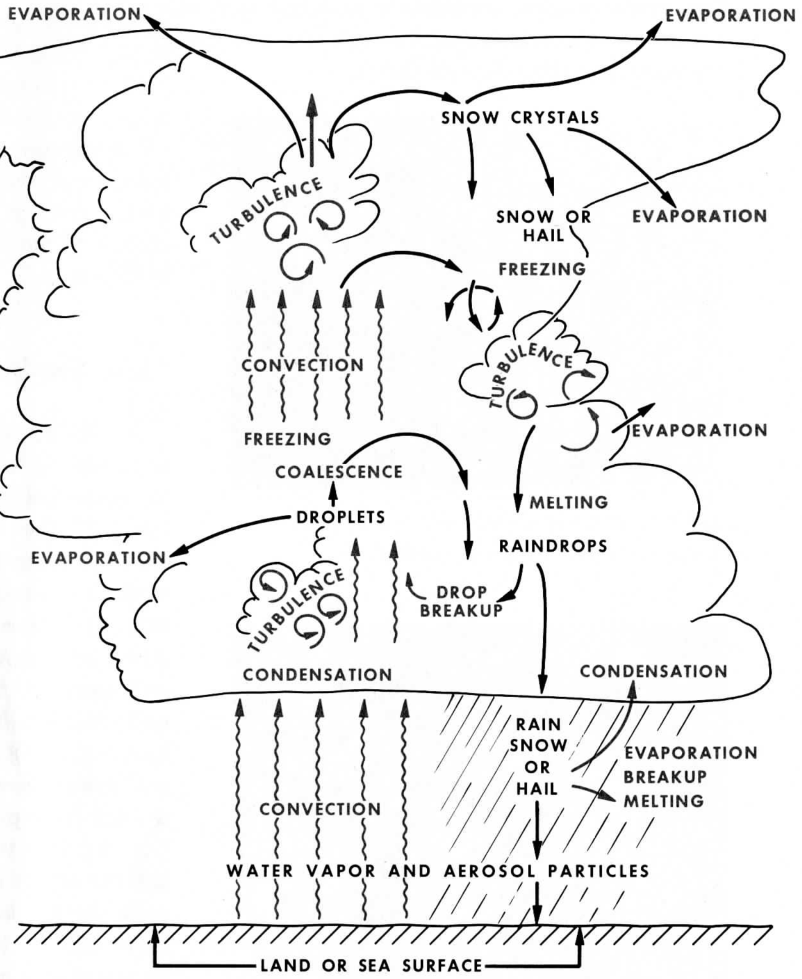
NCAR Quarterly
No. 30, February 1971

The Dynamics of Convection



In the lower atmosphere, which receives most of its heat from the land-sea surface on which it rests, the dominant process of heat transfer is convection. Shimmering air above hot pavement, cloud towers piling up on summer afternoons, invisible thermals rising over deserts or tropical islands, and the widespread upward movement of summer-heated air over central Asia that brings monsoon circulation to India and adjacent areas are all recognized as convective processes. All contribute to the mixing of warm and cold air that is an essential feature in distributing heat through the horizontal and vertical dimensions of the troposphere.

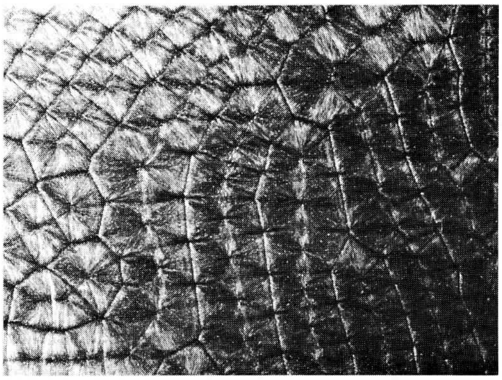
Field Observations and Laboratory Models

Convection can of course be studied in the atmosphere itself. In field experiments during the last few years, surface and aircraft observations have furnished many details of convective processes in hurricanes and small, severe convective storms such as hailstorms, thunderstorms, and tropical squalls. Convective circulations near large bodies of water and over islands and deserts have also been studied, as have invisible convective "bubbles" or "plumes" occurring in clear, dry air.

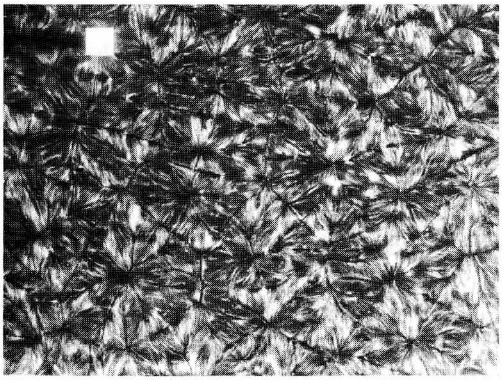
Laboratory models of thermal convection increase our understanding of some of the fine features of convective processes. Principal among laboratory models are parallel plate

A parallel plate model shows the development of turbulent convection. This model uses silicon oil, a moderately viscous fluid; graphite flakes in the oil bring out flow patterns.

Soon after onset of convection the dominant convective pattern is of long rolls or roll segments.



As the temperature difference between plates increases, a cross-roll pattern develops.



With further increase in the temperature difference, regular convective patterns break up, and flow becomes chaotic and turbulent. The white square shows the thickness of the fluid.

experiments, in which two horizontal plates are arranged a few centimeters apart. The lowermost plate is heated, and when the temperature difference between the two plates reaches a critical point, a regular pattern of convective rolls or cells develops in the air or fluid between the plates. Then, as the temperature difference increases, or as the plates are further separated, convective patterns become unsteady and less predictable, and the motions tend to lump together to create irregular, buoyant plumes and bubbles of heated air much like the thermals that occur in the atmosphere.

Laboratory studies have also been extended to experiments in which convection developing in one layer of a fluid penetrates overlying stable layers, exactly as rising convective currents in the atmosphere penetrate into stable atmospheric layers.[1]

However exciting or accurate these physical laboratory models may be, they cannot relate the development of convection to larger scale features of the environment. They do, however, serve as guides which reflect some aspects of the physical processes that function in nature.

Numerical Models

A fuller understanding of convective processes is now sought from numerical or mathematical models incorporating the conditions of the environment and the energy conditions involved in convection. Convection is characterized by such a complexity of interacting processes that it must be broken down into component parts, which can be analyzed and modeled individually, before it can be understood in its entirety. The distribution of heat and moisture, heat conduction, collision and coalescence of moisture droplets, energy derived from phase changes of water, coagulation, the effects of turbulence and wind shear, and the earth's rotation must all be considered individually before equations representing them can be brought together into a truly representative numerical model.

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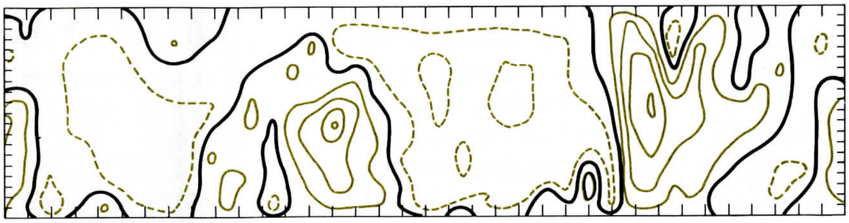
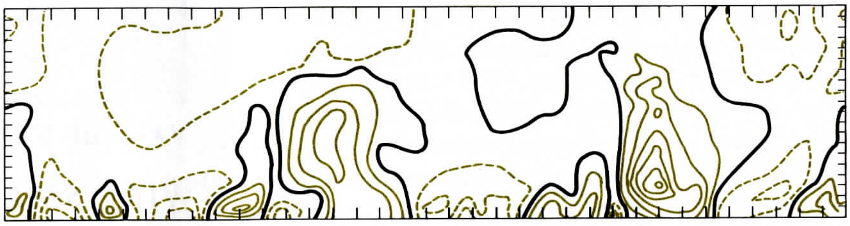
[1] Atmospheric scientists refer to stable air as air which resists vertical movements because the lower layers are denser (colder or dryer) than the overlying air. Unstable air tends to overturn because the lower layers are potentially less dense (warmer or moister) than the overlying air.



a VERTICAL VELOCITY



b POTENTIAL TEMPERATURE DEVIATION

One vertical plane from Deardorff's three-dimensional model shows the patterns of vertical velocity and temperature that develop in a strongly unstable planetary boundary layer.

a. Black lines separate areas of strong upward motion (solid green contours) and weaker downward motion (dotted green contours).

b. Temperature fluctuations are indicated for the same time and place. Solid green contours indicate warmer-than-average areas; dotted contours show cooler-than-average areas.

Three three-dimensional models developed by James Deardorff at NCAR illustrate the evolution of mathematical models of this kind. Deardorff first modeled plane Poiseuille flow, the turbulent flow that develops in a fluid moving between two fixed plates. Laboratory experiments show that eddies of various kinds originate in such flow; Deardorff's numerical model, based on the three equations of hydrodynamic motion and continuity, supported the laboratory findings and yielded a wealth of data on the generation of individual eddies and their actions and interactions.

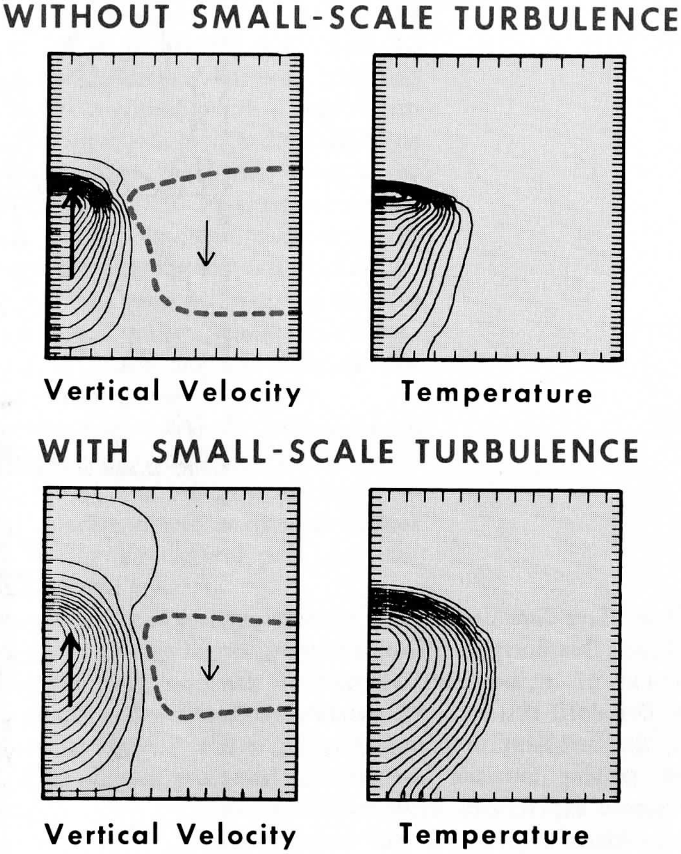
From these studies, Deardorff went on to simulate conditions in the planetary boundary layer, the lowest 1,000 m of the atmosphere, where flow similar to Poiseuille flow is influenced by the earth's rotation. This model used the same three equations, but also included terms related to the rotational forces, as well as different upper boundary conditions.

Then, to simulate convective effects, Deardorff introduced two more factors: heating at the lower surface of the model, and an equation for the conservation of heat. Working with this model, he found that even very small amounts of heating change the nature and structure of the simulated boundary layer, and that the model simulates quite effectively many of the eddies and much of the turbulence observable from balloons and from aircraft flying through dry thermals or below cloud base.

Deardorff's models considered only the convection caused by initial heating at the base of a parcel of air, and did not go into the complications caused by moisture condensation in that parcel. Hence they may be called "dry" models. Other dry models are being developed at NCAR by Douglas Fox and Ronald Drake. In Fox's model, a parcel of air heated at the bottom is allowed to develop free of any boundary effects. Equations representing the changes of mass, buoyancy, and three-dimensional momentum of the parcel (equations similar to those used by Deardorff) are integrated over a volume representing an individual convective plume or bubble and its surroundings. The largest scales of turbulence develop naturally from instabilities in the plume or bubble. Turbulent motions on scales smaller than the spatial resolution of the model cannot be explicitly represented, but their most important interactions with the larger scale motions are included.

Many features shown by Fox's mathematical model are closely similar to those developed in laboratory models; numerical simulation of simple laboratory models is an important step toward understanding the more complex convective situations found in nature. One of the problems encountered in Fox's model is that the length scale of the motion grows continuously, and sooner or later the individual thermal exceeds the size of the numerically stipulated container. This problem can be lessened by allowing the simulated container to expand along with the thermal. Another problem is that of computer capabilities: with models in three dimensions the size of the air parcel that can be modeled or the resolution of the model is limited by the size and speed of the computer. A Control Data Corporation 7600 computer, to be installed at NCAR in 1971, will increase present capabilities by a factor of about five, permitting considerably improved models.

Working with Steven Orszag, Fox is now studying an alternative method for modeling convection. Instead of using the so-called finite difference technique, in which computations are carried out at a multitude of individual grid points, Fox and Orszag use a spectral representation of the equations involved. Recent developments in mathematics indicate that this method, originated by Fourier in the early 19th century for



WITHOUT SMALL-SCALE TURBULENCE

Vertical Velocity **Temperature**

WITH SMALL-SCALE TURBULENCE

Vertical Velocity **Temperature**

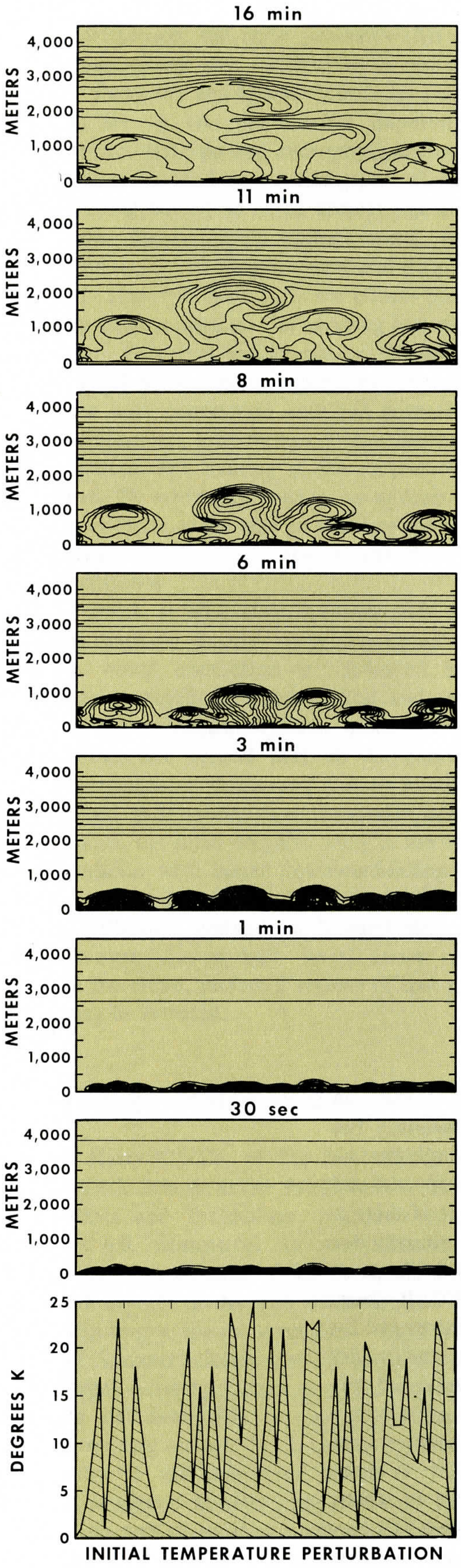
Fox's model shows strong upward motion and increased temperature within a single thermal. With the addition of parameters representing small-scale turbulence, the shape of the thermal changes.

studies of periodic phenomena, gives promise of markedly improving the accuracy and efficiency of simulations of turbulence and large-scale motions.

Coalescence of Thermals

As a further step in the development of models of convection, Drake has developed a two-dimensional model of convective thermals or plumes as a key to understanding the patterns established in nature by coalescing thermals. Convection is initiated by uneven heating along the base of his model; this causes a number of convective plumes to form. As these plumes develop they merge with each other until eventually one large thermal has effectually absorbed the others. The large thermal rises high enough to penetrate a stable overlying layer in a manner that seems similar to natural cloud development, or at least to development of large thermals below cloud base.

By portraying a cross section of heating patterns similar to those that might occur in nature, Drake has used his model to show how circulation develops near a cool lake: as thermals develop over the lake, and spread out below a stable layer, a circulation cell is set up; wind shear develops over the adjacent warmer land surface, closely paralleling lake breeze circulations observed in nature. Drake plans to extend the lake breeze aspect of his study to an analysis of circulation patterns in the Lake Ontario region, in connection with a Colorado State University research program there during 1971.



When heating at the base of a model is uneven, as in Drake's model, resulting thermals are of different sizes. They coalesce as they rise, and spread out when they reach a stable layer. (Sequence reads from bottom to top.)

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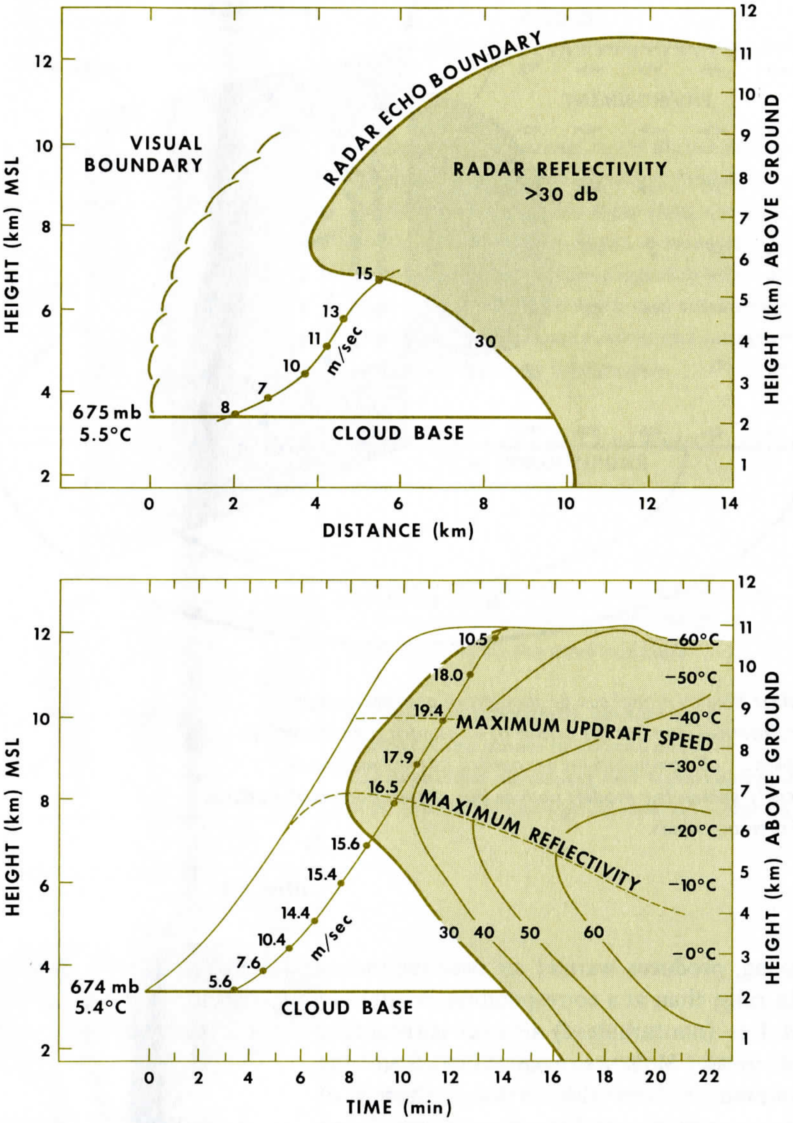
Modeling Moist Convection

In nature, the dynamic aspects of convection, discussed in the previous article, are often closely interwoven with microphysical aspects having to do with the effects of moisture: evaporation, condensation, freezing and melting, and the collision and coalescence of moisture droplets. Purely dry models of convection sometimes portray rising convective air as assuming a mushroom shape, a picture rarely seen in nature. When moist air rises, condensation releases latent heat, reinforcing the upward movement of the air parcel. Field studies have shown that the latent heat released during phase changes of water is a major driving mechanism——perhaps the dominant one——in large convective systems.

To simulate large convective clouds, an NCAR group led by Edwin Danielsen has devised several models which emphasize the microphysical processes involved in rain and hail growth in cumulus clouds. One of these, a simple steady-state model used primarily for predictions in the National Hail Research Experiment, was described in NCAR *Quarterly*, No. 25, November 1969. Developed by Danielsen and Philip Haagenson, this model has the advantage of computational speed, but it lacks an accurate specification of raindrop and hailstone size. A more realistic model developed by Rainer Bleck is a time-dependent one-dimensional model in which hydrometeors (water droplets and ice particles) grow by condensation and random coalescence, the same processes that govern hydrometeor size distribution in real clouds.

Danielsen and Donald Morris are using this model to test the relative importance of several dynamic and microphysical factors on the production and modification of hail. By varying the initial cloud droplet size distribution, the maximum updraft speed, and the probability of drop freezing and drop breakup, they can determine the effects produced by each process on the evolving hail distribution. Danielsen and Morris are extending this model by including continuous solutions of the heat conduction equation governing the sublimation, evaporation, temperature, water content, and melting of the ice particles and hail. By arbitrarily pulsing the updraft speed, they hope to be able to simulate the layered structure that is often observed in large hailstones.

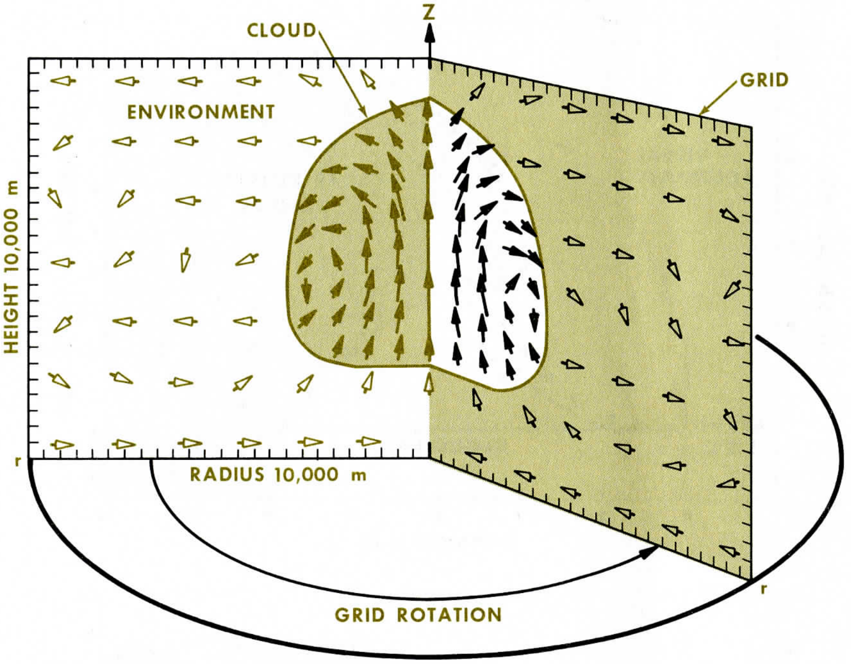
Bleck is now experimenting with a two-dimensional axially symmetric cloud model in which convection is reinforced by the heat released by condensation and freezing of water drops. Upward motion develops within the central part of the cloud, and compensating downward motion outside the cloud, as in nature. As in the models described above, the small droplets rising in the updraft coalesce with larger downward-falling water drops and hail, so that the hydrometeor distribution changes with each time step. Because the updraft speed varies radially in the cloud, preferred regions of hail growth may be revealed.



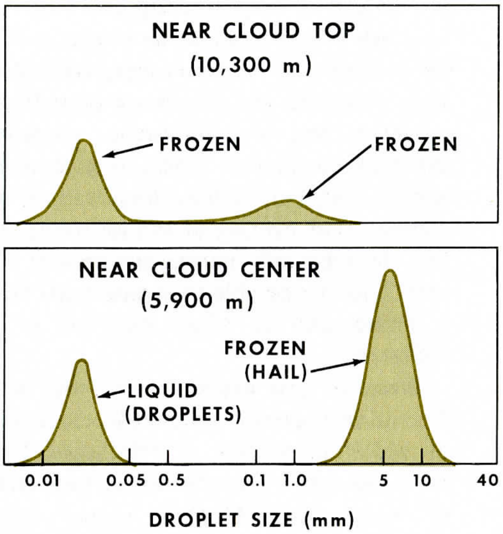
A model developed by Danielsen and Morris simulates many important aspects of an actual hailstorm. In a real storm (above), vertical velocity was measured by aircraft, and hydrometeor distribution by radar. Below, the model replicates these and other features of the storm. Perhaps the most startling result shown by the model is that hail develops and grows beneath the level of maximum updraft speed.

Clouds over Mountains

Harry Orville, of the Institute of Atmospheric Science at the South Dakota School of Mines and Technology, has been using the NCAR computer to work out a two-dimensional model which combines many of the aspects of dry and moist convection. By selecting a special situation––the formation of summer clouds over a linear mountain ridge––and treating it in considerable detail, he has been able to simulate nature with surprising realism. In his model, the mountain ridge is the important factor in reducing atmospheric stability, and therefore in initiating and stimulating convection. Heat from the sun, which causes near-surface turbulent



Rainer Bleck's model can be thought of as representing a cylindrical cloud at the center of a cylindrical environment. However, all computations are carried out in one plane. Axially symmetric models such as this cannot portray the effects of shearing winds.



Bleck's model shows the amount and distribution of hydrometeors 25 min after cloud formation.

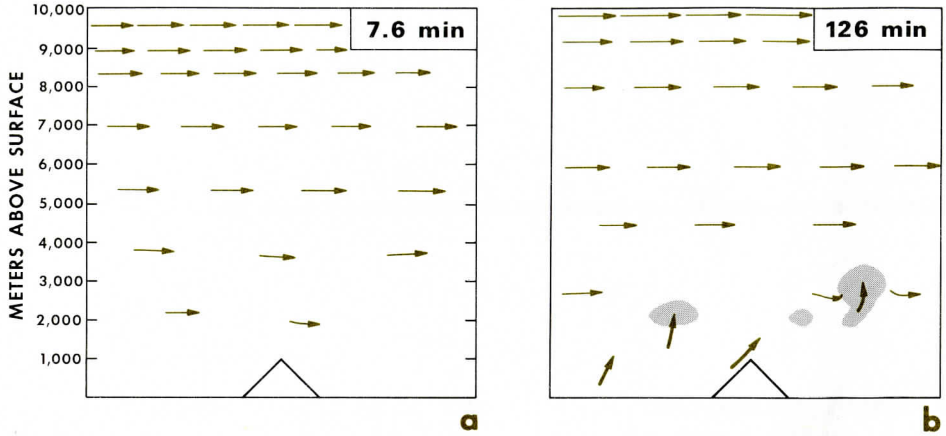
mixing, produces warmer air near the mountain ridge than at a corresponding elevation in the free (nonturbulent) air over surrounding flat areas. Moisture evaporating from the mountain surface adds to the buoyancy of this warmer air, and a rising plume forms above the mountain. If moisture conditions are right (they can be varied within the framework of the model), a cloud forms. It casts a shadow, cooling the surface realistically and interrupting the cloud-forming process. A new cloud forms as the first one drifts away.

Eventually, in Orville's model, a cloud forms that is large enough to produce rain. As the rain falls, added evaporation (and therefore cooling) alters conditions in the lower atmosphere and at the ground surface.

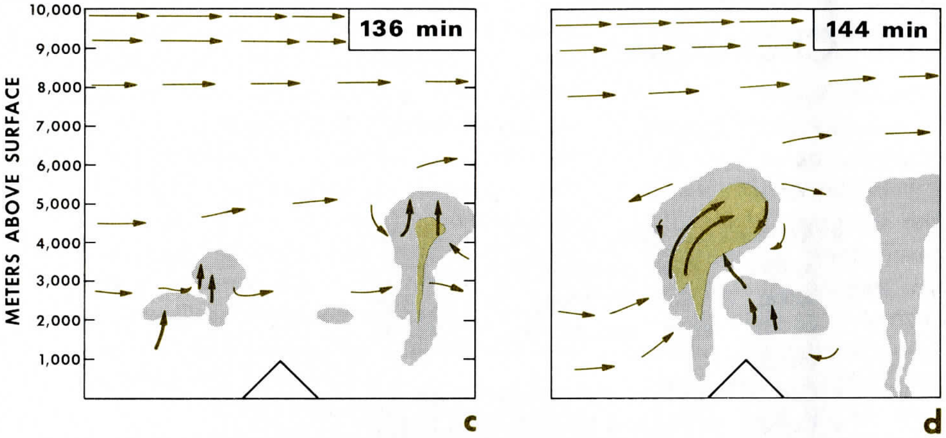
A model such as this, with its realistic values, may be of practical use in evaluating attempts to modify weather. The model may show, for instance, whether seeding under certain conditions will increase the likelihood of rain or will suppress hail, or whether it will bring about so much latent heat release that the cloud will build upward rapidly and develop a larger anvil without immediately releasing moisture.

A Combined Approach

Most present models of convection either consider cloud dynamics and ignore cloud microphysics, or concentrate on microphysics and simplify the dynamics. Eventually, to obtain a truly accurate description of convective processes in the atmosphere, these two approaches must be combined. Newer, larger computers, and continued development of refined computer techniques, will ultimately make it possible to incorporate all the important dynamic and microphysical variables involved in convection into one model. Such a model could be used as a departure point for relating convective models to models of the general circulation, and could contribute in important ways to long-range weather prediction.

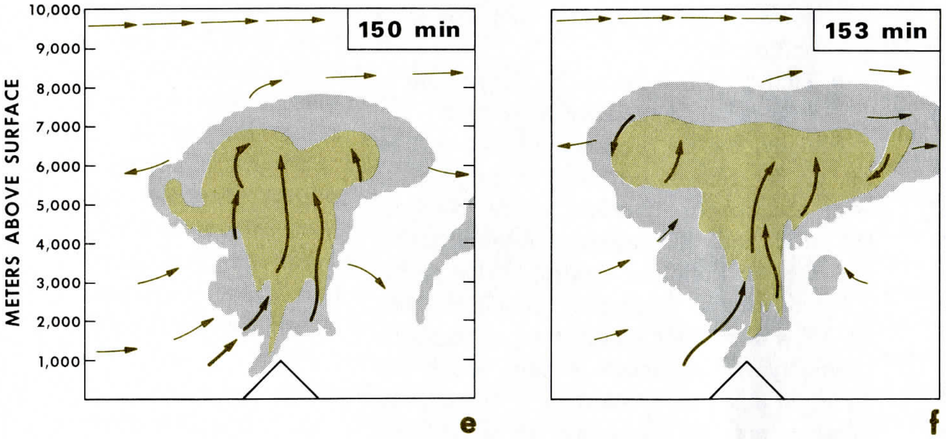


Orville's two-dimensional model illustrates the life history of a summer rainstorm forming in conditions somewhat like those along the east front of the Rocky Mountains. A mountain ridge 1,000 m high projects into a region in which ambient winds blow from left to right, their velocity increasing with height. Water vapor content and temperature (not shown) decrease with height.



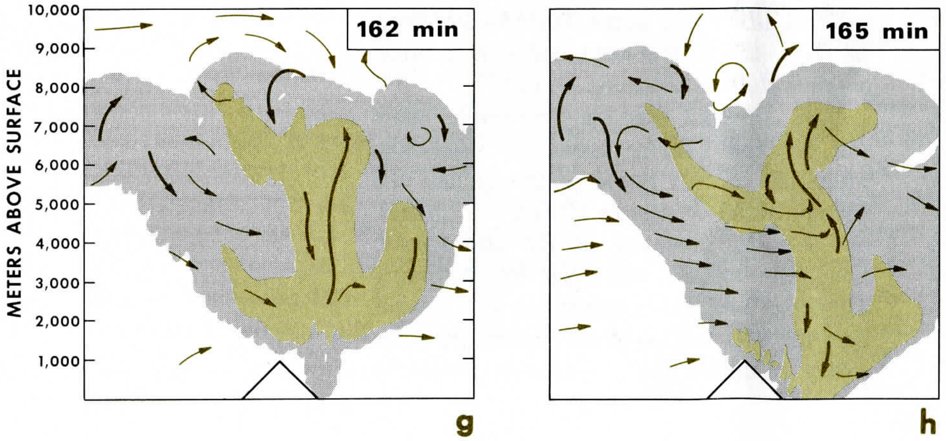
As the first clouds drift away, others develop. Some coalesce into masses large enough to form rain; notice the small rainshaft.

Updrafts and downdrafts, calculated by computer, are shown by colored arrows. The large cloud developing here ingests adjacent small clouds and develops an especially large rainshaft.



The cloud top flattens out at about 8,000 m above the surface, where it meets the temperature inversion at the top of the troposphere.

The rainshaft develops two prongs, one on each side of the strongest updraft region. Rain evaporates before reaching the ground.



Delayed by strong updrafts, rainfall finally reaches the ground.

Computer data show that 7 - 8 mm of rain reached the ground during this storm.

Monitoring Atmospheric Chemicals

What is happening to the chemical composition of the earth's atmosphere? Are any long-term changes taking place on a global scale? How will these changes affect the world in which we live?

Atmospheric chemists find they cannot give certain answers to these questions because adequate data have never been collected. Although the atmosphere has been sampled at many places and at many altitudes, only recently have we developed an ability to sample and measure many of the trace substances that are present in the atmosphere in extremely small quantities. Trace gases and trace particles, some of which come from natural sources such as volcanic eruptions and jungle decay, some from activities of man, may cause critical atmospheric changes over long periods of time.

Richard Cadle and other atmospheric chemists at NCAR have initiated a cooperative program to monitor trace constituents at a number of widely scattered stations. Six proposed sites—all well away from major sources of pollution—are in Colorado, Alaska, Hawaii, Antarctica, the Amazon jungle in Brazil, and an as yet unselected low Pacific island. Stations established at these sites will be the first of an expanding world network, and will test and use a comparatively simple, dependable installation to automatically collect and analyze such trace consituents as:

- Atmospheric particles
- Atmospheric gases that play a role in producing these particles: hydrocarbons, sulfur dioxide, hydrogen sulfide, ammonia, ozone, and various oxides of nitrogen
- Carbon monoxide and carbon dioxide
- Certain chlorinated hydrocarbons which come from insecticides and industrial pollutants
- Turbidity, as measured by the amount of solar radiation reaching the surface

Initially, the six proposed stations will be set up by NCAR, probably in cooperation with atmospheric chemists at the National Oceanic and Atmospheric Administration and the Air Pollution Control Office of the Environmental Protection Administration. NCAR is developing a prototype atmospheric chemistry reconnaissance station, which will be tested this year in Colorado. Eventually the network may be taken over by some international group such as the World Meteorological Organization, and expanded into an international global monitoring system.

Data collected over the first several years will establish baseline levels for substances which are not yet global pollutants, and will also be useful as sources of data for research on chemical processes in the atmosphere. Long-term records will assist in identifying dangerous increases in substances which could alter the heat balance of the atmosphere or its ability to support life.

Notes

UCAR/NCAR GARP Initiatives

Planning for the Global Atmospheric Research Program (GARP)[1] continues on an international scale. During 1970, at meetings held in Brussels (March) and London (July), the U.S. Committee for GARP spoke out strongly for broad international participation, and tentatively committed the United States to contribute scientific and engineering manpower, observational tools, ships, aircraft, satellites, and expanded computational facilities for data compilation and mathematical modeling.

The U.S. GARP Committee of the National Academy of Sciences has developed general concepts of U.S. participation in the international effort, and has asked NCAR to support GARP initially in two specific ways: by establishing means whereby university atmospheric scientists can become actively and effectively involved in GARP, and by providing detailed scientific advice for GARP, in particular for the first large GARP field experiment, which will be conducted in the tropical Atlantic area in 1974.

UCAR and NCAR, on behalf of the 31 UCAR member universities, have established three mechanisms by which university and NCAR participation in GARP can be furthered:

- A UCAR GARP Council, composed of one scientist from each member university. This council will serve as a communication channel insuring that information about GARP opportunities and needs are effectively disseminated to the U.S. academic community and that the views of university groups are effectively injected into U.S. GARP plans. The Council will also help marshal university participation in various research tasks required to keep GARP on schedule, and will advise the UCAR leadership on GARP-related matters.
- The NCAR GARP Task Group, appointed by the Director of NCAR. This group will serve as an integrating focus for all of NCAR's GARP-related work. It will take the initiative in identifying problem areas—–both scientific and developmental—–that threaten to hinder the progress of GARP. The group will maintain an up-to-date schedule of GARP plans at the international, national, and university levels, in order to furnish UCAR with a realistic view of the costs and logistics of various GARP efforts and to identify decision points and alternate strategies.

John Firor, Director of NCAR, has appointed the following NCAR staff members to the Task Group: Daniel F. Rex (chairman), Edward J. Zipser (chief scientist), Paul R. Julian, William S. Lanterman, Cecil E. Leith, John E. Masterson, T.H.R. O'Neill, Stanley Ruttenberg, and Henry van de Boogaard. Visiting scientists and postdoctoral appointees who have research interests in GARP will also participate in Task Group work.

- NCAR GARP Ad Hoc Working Groups, appointed by the President of UCAR. These action-oriented groups, consisting of NCAR and university scientists interested in GARP research, will develop plans for attacking problems in areas identified by the NCAR Task Group, and will in turn identify the university scientists or scientific groups qualified to carry out the plans. (Ideally of course the Working Group members will participate in the work themselves.) The product of a working group will be a joint proposal or several related proposals by interested scientists to accomplish the body of research required to keep GARP on schedule.

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[1] See NCAR *Quarterly* No. 21, November 1968; and No. 26, February 1970.

Notes

NCAR Publication Award

The NCAR Outstanding Publication Award for 1970 was presented to Charles and Nancy Knight of the Laboratory of Atmospheric Science for their three papers on the structure, growth, and behavior of hailstones, published in the July issue of the *Journal of Atmospheric Sciences*. Honorable Mention was extended to James Deardorff for an article on his numerical model of turbulent channel flow, and to Traugott Scholz, Dieter Ehhalt, Leroy Heidt, and Edward Martell for a coauthored paper on stratospheric water vapor, hydrogen, methane, and tritium.

The St. Louis Study

During the next few years NCAR will participate in a large-scale cooperative program centered at St. Louis, Missouri, to study the impact of a large city on the atmospheric environment. St. Louis, which as a city is neither outstandingly polluted nor exceptionally clean, has been selected for this study partly because earlier research on air quality and pollution there is available for comparison, and partly because the geography of the area is relatively uncomplicated, with no large topographic features to affect the motions of the atmosphere and no other nearby metropolitan areas to confuse the pollution picture.

The St. Louis Study will involve scientists from the Air Pollution Control Office of the Environmental Protection Administration, NOAA, the Illinois State Water Survey, the University of Chicago, the University of Wyoming, Argonne National Laboratory, NCAR, and other groups. First emphasis, during 1971, will be on an analysis of pollution-related rainfall patterns in the vicinity of the city. Later portions of the study will define the total impact of various pollution sources on the urban environment and its surroundings, and determine the effectiveness of control technology in safeguarding air quality in cities and in adjacent agricultural, forested, and recreational areas. At the same time the program will provide an opportunity for perfecting instruments and techniques for measuring and monitoring pollution, and for devising mathematical models to simulate and predict the processes and interactions involved in urban and regional pollution.

NCAR's part in the St. Louis study will be an analysis of the pollution that remains in the atmosphere some distance downwind from the city itself, thus identifying those pollutants which have long enough lifetimes to threaten the quality of the atmosphere on a continental or global scale. The major active phases of NCAR's program, directed by James Lodge and John Pate, will take place in the summer of 1973 and the winter of 1973-74. During short periods of intensive sampling, coordinated observations will be made from a network of movable ground-based monitoring stations and instrumented aircraft; data and samples will be collected from the plume of pollutants 80 - 120 km downwind from the city. The program will be supported by NCAR's Field Observing and Research Aviation Facilities, and by temporary field crews. Data reduction is expected to extend through 1975.