtained by the Thunderstorm Project, an extensive study undertaken jointly by the U. S. Weather Bureau and several other government agencies between 1946 and 1949. Using Thunderstorm Project data, Horace R. Byers and Roscoe R. Braham of the University of Chicago showed that the typical thunderstorm is an agglomeration of "cells." These cells, which are one to a few miles across, contain vigorous chimneys of rising or descending air—that is, updrafts and downdrafts. The characteristic lifetime of an individual cell is half an hour to an hour, while a large thunderstorm, as a cluster of continually evolving cells, may persist for up to twelve hours.

Radar observations of "single-cell" storms were analyzed by the Thunderstorm Project in 1949 and by M. G. H. Ligda of the Texas A&M University in 1953. The movement of this type of storm is closely correlated with the average wind through the depth of the cloud layer and with the wind in the middle troposphere, which is often close to the average.

Storm Evolution and Movement

In their studies, Newton and Fankhauser looked at the movement of multi-celled storms. For the southern Great Plains area, they found that the pattern of development and decay of the cells, or the process of "propagation," is one of the most important factors governing the movement of the storm as a whole. In the typical case, diagrammed in the margin, the cells move toward the northeast. The storm, consisting of a cluster of cells, is shown in successive positions. New cells form to the right of the existing cells and old cells dissipate on the left. Thus propagation results in a movement of the thunderstorm as a whole toward the right of the paths of its individual cells.



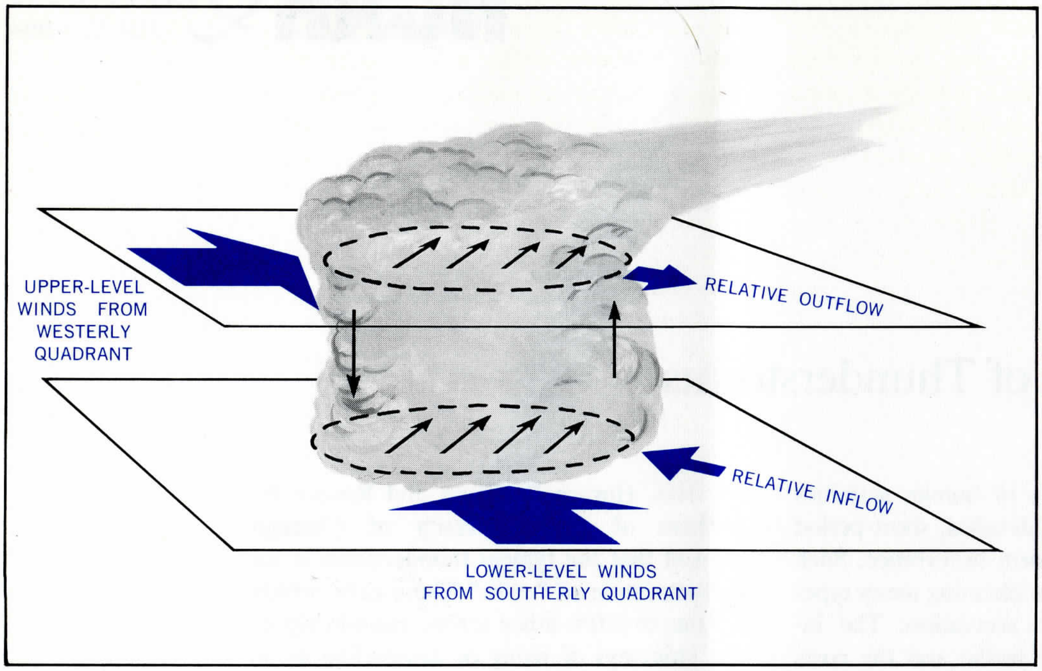


Diagram of a large thunderstorm imbedded in an environment where the wind veers to the right with height. Moist unstable air enters the cloud on the right lower flank reinforcing the formation of new convective cells in that location.

In a typical severe thunderstorm situation over the Great Plains, two storms in the same environment conditions may move in directions differing by as much as 90 degrees. Small storms mostly move to the left of the mean wind direction in the cloud-bearing layer, while large ones move up to 60 degrees to the right.

The great variation in storm movement, Newton and Fankhauser suggest, is due largely to differences in the rate of propagation of new storm cells. Radar observations in this country, and also observations of massive hailstorms in England by Keith A. Browning and Frank H. Ludlam of Imperial College, London, in 1960, have shown that the growth of new cells takes place most typically on the right-hand forward flank of an existing thunderstorm mass, as illustrated in the margin on the previous page. The greater the rate of new cell formation on the right, the greater is the deviation of the storm movement to the right of the individual cell movement.

Wind Speed and Storm Direction

An hypothesis predicting this systematic kind of propagation was offered by Chester W. and Harriet R. Newton in 1959. In a typical situation breeding severe thunderstorms, the wind usually veers clockwise with increasing height, as shown in the diagram above. In the lower levels (around 5,000 feet) the wind is generally from a southerly direction with speeds of 30 to 50 miles per hour, while at the tropopause near the storm top (averaging about 40,000 feet) it usually blows from a direction between northwest and southwest with speeds commonly from 60 to 120 miles per hour. Owing to vigorous mixing by the updrafts and downdrafts, the average horizontal air motions within the storm tend to be intermediate, both in direction and speed, between the winds in the upper and lower levels of the area surrounding the cloud. Consequently, at a given upper or lower level the storm air moves horizontally with a direction and speed that may be very different from the winds surrounding the storm.

It was theorized that the storm acts as an obstacle in the general flow of air in much the same way as a bridge abutment interacts with a running stream, where the water piles up on the upstream side and is depleted on the downstream side. In the atmosphere, however, the interaction is more complicated because the obstacle, the storm, is itself moving and the surrounding substance, the air, is moving against the obstacle from one direction at the lower level and from another at the upper level.

An analysis of the wind field shows that when the wind direction veers to the right with height, the relative motion of wind and storm result in air blowing into the storm on the right front flank at lower levels and out of it on the same flank at upper levels, favoring new cloud growth on that flank, as diagramed on the opposite page.

Thus when the wind veers to the right with height, the model of propagation proposed by the Newtons is compatible with the pattern of storm development observed by radar. Their analysis of the forces of interaction between storm and environment showed that the influence of this kind of propagation is greatest when the overall storm diameter is large, and negligible when the storm dimensions are small. They concluded, therefore, that the larger the storm the farther it will move to the right of the average wind direction.

Available Moisture Calculated

Although the model discussed above provides a qualitative description of thunderstorm structure, it is not susceptible to the kind of quantitative analysis that is needed for practical prediction of thunderstorm tracks. In an effort to derive a quantitative expression for the direction of movement of storms, Newton and Fankhauser examined them from the viewpoint of the supply and demand of moisture.

As a storm moves through the lower level air mass where most of the available water vapor is concentrated, it sweeps up moisture, a certain proportion of which they assumed to be converted into precipitation. Newton and Fankhauser hypothesized that the amount of water rained out is roughly proportional to the storm area and thus to the square of its diameter. The quantity of water vapor carried into the storm by low level winds is, however, directly proportional to the cloud's diameter. The vapor intercepted is also proportional to the relative velocity of the low level winds with respect to the storm. For the moisture supply to balance the loss by precipitation, this relative velocity must be greater in the case of a large than a small storm. The relative velocity is enhanced if the storm moves to the right of the mean wind direction and is diminished if it moves to the left.

Fankhauser and Newton found that a simple formula worked out from the above considerations fairly well describes the typical movements of storms, although in nature, considerable variation around this typical behavior is observed. Statistical analysis of a larger number of observed cases should make it possible to use probability theory to predict the likelihood that a given storm will move over a particular location. While crude in its present form, this concept represents a step toward the eventual development of a physical-statistical basis for short-period thunderstorm forecasting.

Out of Thin Air, the Earth's Highest Clouds

This summer in northern Sweden, Swedish and American scientists are sending Nike-Cajun rockets aloft to sample the ingredients of one of nature's most delicately beautiful and unearthly phenomena, noctilucent clouds. Indeed they *are* the most "unearthly" of terrestrial clouds, far higher than any others. When they were identified by the German scientist O. Jesse in the 1890s, their height, determined by triangulation, was scarcely to be believed. They were at approximately 80 kilometers (50 miles) altitude, where the atmosphere is 100,000 times thinner than at the surface.

Noctilucent clouds are so named because their delicate blues, whites, yellows and oranges are seen in the sub-arctic summer before and after midnight, when the sun has descended 6 to 15 degrees below the horizon, and the earth's surface, as well as the dust and clouds of the lower atmosphere, are in deep shadow. The clouds, often so tenuous that stars shine through them with scarcely diminished brightness, are marked by ocean-like waves and billows, and apparent speeds of the moving cloud banks have been estimated as high as 400 miles per hour. No wonder they have aroused the curiosity of scientists.

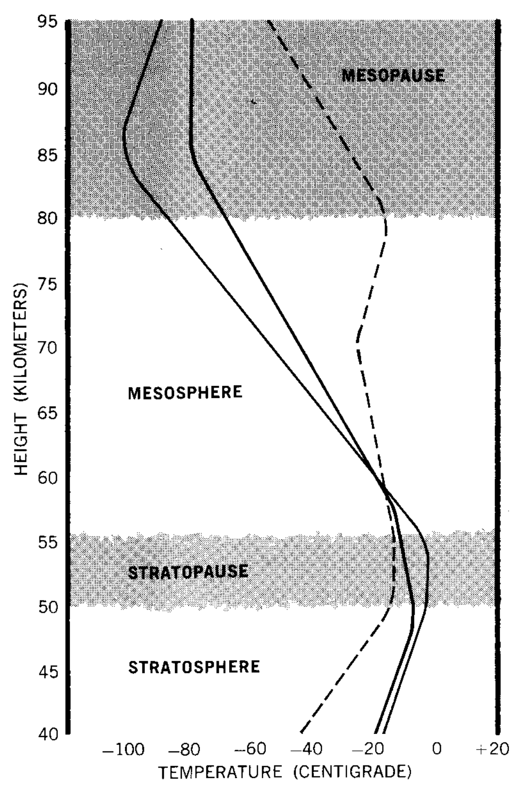
The rocket program, directed by Georg Witt of the University of Stockholm, C. L. Hemenway of the Dudley Observatory at Albany, New York, and R. K. Soberman of the Air Force Cambridge Research Laboratories, is designed to inquire further into the question of whether the clouds are formed of dry meteor dust or of ice crystals that have sublimated on meteor-dust nuclei, and to collect samples to determine composition. A positive determination of composition, however, would still leave many questions only tentatively answered.

It is a tribute to the power of scientific reasoning that despite the scarcity of direct high-altitude measurements, plausible tentative answers to these questions exist.

■ *Why are the clouds restricted to the 80-kilometer level?* This level is the top of the mesosphere. Below it, for 30 kilometers, the temperature drops very rapidly with increasing altitude until, at the top of this layer (the mesopause), temperatures are the lowest in the terrestrial atmosphere—often more than 100 degrees below zero Centigrade. Through this vertical region, air could rise (or sink) more easily than elsewhere in the upper atmosphere, especially in summer. Above this level, however, temperature stays constant for a few kilometers and then rises sharply (hence the name thermosphere). The effect is to put a "lid" on the rising air currents. Whether the clouds are dust or ice crystals, the 80-km level is the most favorable place for their formation—a zone where possible strong upward currents would abruptly stop, and where the extremely low temeratures can best induce sublimation of ice crystals from water vapor, if indeed sublimation is possible anywhere above the stratosphere.

■ *Why are the clouds seen only in certain latitudes?* Models of circulations at the mesopause indicate why. Such models are rather new, the first having been hypothesized in 1951 by W. W. Kellogg of UCLA (now of NCAR) and G. F. Schilling then of the University of Vienna and UCLA. A recent study by Adam Kochanski of the U. S. Weather Bureau, utilizing high-level winds calculated from radio meteor trails observed at Adelaide, Australia, and Joddrell Bank, England, as well as scattered rocket soundings, shows (1) extreme low mesopause temperatures near the summer pole, (2) a general area of low pressure at about 65 degrees from the Equator in the summer hemisphere, and (3) perhaps a series of low-pressure *cells* in this region. Jan Rosinski and Jack Pierrard of NCAR have commented that if these low-pressure cells exist, both particles of meteoric origin and any existing water vapor could tend to collect in them.

Most scientists thus believe that noctilucent clouds form only at these latitudes and only when all conditions are favorable. Several have pointed out that, though solar-terrestrial geometry limits possible viewing times at lower latitudes to only a few minutes (as compared with several hours in the sub-arctic summer), the times come at early, convenient hours. If the clouds form nearer the Equator, they should already have been observed.



Graph at left compares average mesospheric temperatures at high latitudes in summer (solid black), at high latitudes in winter (dashed), and at low latitudes (solid blue), where average temperatures tend to remain constant year-round. It appears that only in one region (in high latitudes at approximately 80 km altitude) and at one season (summer) are temperatures sufficiently cold (below −100°C) to allow currently estimated water vapor concentrations to condense into clouds.

■ *Are the clouds equally prevalent in the Southern Hemisphere?* Since there is virtually no land between 45 and 60 degrees in the Southern Hemisphere, the record of observations is understandably skimpy. A definitive answer to the question cannot be given without long, systematic observations. It is possible, however, to hypothesize that the clouds may not be as prevalent in the Southern as in the Northern Hemisphere. Building on the correlation proposed by E. G. Bowen of Australia between variable meteorite influx and world rainfall anomalies, Rosinski and Pierrard believe that, since the average number of meteorites entering the earth's atmosphere is low during the Southern Hemisphere summer, the rate of particle flux into the mesophere is also seldom sufficient to provide nuclei for significant numbers of noctilucent cloud droplets.

■ *Are the clouds dry meteoric particles, or ice crystals forming on such particles?* Before the first rocket soundings of noctilucent clouds in the summer of 1962, and even since, this question has aroused the most vigorous controversy. A most important bit of information has been, and still is, missing—the distribution of water vapor in the mesophere. If the mixing ratio of water vapor to air is constant throughout the layer from 30 km upward, then ice crystals cannot sublimate at the average temperature of the mesopause. There would be simply not enough vapor to freeze out at this temperature, even if there were freezing nuclei. But no one knows if the mixing ratio is constant, and there is now evidence that during periods of noctilucent clouds the temperature is colder than the average.

Until recently, the majority of interested scientists tended toward the theory that the clouds were dry dust held at the mesopause by upward convection. Among this majority were E. H. Vestine of the RAND Corporation, who wrote a classic paper on noctilucent clouds in 1934, and F. H. Ludlam of Imperial College, London, who published a comprehensive paper in *Tellus* in 1957. Scientists who have held the ice-crystal theory of formation include the late W. J. Humphreys of the U. S. Weather Bureau in the 1930s, I. A. Khvostikov of Russia in the early 1950s, and more recently, Eigil Hesstvedt, of the Institute of Meteorology of the University of Stockholm. Hesstvedt, writing in *Tellus* in 1961 and *Geofysiske Publikasjoner* in 1964, has argued for a higher water vapor mixing ratio in summer, based on a model of the general circulation proposed earlier by R. J. Murgatroyd and F. Singleton, of the British Meteorological Office; this would make ice formation at 80 km possible. Moreover, Hesstvedt offered a reasonable explanation of why the clouds seem more prevalent after midnight than before. As the sun declines late in the day, he said, the mesopause temperature begins to drop, and the ice crystals begin to form, continuing to grow during the night and attaining maximum size, and therefore maximum brilliance, in the hours just before sunrise.

The 1962 rocket soundings, as reported by Witt, Hemenway and Soberman at the Fourth International Space Symposium at Warsaw in June, 1963, successfully gathered particles near the mesopause, once when noctilucent clouds were present and once when they were not. Samples collected from the clouds contained particle concentrations 100 to 1,000 times greater than samples collected when no cloud was sighted. The larger cloud particles, captured on aluminum-nitrocellulose and calcium-nitrocellulose surfaces, had halos around them caused by the reaction of a volatile substance with the surface. The non-cloud particles showed no such halos. The three scientists concluded that the volatile substance was ice, and therefore that at least the larger particles gathered from the cloud had been coated with ice.

The origin of water vapor at the mesopause sufficient to form clouds has not yet been adequately explained. It is a question whether it is convected upward from below, as suggested by Hesstvedt, or is caused by chemical reactions at or above the mesopause, or both. The water vapor concentration may be increased by turbulent diffusion of oxygen and hydrogen compounds. A similar theory, that the water vapor supply at the mesopause is enhanced by the combination of hydrogen from the solar wind with atomic oxygen, has prompted Bernhard Haurwitz of NCAR somewhat jocularly to suggest that if that is the case, the

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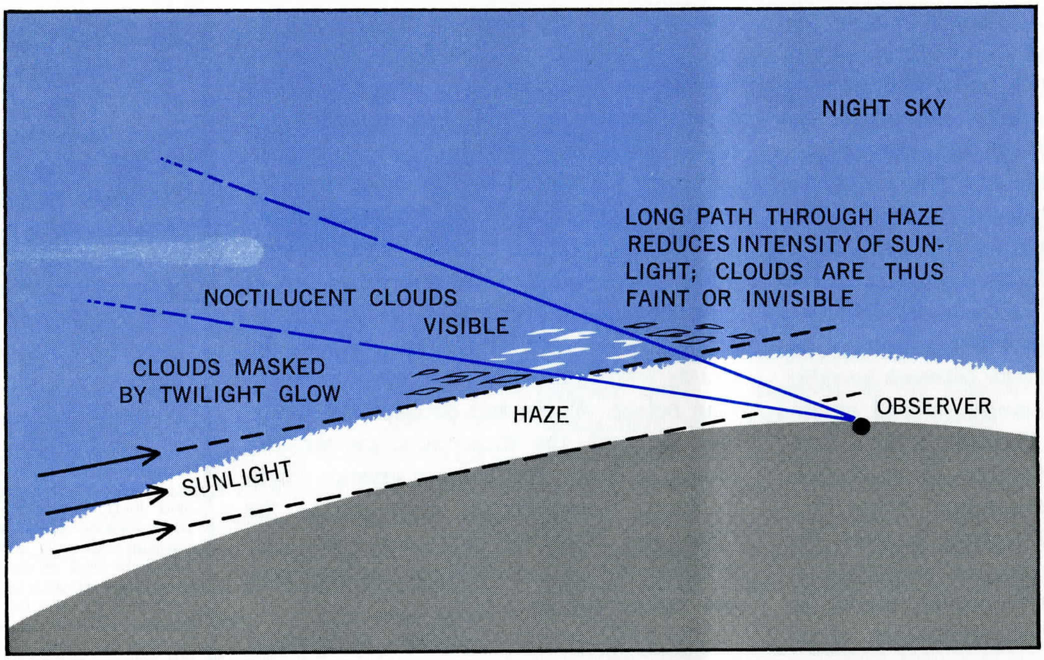
The National Center for Atmospheric Research was established in 1960 to conduct and foster basic research in the atmospheric sciences, to supplement and augment the research and educational programs of universities and research groups in the United States and abroad, and to work toward increasing the effectiveness of atmospheric research efforts as a whole. It is operated by the University Corporation for Atmospheric Research, a private non-profit organization, and sponsored by the National Science Foundation.

In pursuit of its goals NCAR seeks to develop interdisciplinary research programs across the broad spectrum of the atmospheric sciences; to develop major research facilities essential to national and international interests in the atmospheric sciences, and to carry on strong and continuous communications and cooperation with universities and the scientific community.

NCAR operates two laboratories, the Laboratory of Atmospheric Sciences and the High Altitude Observatory, and a Facilities and Administration division. The Center receives primary support from the National Science Foundation. Contracts, grants and gifts are also provided by other government agencies, and by individuals, corporations, and foundations, notably to the High Altitude Observatory by the Air Force Cambridge Research Laboratories, the Office of Naval Research, the National Aeronautics and Space Administration, and the National Bureau of Standards.



Geometry of noctilucent clouds is shown schematically at left, with the sun some 6 to 16 degrees below the horizon of the observer (black circle). The cloud displays are seen most often and appear most brilliant in the portion of the sky just above the twilight arch, both because of the geometry involved, and also because the cloud particles scatter light most efficiently in a forward direction.

solar wind might be renamed the "solar rain."

■ *What is the extent of cloud formation?* There have been some systematic observations of noctilucent clouds in Britain, Sweden, Russia, and the North American continent, and the most extensive attempt at synoptic-scale studies of the displays has been that organized in the past two summers by Benson Fogle of the University of Alaska. They are now believed to form over considerable distances, and on one occasion have been observed on the same night (July 3-4, 1959) from Russia, Scotland, and the St. Lawrence estuary. There have been hypotheses offered that the clouds tend to form in the low-pressure cells believed to exist in the high mesosphere, and a correlation has even been claimed for the formation of the clouds and rapid rises of pressure at the earth's surface. But this area of investigation is perhaps more tentative than any other concerning noctilucent clouds.

■ *Motions of clouds: waves and billows.* An equally puzzling piece of the noctilucent cloud mystery concerns the movement of entire cloud formations, and of waves and billows within the clouds. Apparent speeds of cloud displays have often been reported as exceeding 100, 200, and on one occasion, 400 miles per hour. No concept of mesosphere circulation, however, has indicated such tremendous speeds at corresponding latitudes, and the relation of apparent cloud movement to real wind speed is unsolved.

Within the clouds, there are waves and billows. Their definition and movement is often so pronounced that if a photograph is turned upside down, the cloud banks resemble the ocean surface. Haurwitz has shown that the hydrodynamics of a zone of atmospheric discontinuity like the mesopause, where radio meteor trails have indicated radical wind shears, can produce the wave motions observed, even when their motion is in a direction opposite to that of the whole cloud deck (as Hesstvedt observed in 1958). But no comprehensive description of the conditions that actually produce the waves has yet been advanced, and this probably awaits more detailed knowledge of various conditions at the mesopause, and a better theoretical explanation of the complex internal gravity waves in the upper atmosphere that are probably also involved.

Research results on noctilucent clouds, and on the mesosphere in general, are so tentative that it cannot be predicted whether further investigation of the clouds will contribute significantly to our knowledge of the upper mesosphere, or whether a conclusive explanation of why the clouds form as they do must await greater knowledge of the composition and dynamics of the region as a whole.

Notes

Aviation Facility Assists Cloud Studies

The NCAR Aviation Facility has undertaken its first operational activities at Key West, Florida, this summer in support of J. Doyne Sartor of NCAR and Dr. Stig Rossby of the University of Wisconsin. Sartor's program to record radio emissions from clouds, described in the April *NCAR Quarterly,* and the Rossby program of recording sferics created by thunderstorms complement each other and are being pursued concurrently from June through mid-August with the Aviation Facility's recently acquired Beechcraft Queen Air 80.

Establishment of the Aviation Facility at NCAR, following a recommendation of the NCAR National Aircraft Survey Group, was described in the last issue of the *Quarterly.* An Advisory Panel was appointed in April to assist NCAR in developing policies governing the use of the Facility by the scientific community and to establish priorities among the various requests for Facility support. Members of the Panel, which held its first meeting in Boulder on May 7 and 8, include:

Dr. Roscoe Braham, Jr., Panel Chairman, Department of Geophysical Sciences, University of Chicago;

Dr. Robert A. Ragotzkie, Panel Vice-Chairman, Department of Meteorology, University of Wisconsin;

Dr. Charles E. Anderson, Atmospheric Sciences Branch, Douglas Aircraft Company;

Dr. Fred C. Bates, Department of Geophysics and Geophysical Engineering, Saint Louis University;

Dr. Armin J. Deutsch, Mount Wilson and Palomar Observatories;

Mr. Cecil Gentry, National Hurricane Research Project, U. S. Weather Bureau;

Dr. Herbert Riehl, Department of Atmospheric Science, Colorado State University.

Support for the University of Wisconsin program was approved by the Panel in early June and operations commenced at Key West almost immediately. Rossby's long-term objective is to measure thunderstorm distribution over the earth with instrumentation to be flown in a satellite. The immediate objective is to determine the characteristics of sferics emitted by large scale thunderstorms. Equipment to record such radio emission can then be developed for use on the satellite.

In addition to field support of NCAR and university research programs, the Aviation Facility is beginning research on a variety of aircraft instrumentation problems. It also plans to serve as a center for exchange of information among scientists interested in the use of aircraft for atmospheric research.

Radar Support Group Established

Radar has been increasingly recognized since World War II as a highly effective and versatile tool for exploring the atmosphere. NCAR scientists working on problems of atmospheric electricity, cloud physics, stratospheric circulation, atmospheric physics and synoptic meteorology all have research goals that can be approached with appropriately designed radar equipment. In addition, the NCAR Balloon and Aviation Facilities require radar support from time to time.

A group of NCAR scientists making up the Facilities Advisory Board recommended in January 1964 that the NCAR Facilities Division provide a central source for procurement, modification and maintenance of radar systems for internal use in NCAR's research programs. To meet these needs as rapidly as possible, NCAR has acquired four obsolete Army M-33 radar sets with an estimated useful life of three years. Under the direction of Jack D. Tefft, these sets are being modified for specialized research objectives.

With the cooperation of the National Science Foundation and the General Services Administration, NCAR has procured additional spare components for the sets, making it possible to extend their useful life to at least five years. NCAR is also serving, at the request of the NSF, as an outlet for spare parts to other scientific users of M-33 radar systems. First priority is given to NSF-sponsored radars, but service is also extended to other research groups using this type of equipment when parts can be made available. There are fourteen groups around the country operating M-33 radar, nine of them associated with universities.

The radar group is currently providing support to two NCAR scientific programs, under J. Doyne Sartor and Dr. Patrick Squires, and to a University of Wisconsin project under Dr. Stig Rossby (see above). In 1963 Sartor's atmospheric electricity group found, through laboratory studies and preliminary flights at Key West, Florida (see *NCAR Quarterly,* April 1964), that growing cumulus clouds produce radio emissions even when they are in a completely liquid state. During the summer of 1964, Sartor has been collecting further data on the radio emission from developing cumulus clouds, and simultaneously on the ambient atmosphere, while circling the periphery and flying "over the tops" of the clouds. The M-33 radar used in these studies has an operational computer, tracking system, and horizontal and vertical plotting boards.

During the coming winter Sartor plans to use an M-33 for studies of blowing snow-electrification at a site on Niwot Ridge near Ward, Colorado.

The cloud physics group under Squires is using another M-33 set for preliminary studies of thunderstorms in its program to develop dropsondes for measuring temperature, pressure, and humidity within such storms. This radar set is being operated during the summer in cooperation with Colorado State University at a site near Fort Lupton, Colorado. The system has a 10-centimeter radar which can be used for cloud measurements, and a 3-centimeter radar which can be used simultaneously for tracking research instrumented aircraft. Dr. Robert H. Bushnell in Squires' group will use the set to obtain measurable photographic records of thunderstorm characteristics as shown by radar echoes.

For use in conjunction with the M-33 radar on Bushnell's and other projects, NCAR is also acquiring a precision 12-foot, horn-fed, parabolic antenna. It will have a 2-degree pencil beam, and side lobes more than 30 decibels below the maximum power density in the frequency range of 3400 to 3420 megacycles per second measured with one-way transmission. This antenna can be disassembled, moved, and reassembled to meet the original specifications without adjustments requiring electrical measurements.

NCAR Begins Advanced Studies Program

An Advanced Studies Program was initiated on July 1 under the direction of Dr. Philip D. Thompson. Major elements of the program are:

Seminars and informal discussions conducted by senior scientists of the resident and visiting staff will, it is hoped, help identify or further define significant problems in the atmospheric sciences. Ragnar Fjortoft, Director of the Norwegian Meteorological Institute, who is on a year-long visit to NCAR, Bernhard Haurwitz, and Thompson will conduct seminar series during the first year. Members of the NCAR scientific staff and visiting scientists will also participate in the seminars;

Scientists who have recently completed their doctorates, or who are pursuing a new interest in atmospheric problems, will also join the program on one- or two-year appointments. The first of these are William Blumen, University of Oslo (Norway); Dieter Ehhalt, University of Heidelberg (Germany); and Jack W. Powers of the Department of Chemistry, Ripon College, Wisconsin;

Working groups of invited scientists will join with members of the NCAR staff for periods of a few weeks to a few months to probe a specific problem or research area, with the aim of planning an informal but concerted attack on the problem after the members of the group return to their home institutions. Subsequent meetings may follow. The first working group is expected to be formed next summer.

Thompson will continue to coordinate other aspects of the NCAR visitors program and to administer the UCAR Fellowship Program.

Kellogg Appointed Associate Director

This month Dr. William W. Kellogg joins the NCAR staff as Associate Director. He will serve as Director of the Laboratory of Atmospheric Sciences, taking over from Dr. Philip D. Thompson who has assumed organizational responsibility for a special program of advanced studies in NCAR.

Kellogg comes to NCAR from the RAND Corporation in Santa Monica, California, where he was head of the Planetary Sciences Department. He has participated in planning for rocket and satellite observational programs as a member of the Space Science Board and other committees and panels of the National Academy of Sciences, the National Aeronautics and Space Administration, the World Meteorological Organization and other scientific groups. His research has included studies of radioactive fallout, stratospheric turbulence and general circulation theory. His special scientific interests are in dynamics and chemistry of the upper atmosphere and the atmospheres of Mars and Venus. He received his A.B. from Yale in 1939 and obtained his Ph.D. in meteorology from the University of California at Los Angeles in 1949.