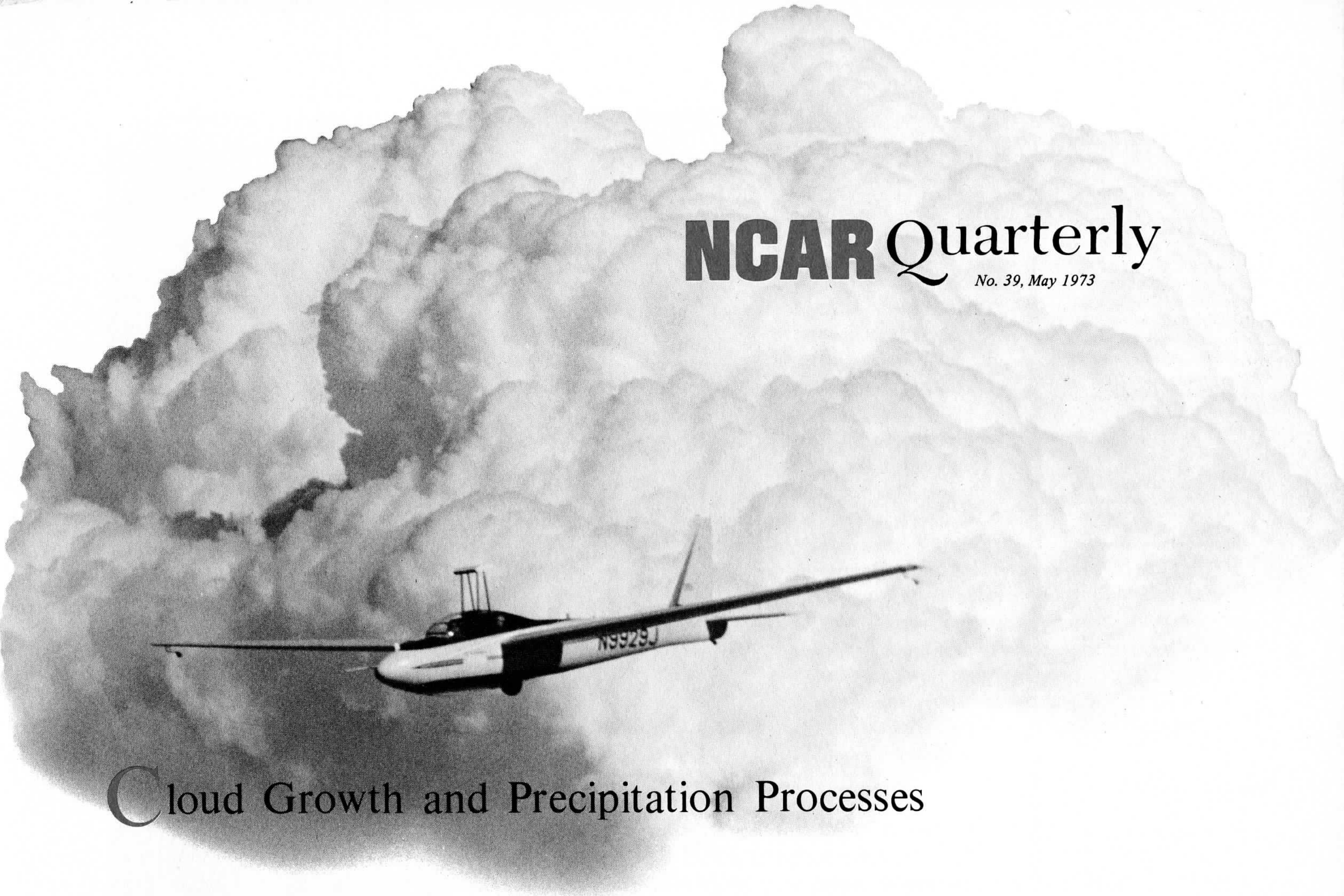


NCAR Quarterly
No. 39, May 1973

Cloud Growth and Precipitation Processes

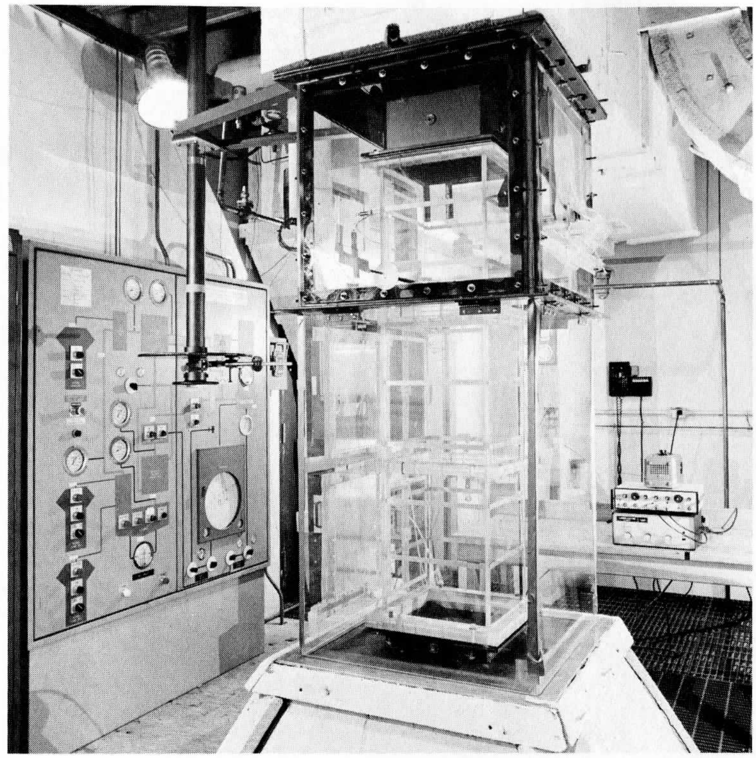
A blue and white sailplane glides silently above the farmlands east of the Rocky Mountains in Colorado. Gently, effortlessly, it approaches the base of a cumulus cloud. The pilot watches his instruments, circles to find an updraft. Close to the core of the developing cumulus he discovers it——a vertical wind greater than the sinking rate of his long-winged aircraft. The sailplane vanishes into the base of the cloud.

Within the cloud, the plane moves slowly, as if it were a part of its surroundings. The cloud is almost undisturbed; without an engine the aircraft does not drive through or pollute the air around it. The pilot (a scientist himself) and a scientific observer examine the cloud in its natural state, measuring physical processes that change water vapor into droplets and droplets into rain and ice particles.

In its Cloud Physics Program, NCAR is now using a Schweizer 2 - 32 sailplane donated to NOAA by the Explorers Research Corporation. Instrumented for scientific studies, this sailplane bears a small extra wing above the cockpit canopy, providing a black optical background for photographs of cloud droplets and ice particles. A slim pointed boom——an instrument to measure cloud droplet size——protrudes from the nose. The aircraft is a self-contained laboratory equipped with temperature and altitude sensors, air motion detectors, and FM telemetry equipment linking it to a mobile ground station and eliminating the need for heavy recording devices in the sailplane. Extra space is crammed with small low-power instruments, a compact silver-zinc battery, gyroscopes to aid instrument flying, flight safety equipment, and real-time display panels for meteorological sensors.

Cloud Development

Clouds form when water vapor condenses onto tiny airborne particles or nuclei, usually smoke, dust, or fine salt derived from sea



In NCAR's particle control chamber, the behavior of falling droplets can be studied under controlled conditions of droplet size, temperature, humidity, and electric charge and field. Horizontal aluminum tapes on the glass chamber provide the electric field. Drops "fall" in an upward airflow established by a fan below the chamber. A control panel is at the left.

spray. These particles are necessary to cloud formation, and the number of droplets varies according to the concentration of particles and their chemical and physical properties.

Cooling is a vital factor in cloud formation, since water vapor must be below its dew point to condense. Cooling usually occurs as air rises and expands—lifted by convection, flowing across mountains, or sliding upward over air of greater density. Weather conditions conducive to cloud growth therefore include an adequate water vapor supply and circulation favorable for upward motion.

Depending on the temperature of the surrounding atmosphere, rain may develop as nucleated droplets enlarge, collide, and coalesce; or ice crystals may form, and from them snowflakes or hailstones grow by accretion of supercooled droplets and other ice crystals.

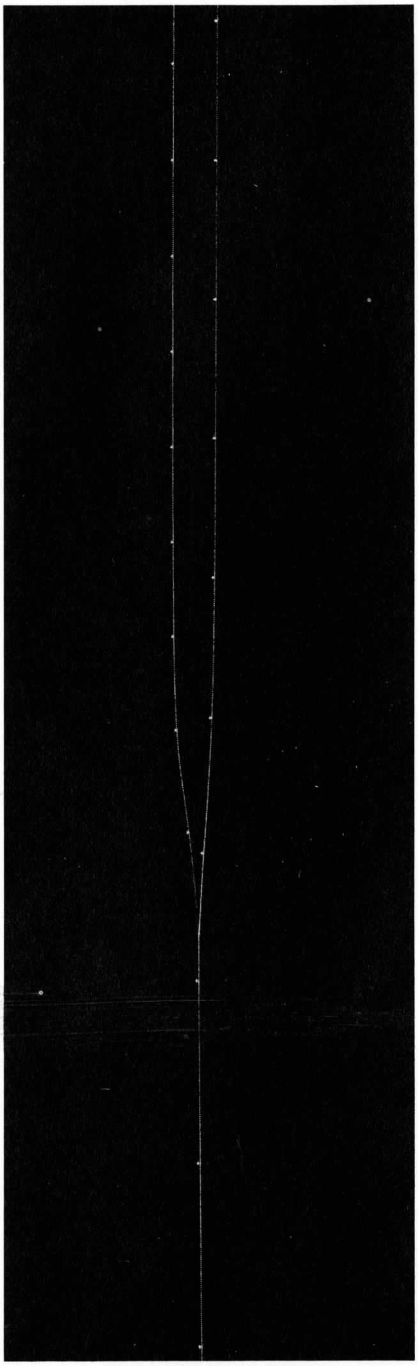
Laboratory Studies

Recent cloud studies at NCAR and elsewhere have progressed along three lines:

- Laboratory studies of precipitation and its causes
- Theoretical studies of convection, cloud droplet formation, and the growth of rain, hail, and snow
- Field studies in the clouds themselves

NCAR's research on the behavior of clouds and precipitation (see *NCAR Quarterlies* No. 9, 20, 21, and 30), under the direction of Doyne Sartor, has shown that precipitation growth and electrification processes in thunderstorms may be highly interactive; each may affect the other during cloud growth and development. Laboratory models involve strictures not present in the free atmosphere, but two new instruments aid in reproducing physical processes that cannot be observed in the atmosphere.

A particle control chamber designed by Theodore Cannon and Louis Breyfogle (after a prototype built at UCLA) offsets the gravitational fall of droplets with a smooth upward flow of air. The airflow can be controlled from a few centimeters per second (corresponding to the fall velocity of very small droplets) to 10 m/sec (the fall velocity of large raindrops or small hailstones). Temperature, relative humidity, particle charge, and the electrical field can also be controlled. With



In the laboratory, two tiny electrically charged droplets are photographed as they collide and coalesce. Bright dots on the droplet trajectories serve as time markers; they were produced by a strobe light flashing every 0.05 sec.

the particle control chamber, drop-to-drop interactions and the growth of raindrops and ice particles can be studied in a nearly natural environment, without artificial supports or constraints.

A new drop-producing instrument forms charged or electrically neutral droplets as small as 5 μm (micrometers) in radius, positioned so that they will collide with each other in front of a camera. The instrument was developed by Charles Abbott and Cannon. Abbott and Sartor are now photographing the minute droplets and calculating the efficiency with which they collide and coalesce under controlled electrical conditions. Although many problems await further experimentation, data from these studies confirm earlier theoretical calculations of fall velocity and collision efficiency of small droplets, especially in strong charge and electrical field ranges.

Theoretical Modeling

Theoretical studies of cloud droplet behavior have been a major concern of NCAR's cloud physics research group for some time. The numerical models are complex and mathematically sophisticated, even though each process involved is at first modeled independently and in simplified form. To design a useful mathematical model of an entire thunderstorm, the many critical processes must ultimately be simplified to speed up calculations, and combined into a single model.

Adiabatic expansion—the expansion of air as it rises in the free atmosphere—must enter into the model, as must calculations of nucleating properties of atmospheric particles, the rates of diffusion of water vapor relative to cloud droplets and ice crystals, and the accretion of cloud droplets and ice particles under a wide variety of electrical charge and spatial distribution patterns. A fully three-dimensional mathematical model of a convective cloud, including interactions of cloud particles, air motion, and electric fields, is beyond the capability of the largest computers likely to be available in the near future. One- and two-dimensional models are used now, models that compromise specifications of cloud geometry or vertical motion or

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These cloud droplets and ice particles were photographed inside a cumulus cloud. Large ice crystals are 0.1 - 0.7 mm across; cloud droplets are smaller than 10 μm in radius.

buoyancy in order to consider other important parameters. A cloud shown in a cross-sectional, two-dimensional model, for instance, may represent a radially symmetric cloud cell, without any of the asymmetrical features caused by wind shear or other spatial inhomogeneities.

Even with these constraints, numerical models reveal many features relevant to cloud growth and precipitation. Cloud microphysics models confirm that the number, density, size, and type of particle (whether aerosol, liquid droplet, or ice particle) are important factors controlling nucleation of droplets. Air and particle temperature, humidity of the air, and the nucleation properties of the aerosols and cloud drops control the rate at which particles change from aerosols to droplets to ice in a rising parcel of air.

Airflow around droplets, the drag force exerted as droplets fall, and electrostatic forces between pairs of droplets dictate the probability that two drops, initially a prescribed distance apart, will collide. For droplets below 40 or 50 μm in radius, electrical forces, which are observable in nature in mature convective clouds, are particularly important: the efficiency with which droplets collide and coalesce varies considerably with the charge carried by the particles or with the presence and strength of the surrounding electric field. Larger drops, drizzle or raindrop size (more than 50 μm in radius), fall faster and are less likely to be influenced by electrostatic forces. Calculations show that the larger the drops grow, the more likely they are to collide with other drops; collision efficiency ranges from 70 to nearly 100%.

Both mathematical and laboratory studies show that drops do not necessarily coalesce when they collide——they may simply bounce apart. Small droplets, charged droplets, and droplets in an electric field are more likely to coalesce than large drizzle-size or rain-size drops, or drops of any size not in an electric field.

One of the interesting problems in theoretical cloud physics is how thunderstorms become electrified. Evidence now suggests that the collisions of cloud droplets with raindrops or ice particles in the developing electric field of a cloud organize the electrical conditions in the cloud.

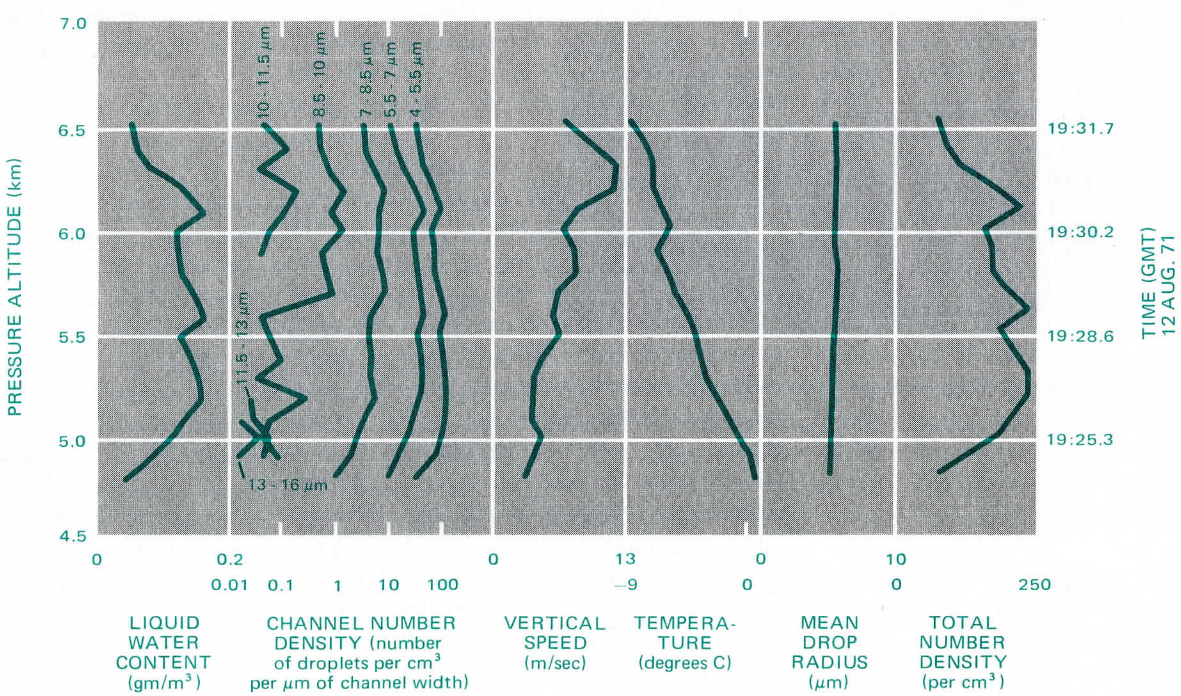
Sailplane Studies

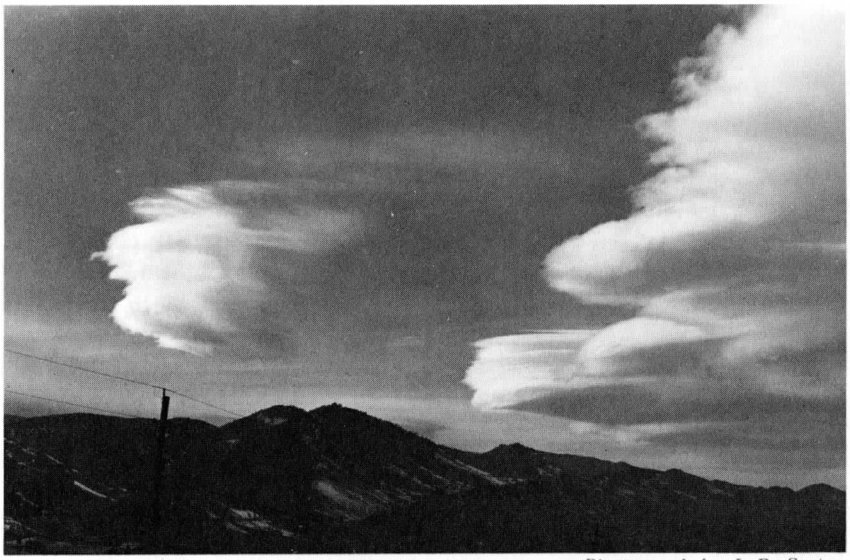
In the lofty cumulus clouds of summer, in wave clouds forming where winds roll across mountains, and in the cloud-free atmosphere, nature offers environments in which physical processes that relate to cloud growth can be studied. The Schweizer sailplane makes possible detailed studies of droplets and ice crystals within clouds, their growth and development into rain and hail, and the relation of atmospheric dust particles or silver iodide used in cloud seeding to nucleation and precipitation. Droplet sizes can be recorded with the cloud droplet probe or photographed with the cloud particle camera. Data from these studies can be related directly to recorded observations of the buoyancy and vertical motion of air within the cloud.

Sailplane studies shed light especially on processes within the core of convective clouds. These clouds are the sources of heavy precipitation, hail, and most or perhaps all cloud-to-ground lightning; they often give rise to tornadoes. Inhomogeneities within the cloud can be recorded directly; they are particularly important because most present models are not designed to include them. The properties of air drawn horizontally into the cloud can be observed from the sailplane during its descent outside the cloud.

The sailplane used in NCAR studies is piloted by Wim Toutenhoofd, once soaring champion of Holland. During 1971 and 1972, Toutenhoofd and Cannon made frequent flights into growing summer cumulus clouds and the stationary mountain wave clouds that form in winter over the Colorado Rocky Mountains. Data from these flights show that liquid water content and density of droplets vary considerably within clouds, as might be expected, but that droplet size remains surprisingly constant. Photographs of cloud droplets and ice particles in the free air above

Data from sailplane instruments are telemetered to a mobile ground station for recording. Computer plots of a typical data set are shown below. Colored lines show physical features of the cloud averaged over 100 - m altitude increments.





Photograph by J. R. Sartor

Wave clouds forming over the Rocky Mountains near Boulder, Colorado, are ideal outdoor laboratories for studies of the formation of ice particles in cold clouds.

the sailplane aid in analysis of particle size and concentration and so far confirm the droplet distributions measured by the droplet probe in the sailplane nose boom.

In mountain wave clouds, droplets are continuously forming and growing on the upwind side and dissipating on the downwind side. Because the clouds themselves are practically stationary they are ideally suited for cloud microphysics experiments. The steady-state nature of a mountain wave—a large standing wave in the atmosphere—enables the sailplane pilot to maneuver with ease, gathering data from various parts of the cloud.

Wave clouds are very cold, well below 0°C, and photographs taken from the sailplane reveal coexisting ice particles and supercooled droplets. Further studies should clarify the relationship between ice particles and droplets and lead to a greater understanding of how snow and ice crystals form.

Remaining Problems

Clouds and the precipitation they release strongly influence man's environment. Surface observations and satellite photographs show that clouds usually cover about 50% of the earth's surface, controlling the amount of solar energy that reaches the surface and becomes available for heating the lower atmosphere. Clouds also act as a blanket to hold heat in the lower atmosphere. Precipitation waters the land, cleanses the air of man-made and natural pollutants, and in the form of snow alters the amount of sunlight reflected back into space. Storms arising from cloud systems sometimes threaten life on earth, but they are ultimately more beneficial than harmful.

Many problems in cloud physics are still unresolved, but NCAR studies are bringing closer a real understanding of clouds and the tiny droplets of which they are formed. Sartor and his colleagues feel that they have crossed the threshold in observing clouds and cloud processes, but that a complete model of physical processes within clouds is not yet in sight. However, even simple theoretical models prove to be useful guides for observational programs in the laboratory and in natural surroundings. Such programs can ultimately add to our understanding of all the properties of clouds, and will contribute to weather forecast models, techniques for weather modification, and man's ability to control or remove pollutants from the atmosphere.

Atmospheric Measuring System

Atmospheric chemists at NCAR have established three global remote atmospheric measuring stations to sample atmospheric trace constituents on a long-term basis. A prototype station on the roof of the NCAR Mesa Laboratory in Boulder has functioned for a year, and a second station is operating near a NOAA research site on Mauna Loa, Hawaii. A third station is being set up in American Samoa where, as at Mauna Loa, instruments designed and built at NCAR will be operated by NOAA.

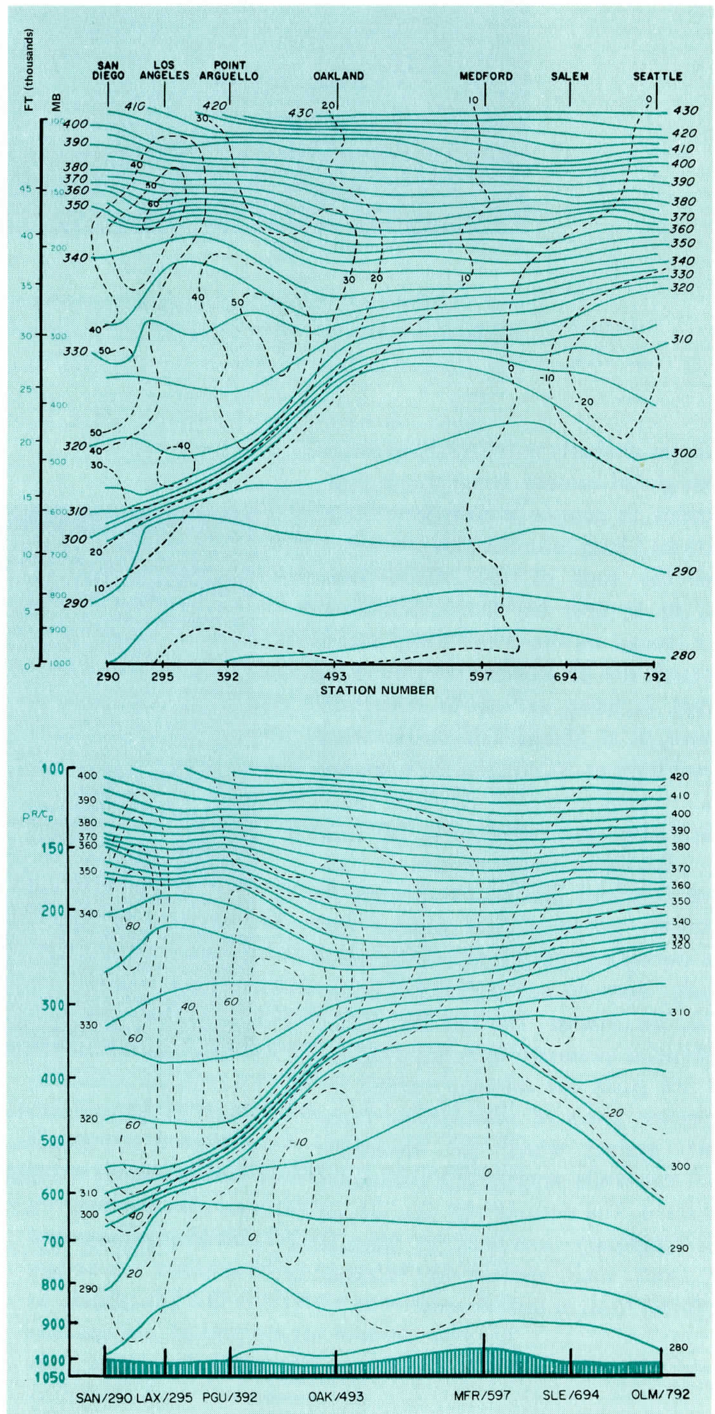
The measuring stations consist of four portable cases containing air-sample collectors, bubblers and filters to trap gases in liquid solutions, meteorological sensors, and power and timing equipment. Operating semi-automatically, they do not require the attention of a skilled chemist. The stations collect trace constituents occurring in concentrations as low as ten parts per trillion, thereby recording baseline levels of atmospheric trace constituents against which the increasing amounts of man-made atmospheric pollutants can be measured. The stations may also record occasional temporary increases in natural pollutants from such sources as volcanic eruptions, forest fires, or dust storms.

One of NCAR's remote measuring systems tests the virtually uncontaminated atmosphere from a barren, dust-free lava field 3,400 m above sea level on the slopes of Mauna Loa. These systems were designed to provide an economical basis for a worldwide chemical monitoring network; several other sites are now being investigated.

Forecasting Fronts and Clear Air Turbulence

Traditional techniques used in weather prediction rely on analyses based on pressure levels, a system that was established by international agreement during the 1930s and 40s. "Lows," "highs," and isobars––lines of equal pressure––are now almost as familiar to the television audience as to the professional meteorologist. Weather is usually portrayed in its horizontal dimensions on a map showing isobars at a predetermined geometric altitude (commonly sea level). Even if "upper level," "stratospheric," and "jet stream" conditions are described, they are rarely shown as linked with surface pressure and temperature features.

Historically, however, meteorologists have often used vertical cross sections to define the spatial and temporal distribution of temperature and wind velocity, especially in studying



Cross sections derived from 21 April 1963 radiosonde data reveal tightly packed, sloping isentropic surfaces (solid lines) that do not show up on standard weather maps. The upper cross section was drawn by hand, a tedious and subjective process. The lower one is an objective analysis produced by NCAR's computer using a technique developed by Melvyn Shapiro and Jordan Hastings. The computer is less "skilled" than a human meteorologist, but produces good results when isentropic coordinates are used. Its great advantage is speed: in less than a second the computer produces a cross section based on six soundings, with 50 grid points in the horizontal and 200 isentropic surfaces in the vertical. Dashed lines in the upper figure show observed winds, those in the lower figure show geostrophic winds, both in meters per second.

and describing mid-latitude fronts. Data for cross sections are derived primarily from the established radiosonde network, with stations spaced 200 to 300 km apart in most northern hemisphere land areas. Radiosonde data show high resolution in the vertical direction, and the cross sections, slicing through the layered structure of the atmosphere, often reveal narrow frontal regions, with steep temperature and wind velocity gradients that are not shown in conventional analyses or by atmospheric models.

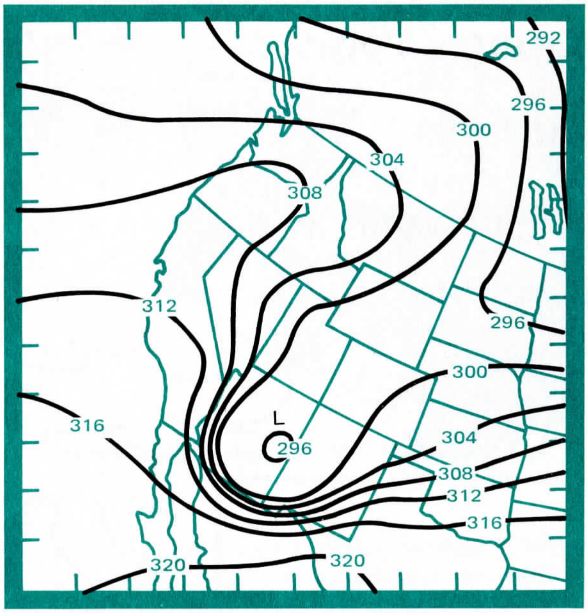
Three-Dimensional Isentropic Analysis

At NCAR Melvyn Shapiro and Jordan Hastings have recently succeeded in developing a computer program for drawing such cross sections rapidly and accurately. Rainer Bleck and Shapiro have devised a modeling technique to show frontal regions in weather map form, so that they can be used in forecasting. This procedure, called isentropic modeling,[1] relies on a three-dimensional analysis technique developed several years ago by Bleck and Philip Haagenson for studies of atmospheric chemistry. The model analyzes pressure and wind velocity along potential temperature surfaces, surfaces which seem to define material atmospheric layers and hence closely parallel air-mass boundaries.

Isentropic Forecasting

Bleck and Shapiro use their isentropic analyses as input for two forecast models, one of which has already been shown to outperform conventional models in predicting strong temperature gradients, strong vertical wind shear, and spontaneous, often explosive development of mid-latitude cyclonic storms. One of the values of forecasting from isentropic analyses is that variable vertical resolution is inherent in the forecast models, a feature that reduces the computer time needed for forecasting. Across large areas, layers separated by isentropic surfaces are relatively thick and their boundaries are essentially horizontal; data points in the vertical are widely spaced. Yet in frontal zones, where fine resolution is desirable, the surfaces of potential temperature are packed closely together, and the vertical density of data points accordingly increases, giving detail where detail is needed.

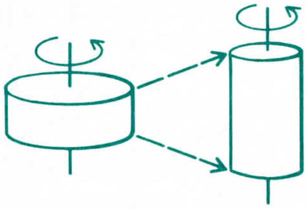
[1] Isentropic: having constant entropy or potential temperature.



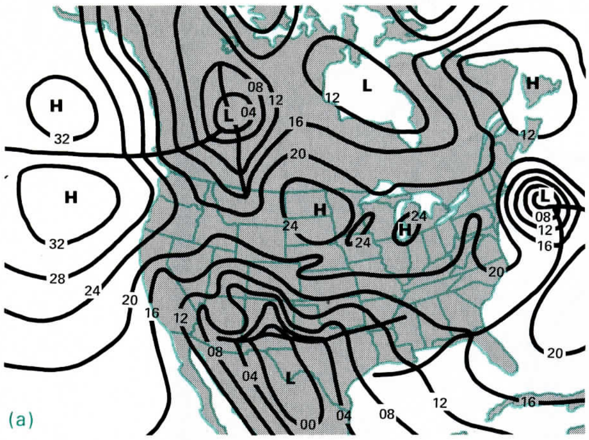
70 POTENTIAL TEMPERATURE 500 MB

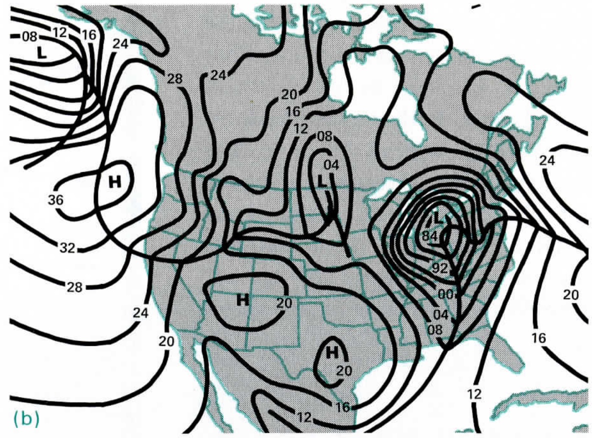
A 500 - mb map derived by three-dimensional isentropic analysis from 1 April 1970 data retains the tight packing of potential temperature surfaces shown on cross sections, and reveals a concentrated zone of temperature changes that represents a front.

One of the two multilevel models used within the isentropic coordinate framework is a refined version of a model developed by Arnt Eliassen and Elmer Raustein in Norway, using the basic momentum equations—the so-called "primitive" equations. The other is a new model designed by Bleck based on conservation of potential vorticity.[2]

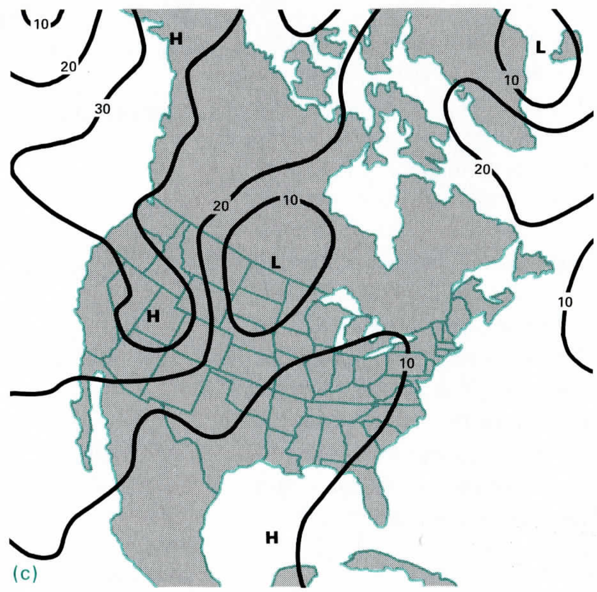


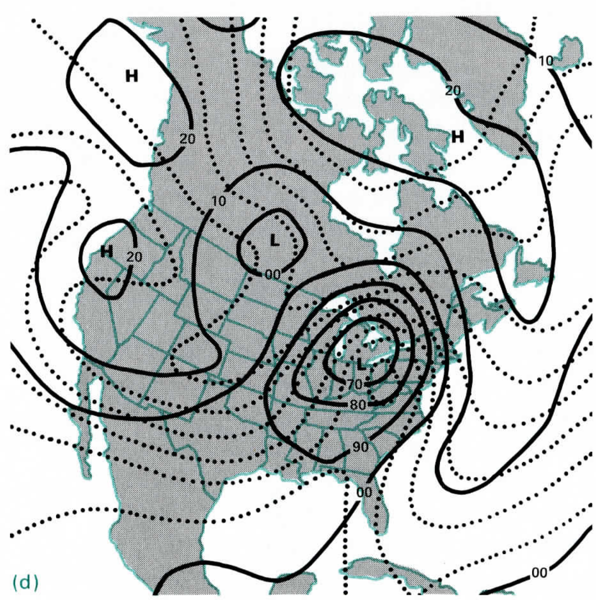
[2] For the atmosphere, the potential vorticity theorem describes the tendency of a mass of air to retain its angular momentum, either increasing in speed of rotation as it contracts vertically, or decreasing its rotational motion as it expands.





Observed surface pressures for 1 April 1970 (a) show no sign of impending storm development. However, after 36 hr a large cyclonic storm has developed in the eastern United States (b). The 36 - hr Weather Service forecast (c) failed to predict this storm, but a 36 - hr isentropic forecast (d) shows the storm's development.





After testing both these models on artificial initial conditions, Bleck has gone to the other extreme, so to speak, and tried the potential vorticity model on real-data examples for which traditional forecasting methods failed to predict explosive storm development. In four cases selected, the model predicted the developing storms and their associated frontal zones successfully. Similar tests with the primitive equation model are in progress. Bleck and Shapiro point out that these forecasting techniques are particularly suited to mid-latitude regions, where cyclogenesis and developing fronts are significant weather features.

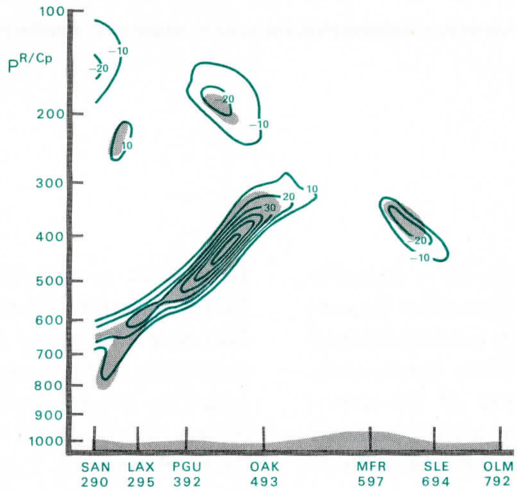
Clear Air Turbulence

The isentropic forecast technique is also applicable to prediction of regions of strong vertical wind shear and strong horizontal temperature gradients, i.e., areas where dangerous turbulence may occur. As such, it holds considerable promise for operational forecasting for aircraft flights. David Fulker of NCAR and Jerry Stevens and James Kemper of Florida State University are now co-operating with Shapiro and Bleck on the development of more advanced analysis schemes using the new technique. The usefulness of these schemes will be assessed by Mark Lutz, a graduate student at the Massachusetts Institute of Technology, who will compare experimental forecasts with clear air turbulence data gathered by commercial airlines.

Global Forecasts

So far, isentropic models have been applied only to limited mid-latitude areas such as the continental United States, where cyclonic development is pronounced and where radiosonde density reflects the desire for accurate short-term forecasts. A question that has been raised is whether isentropic models will be useful on a global scale, during GARP experiments or as part of future worldwide forecasting systems. Satellite data, on which many future systems may depend, do not give precise vertical profiles like those obtained from radiosondes. Failure to include frontal-scale processes will cause errors in initial data, and if frontal-scale processes are ignored the errors may grow as global data are processed, to the extent that forecasts for one week or longer are not possible.

This question is now being examined by Shapiro and Bleck. They will run their models



Regions of sharp temperature contrast may contain clear air turbulence dangerous to aircraft. This figure, derived from the 21 April 1963 isentropic cross sections illustrated above, shows areas of strong vertical wind shear where turbulence can be expected.

with simulated satellite data to see whether failure to include fronts in the satellite-data run affects forecasts. Their tests may show that over data-sparse areas accurate profiles will have to be obtained by sondes dropped from balloons or aircraft (such as the Mother GHOST carrier balloon system and the wind-finding dropsondes now being developed at NCAR) or released from buoys.

Notes

Meteorological Society Awards

At the January 1973 meeting of the American Meteorological Society in St. Petersburg, Florida, two NCAR scientists and a former NCAR scientific visitor received awards for outstanding contributions to man's understanding of the atmosphere.

Douglas Lilly was awarded the Society's Second Half Century Award for his "theoretical, experimental, and observational contributions to the study of small-scale atmospheric phenomena, including thermal convection, mountain waves, and turbulent interactions."

Robert Dickinson, who, like Lilly, is a member of NCAR's Atmospheric Dynamics Department, received the Meisinger Award for "prolific and imaginative work on a variety of problems concerning the dynamics of terrestrial and other planetary atmospheres."

Christian Junge, of the Max Planck Institute for Chemistry in Mainz, Germany, received the Society's highest honor, the Carl-Gustaf Rossby Research Medal. Junge has been at NCAR several times as a scientific visitor in the Atmospheric Chemistry Department. He was honored for his investigations of atmospheric aerosols and their distribution, particularly for the discovery of the stratospheric sulfate layer, and for his international leadership in the study of atmospheric chemistry.

Annual NCAR Awards

In 1967 NCAR established an Outstanding Publication Award to encourage and reward excellence in scientific research and communication. Last year two additional award categories were created: a Technology Advancement Award for the most significant technical development in support of the atmospheric sciences and a Research Support Award for outstanding performance supporting research, management, or administrative functions within NCAR.

The Outstanding Publication Award for 1972 was shared by Arthur Hundhausen of the High Altitude Observatory and James Deardorff of the Laboratory of Atmospheric Science (LAS). Hundhausen's award was for his book, *Coronal Expansion and Solar Wind*, published by Springer-Verlag, Heidelberg. Deardorff's was for "Numerical investigation of neutral and unstable planetary boundary layers," a paper published in the *Journal of Applied Meteorology*. Honorable mention was accorded to Stuart Patterson and Steven Orszag, LAS visitors, for two joint papers on simulation of turbulence.

The Technology Advancement Award was presented to Rainer Bleck, David Fulker, Jordan Hastings, and Melvyn Shapiro of LAS for their cooperative effort in developing, testing, and applying objective isentropic analysis schemes to numerical forecasting. Their work is described in this issue of the *NCAR Quarterly*. Honorable mention went to Theodore Cannon of LAS for designing and developing a cloud particle camera (also discussed in this *Quarterly*), and to Paul Rotar, Gilbert Green, David Kitts, Bernard O'Lear, David Robertson, Eugene Schumacher, and Vincent Wayland of the Computing Facility for development of a new software system for the NCAR Control Data 7600/6600 computer complex.

Robert McBeth of the Field Observing Facility received the Research Support Award in recognition of a year of outstanding achievement in support of seven field programs. Honorable mention for research support went to John Masterson for work on the concept of expendable, satellite-interrogated drifting buoys, and to Roy Jenne and Dennis Joseph for work on the NCAR set of climatic data.

Student Participation in GATE

The GARP Atlantic Tropical Experiment (GATE), planned for the summer of 1974, will provide opportunities for employment of students as observers and operators of various data acquisition systems aboard ocean vessels and at land sites in Africa. Wages will be equivalent to those typically paid to student assistants, and transportation costs will be covered. Arrangements can be made at most universities for students to earn academic credit for their participation.

For further information students should contact GARP councilors at UCAR member universities (the universities listed on p. 3 of this *Quarterly*) or write directly to Dr. Philip Merilees, Executive Secretary of the UCAR GARP Council, P.O. Box 1470, Boulder, Colorado 80302.