

Magnetic Fields in Solar Prominences

Studies of the sun at eclipse were a prominent part of nineteenth century solar astronomical endeavors. The eclipse of 1842, in particular, was observed by many of Europe's most eminent astronomers, and led to material advancement in knowledge of solar phenomena. This eclipse, with a path of totality crossing France, Italy, and Austria, gave impetus to the study of solar prominences; among the features recorded by several of the observers were amazing clouds of incandescence referred to in the writings of the time as "protuberances" and "flames."

These features had been observed at earlier eclipses, but had previously been regarded as phenomena of a lunar atmosphere. Now, with improved telescopes, the edge of the moon was seen to move across them: they were definitely solar features. What was their physical nature? Were they clouds floating above the surface of the sun? Were they part of the corona, once also thought to be an illusion caused by the moon's atmosphere? Or were they great incandescent solar mountains?

Several prominences were recorded at the 1851 eclipse, and these records as well as later photographs (photographs were becoming increasingly important as eclipse study tools) raised more questions. Prominences were too permanent to be clouds, yet not permanent enough to be mountains.

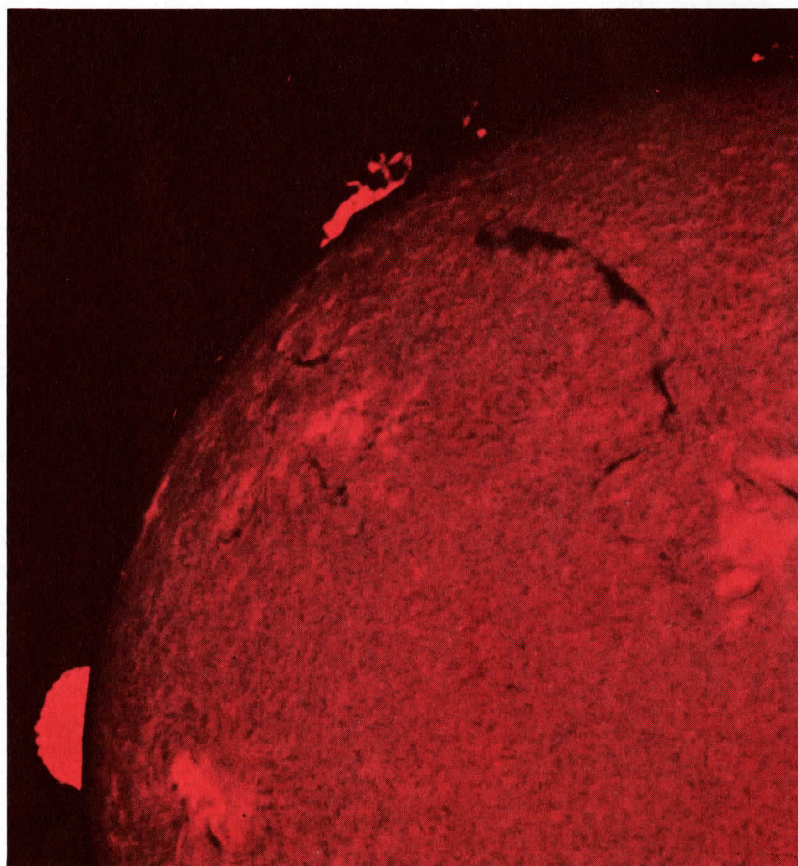
In 1868, new techniques of solar spectroscopy were used during an eclipse visible from India and Malaya. Spectroscopic studies made



by a number of observers showed that prominences produced bright-line spectra, indicating that they were gaseous. Hydrogen lines were particularly brilliant, suggesting that this gas was their major component. Later, improved spectrographs with special lenses and filters gradually made it possible to study prominences and the adjacent chromosphere spectroscopically from day to day, outside of eclipse. The development of the coronagraph led to visual and photographic study of changes at the edge of the sun, and prominences of many previously unrecognized varieties were observed and recorded.

Quiescent Prominences

It soon became obvious that the many kinds of prominences were difficult to classify. However, most fall into two main types—quiescent and active. Quiescent prominences, which endure for weeks or even months, are like enormous curtains suspended above the surface of the sun. Seen against the brilliance of the solar disk, they appear dark, wispy, and filamentous, for they are somewhat cooler than the sun's surface. But seen at



Quiescent prominences, curtains of cooled coronal material, are held in place by magnetic forces. Photographed against the solar disk by $H\alpha$ light, they appear as long, dark filaments.

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the edge, or limb, of the sun they are far more brilliant than the surrounding corona, for they are many times denser than the corona.

Because they are long-lasting, quiescent prominences can be followed across the disk as the sun rotates. They can often be recognized and studied at the limb and against the disk during several successive solar rotations. Although the mechanism of their formation is not clear, they are generally thought of as incandescent coronal material cooling and condensing along magnetic field lines. Their structure is most fully revealed when they are seen at the limb of the sun: within the relatively stable prominence structure, matter from the corona, temporarily luminous, can often be seen cascading toward the surface of the sun.

Active Prominences

Active prominences, hotter than quiescent prominences but still far cooler than the surrounding corona, usually occur in association with sunspot groups. Characterized by rapid change, they often appear and disappear within a single day. They may take the form of well-defined loops or arches, or appear as knots of incandescence that flow on curved trajectories. Sometimes they resemble bright clouds showering incandescent rain in arching patterns. The source of the material that replenishes them is unknown; the corona is usually denser near them than elsewhere, as if strengthened by a common source. A few types, surges for example, appear to derive materials from the surface of the sun.

Prominence Magnetic Fields

The very form of many prominences, particularly the arches and loops of active ones, suggests that the forces which hold them above the solar surface are electromagnetic. Research on prominences during the early part of this century showed that magnetic fields are fundamental features of the corona, especially in active areas, and that they are often powerful enough to maintain prominence structures against the pull of solar gravity. As soon as photographic, photo-

metric, spectroscopic, and polarimetric techniques were applied to solar astronomy, detailed study of the magnetic fields became possible. In 1913, George Ellery Hale at Mt. Wilson Observatory (California) measured the spectra of sunspots and determined the intensity of magnetic fields in the centers of the spots. When a light source is associated with magnetic forces, most of the spectral lines derived from the light source split into two or more components, a phenomenon known as the Zeeman effect. In the simplest examples two Zeeman components are produced, one left-circularly polarized and one right-circularly polarized, with slightly different wavelengths. Since separation of the Zeeman components is proportional to the intensity of the magnetic field, sunspots, which have especially intense magnetic fields, show Zeeman separations so great that they can be measured directly on spectrograms. Hale calculated that sunspot fields had intensities of thousands of gauss, and showed that sunspots north and south of the solar equator have opposite polarities, which reverse with each successive 11-year sunspot cycle.

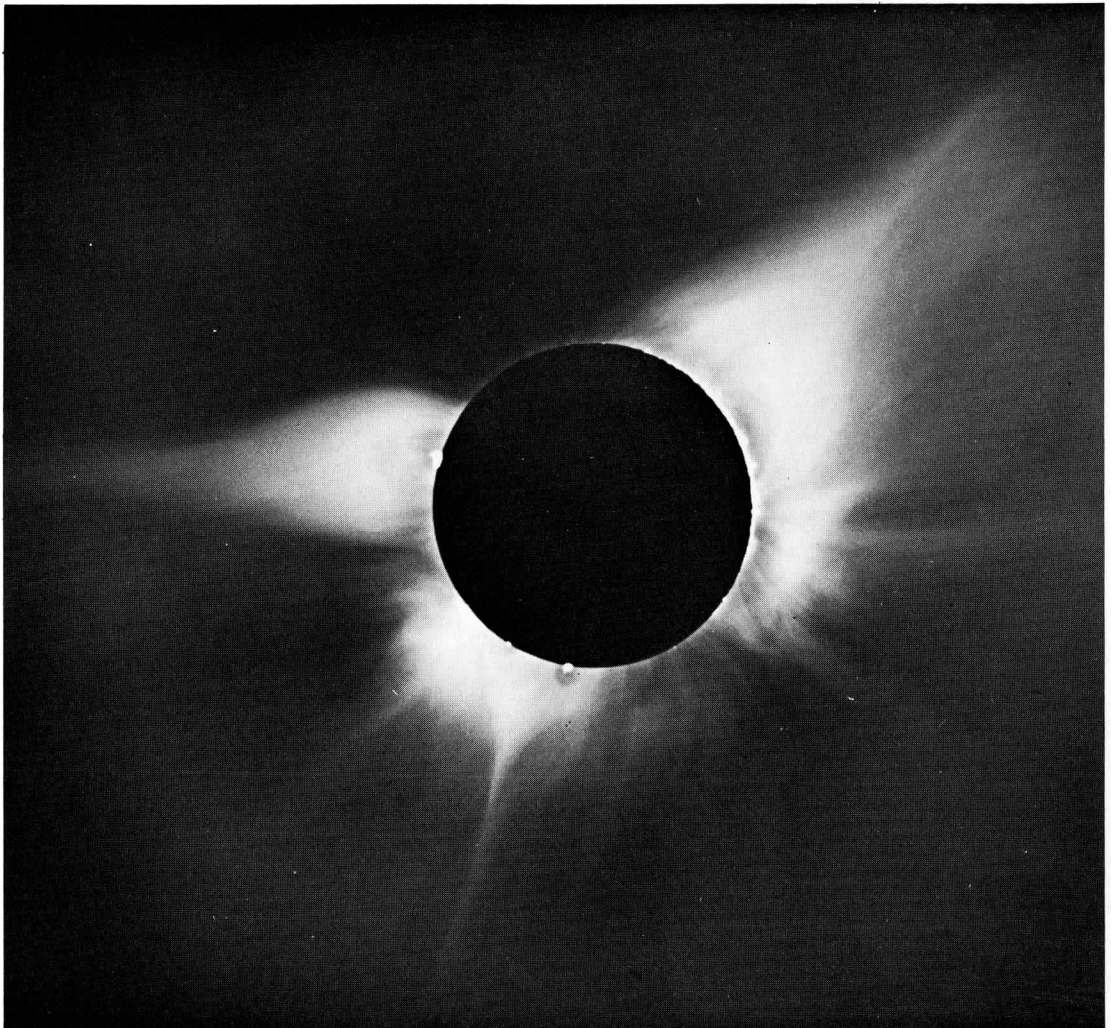
Magnetograph to Measure Fields

The development of refined photoelectric instruments has now made it possible to measure very much smaller wavelength shifts by observing the different state of polarization in the Zeeman components. In 1953, H. W. Babcock at Mt. Wilson and K. A. Kiepenheuer in Germany independently developed magnetographs to measure magnetic fields directly as functions of the Zeeman separation. Babcock's instrument, which offered greater resolving power and more accurate definition than Kiepenheuer's, gave readings on magnetic fields in many parts of the sun. It was only natural that he and his associates would turn their attention to studies of the fields around prominences. Comparing photographic records with magnetograph maps, they observed that filaments, the dark lines formed by prominences as seen against the solar disk, usually lie between fields of opposite polarity, and seem to parallel the neutral or zero-gauss lines between these fields. Unfortunately, the prominences

themselves, much less brilliant than the surrounding solar surface, were not bright enough to produce the light levels on which their Zeeman-effect measurements could be based.

In 1964 a new type of high-sensitivity magnetograph was installed at the High Altitude Observatory station at Climax, Colorado, where it could be used in conjunction with the 40-cm coronagraph-spectrograph already at the station. This three-instrument combination, the only one of its kind, offers spatial resolution high enough and magnetic sensitivity great enough for studies of prominence magnetic fields on the solar disk or, with the coronagraph, at the sun's limb. The magnetograph is designed to operate on the hydrogen alpha ($H\alpha$) line, at $\lambda 6563 \text{ \AA}$, the brightest

As shown in this photograph taken at the 1966 eclipse, quiescent prominences draw their material from the corona, leaving a dark halo-like vacuum. The hazy loops of coronal material high above the prominence may also be governed by the prominence magnetic field.



line in the visible part of the solar spectrum. On the H α line, Zeeman separations can be measured with relative accuracy.

Two Definitive Studies

Two graduate students at the University of Colorado, working under the guidance of Einar Tandberg-Hanssen and other HAO staff members, used the new Climax magnetograph to define major magnetic features in prominences. David Rust, measuring magnetic fields shown by H α lines from nearly 100 quiescent prominences, demonstrated that magnetic field lines exist with a component perpendicular to the plane of the prominences, entering the prominences on one side and leaving them on the other. The strength of the fields increases with height above the solar surface; their intensity appears to vary also with the intensity of the underlying photospheric fields. Most quiescent prominences have fields of about 5 G although sunspot-related prominences may have fields in excess of 50 G.

John Harvey, measuring some 200 active prominences, found that magnetic fields in most types of active prominences are stronger than those in quiescent prominences, averaging 26 G and ranging to 200 G. Active prominences change rapidly and can be observed for only short periods of time; Harvey drew his deductions from only a few readings for each prominence.

Adjustable Slit Assembly

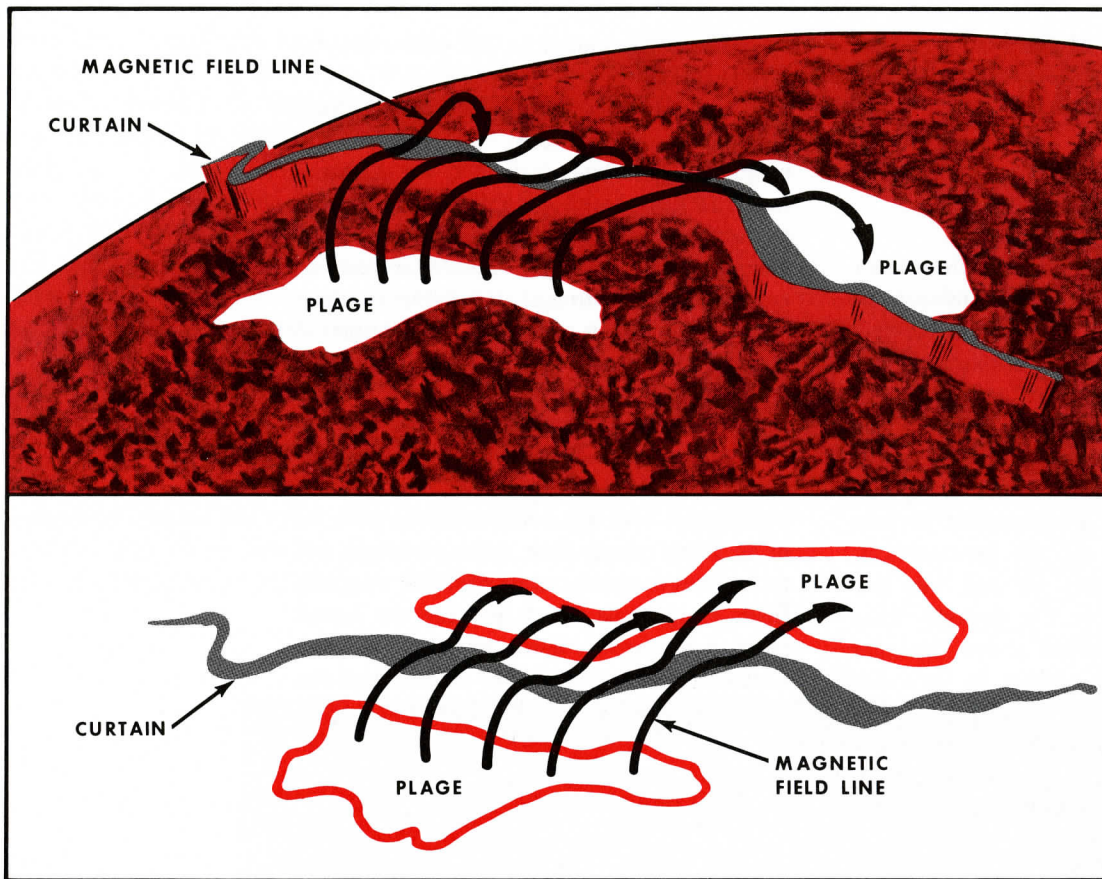
In the course of Harvey's work, it became apparent that observations from other lines of the solar spectrum would be useful in analyzing the magnetic fields controlling higher-temperature components of prominences. Adaptations of the Climax instrument system, particularly the development of a narrow slit assembly admitting light from narrow lines of helium and some metals, were undertaken in 1969. With these adaptations, it became possible to measure magnetic fields in different temperature regions of prominences, since hydrogen, neutral and ionized helium,

and the metals radiate in different temperature regimes.

Recent data analyzed by Tandberg-Hanssen show that in quiescent prominences the magnetic field lines indicated by measurements of helium and metal lines are the same as those measured on the H α line, but that the magnetic field in active prominences seems to vary markedly in strength depending on which lines are used. This suggests that in long-lived quiescent prominences the forces of different temperature regions have time to stabilize, so that the fields controlling the different parts of the prominence are about the same, whereas in short-lived active prominences such equilibrium does not develop. Cooler portions of an active prominence, where hydrogen and metal lines originate, retain different magnetic fields from those which pervade the hotter parts of the same prominence. However, there does not seem to be a simple relation between strength of magnetic field and temperature.

Longitudinal Fields

In his work on active prominences, Harvey found some evidence of fields lying parallel to the long axes of a few elongate prominence structures. During 1968-69, Tandberg-Hanssen and Ulrich Anzer, a visitor from the Max Planck Institute for Physics and Geophysics, Munich, mapped 135 long-lived quiescent prominences as they appeared on successive solar rotations. Their observations showed that the magnetic fields in quiescent prominences rise from plages on the solar disk, penetrate the more or less vertical, curtain-like prominences, and arch down into the sun again. By relating the line-of-sight strength of prominence fields to the position of the long axes of the prominences, Tandberg-Hanssen and Anzer produced evidence that field lines in quiescent prominences tend to follow the prominence axes before arching downward toward the solar surface. Tandberg-Hanssen is now extending these studies to active prominences, but again there is the problem of making enough observations during the short life of the features. The magnetograph is operated at Climax whenever good seeing and bright active



Recent research suggests that magnetic field lines rising from plages on the surface of the sun bend as they penetrate a highly ionized prominence region.

prominences occur together, in the hope that accumulated data may eventually indicate more details of the magnetic patterns.

The Climax instrument, like most other magnetographs, can measure magnetic fields or their components only along the line of sight. This restriction severely limits the study of prominence magnetic fields. HAO is now building a more sophisticated magnetograph that will measure the magnetic component both along the line of sight and transverse to it, defining the magnetic vector fields. Such a technique has been applied at other observatories to the strong-light features on the solar disk. Tandberg-Hanssen and others at HAO hope that when the new magnetograph is used with the Climax coronagraph and other sensitive Climax instrumentation, much more can be learned about solar prominences and their magnetic fields.

"Immediately after the totality two magnificent prominences appeared; one of them, more than three minutes of arc high, shone with a splendour which is difficult to imagine. The analysis of its light showed me immediately that it was formed by a huge gaseous incandescent column, composed mainly of hydrogen."

P. J. C. Janssen 1868

The Atmosphere in Two Dimensions

The troposphere, the lowest layer of the atmosphere, contains three-fourths of the atmosphere's mass and most of its storm systems and weather fronts. Encompassing a globe 40,000 km in circumference, it is only 8-16 km thick. In satellite photographs it is the scarcely visible, cloud-filled lowest part of the thin blue haze between earth and sky.

Weather is produced in the troposphere by interactions of various meteorological elements, primarily temperature, humidity, pressure, and winds—all of which are due ultimately to the effects of solar heating on the atmosphere of the rotating earth. Atmospheric motions are thus part of a physically determinate system explained by basic physical laws, and as such should be predictable. But because of the complexity of the laws involved, and of the interactions between the meteorological components, weather forecasting for more than a few days at a time has so far been an elusive problem.

Since its horizontal extent is so much greater than its vertical extent, the troposphere *can* be visualized in just two dimensions. Within it, large-scale horizontal motions

predominate over the relatively much smaller vertical motions. A new approach to understanding and predicting the world's weather is based on this two-dimensional nature, and describes the atmosphere in terms of its north-south and east-west motion fields.

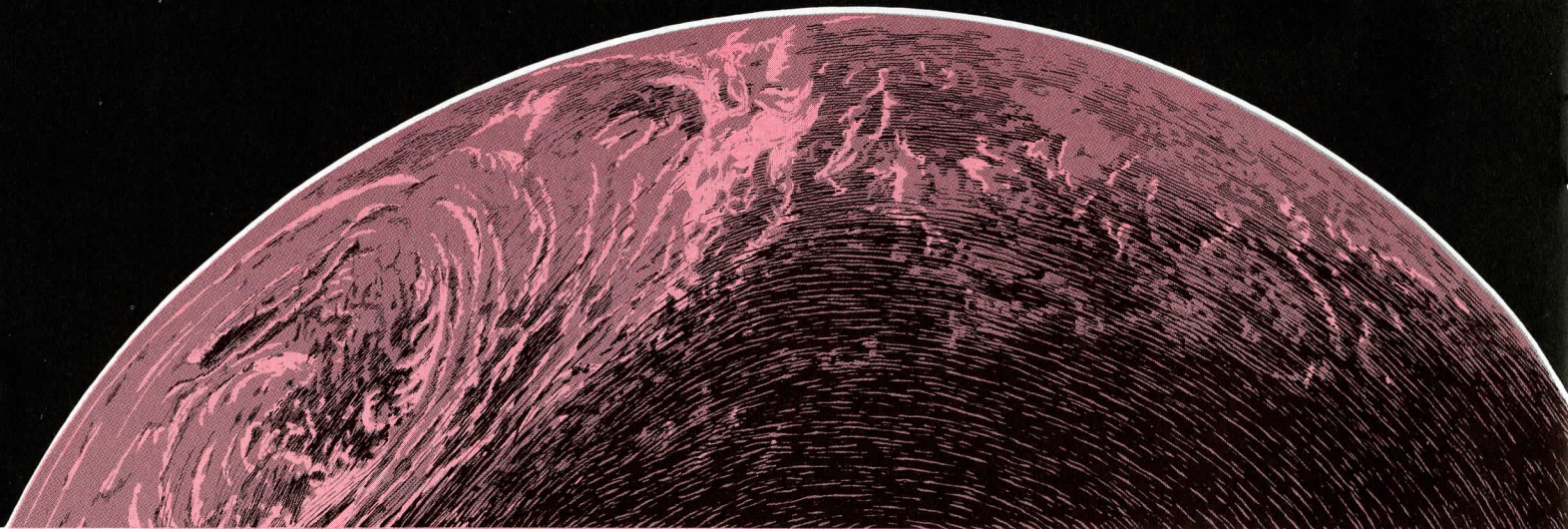
Numerical Modeling

In the 1960s, scientists interested in weather prediction began to devise numerical models of global atmospheric circulation for analysis on high-speed computers. In these models, atmospheric processes involving changes in temperature, humidity, and pressure were approximated by mathematical equations. Computer techniques were developed which put the equations together to simulate the atmosphere in three dimensions.

With these techniques, atmospheric scientists hoped to show evolving weather patterns so that they could forecast weather reliably many days in advance.

However, analysis of the computer models soon revealed that inaccuracies in initial data made the models almost useless for long-range predictions. Errors in initial atmospheric measurements, when fed into a computer, doubled within a few simulated days. For example, temperature errors of about 4° increased to 8° in two or three days, and to 16° in five days, so that measurements lost their predictive value. Errors due to human misjudgment and instrument limitations can of course be reduced, but other kinds of errors cannot—particularly those introduced by variations in the atmospheric structure with spatial scales smaller than the distance between observation points.

Seen from a satellite 17,000 km above the earth, the troposphere is only the lowest fifth of the thin blanket of air which surrounds the earth. Within it, large-scale horizontal motions, such as those that shape the cloud patterns at the lower left, predominate over vertical motions.



The Problem of Turbulence

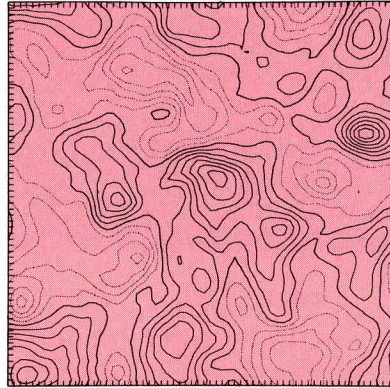
The churning motions of the atmosphere, capable of transporting energy at an exceedingly rapid rate, are not easily analyzed. These powerful, irregular, random currents are actually deformations of the atmosphere's normal easterly and westerly winds, and have many of the intricate characteristics of turbulence in fluids. For example, theoretical studies of the behavior of two-dimensional turbulent fluids show that small-scale currents characteristically feed energy into larger scale motions, just as middle latitude storms (relatively small in scale) feed energy into the planetary scale zonal winds of temperate, tropical, and polar regions.

By treating the atmosphere as a two-dimensional fluid, and applying to it what is known about the turbulent behavior of such theoretical fluids, scientists find that they can better interpret the complex phenomena of the three-dimensional atmosphere. The resemblance of two-dimensional motions to the large-scale atmospheric circulation is no great surprise to atmospheric dynamicists, since the early (and partially successful) numerical weather prediction models were essentially two-dimensional. The existence of a coherent theory of two-dimensional turbulence is, however, a recent development.

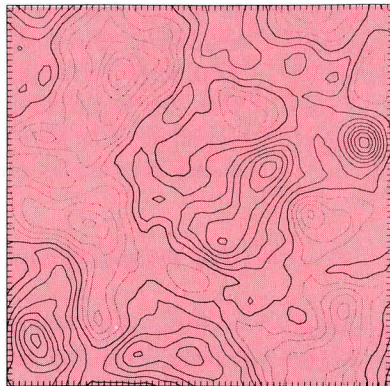
At NCAR, Douglas K. Lilly, assisted by David Fulker as programmer-analyst, has designed a computer experiment in two-dimensional fluid dynamics which, among other things, simulates the tendency of small-scale motions to feed energy into large-scale motions. To drive their two-dimensional fluid model, Lilly and Fulker introduce an artificial forcing function which simulates the energy release of mid-latitude storms; to simulate dissipation of energy, they introduce a drag term that represents surface friction. The forcing function adds energy at a known rate, while the drag term subtracts energy according to the amount of energy in the system—friction is not present unless the

WITHOUT ERROR

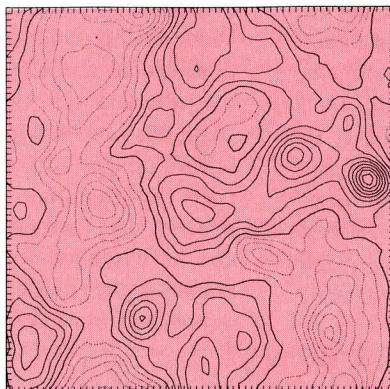
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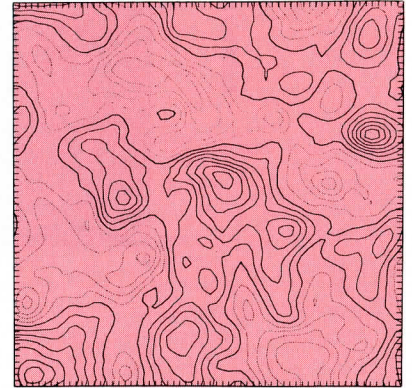


10 Days

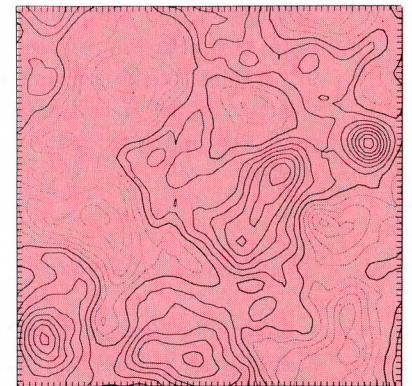


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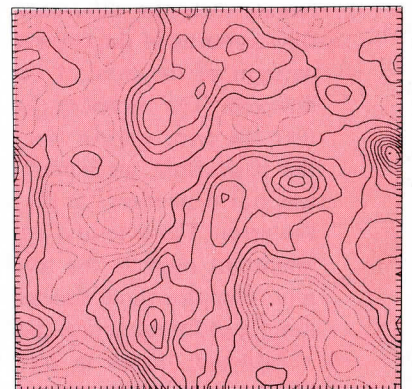
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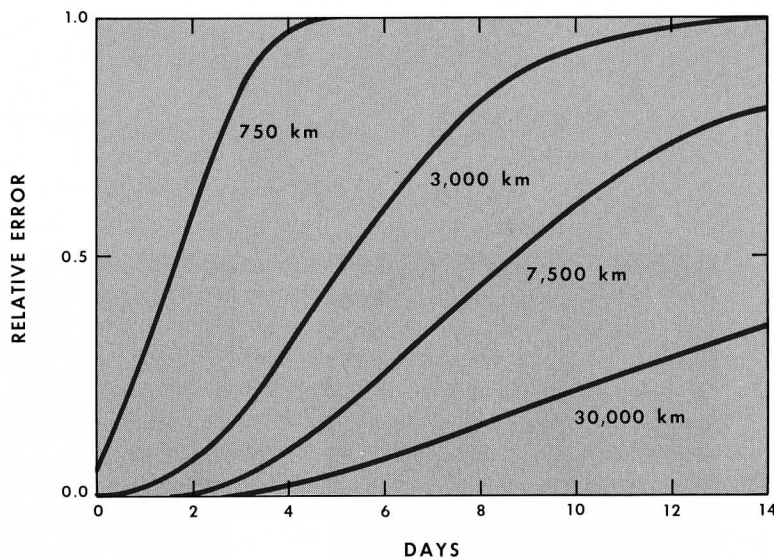
5 Days



10 Days



Two computer time runs with theoretical data analogous to the highs and lows of weather maps show how simulated weather patterns diverge with error.



In computer studies, error growth for large atmospheric motions is measurably less than for small atmospheric motions. For motions less than 6,000 km in diameter, the error soon becomes as large as the waves themselves, so that forecasts become meaningless.

fluids are in motion. As the system gains energy from forcing, it dissipates energy through friction until the two terms balance. From this point on, the energy in the system is constant except for random fluctuations, and the model is statistically similar to the real atmosphere with its stable energy content.

The Growth of Errors

Lilly and Fulker used their two-dimensional stable-state model to examine the error growth that reduces the effectiveness of three-dimensional prediction models. They inserted a small perturbation (to represent an error) into one of two computer time runs. At first, the two runs seemed only slightly different; then the difference increased as the flow patterns of the two runs, which resemble patterns of the flow of the real atmosphere, diverged. The experiments clearly indicated that the error growth rate was a property of the basic fluid mechanics of the model and was not dependent on the detailed nature of the error. These results duplicated in several important respects the behavior of the much more complex three-dimensional models being developed for numerical predictions.

Although errors in starting data are still compounded in the two-dimensional model,

the loss of accuracy in large-scale flow patterns occurs slowly enough that prediction of major features of atmospheric behavior beyond a few days should be feasible. In small-scale three-dimensional motions, however, the errors in the flow pattern can be expected to amplify quickly, so that predictability deteriorates within a short time.

The Future of Forecasting

Lilly and Fulker's research results are timely. Scientists associated with GARP¹ are now defining standards of accuracy for the atmospheric measurements that will form the nucleus of GARP research. Lilly and Fulker have indicated that improved measurements, providing more accurate data for numerical models, can noticeably upgrade long-range forecasting, and they believe that two-dimensional models will aid in understanding the meaning of numerical simulation. Cecil Leith, also of NCAR, has analyzed the theory of two-dimensional turbulence and its application to atmospheric predictability, and he believes that forecasting of large-scale features can be extended to about one week; other scientists place the limits for detailed forecasts anywhere from three days to three weeks.

¹ Global Atmospheric Research Program.

Notes

UCAR Members' Meeting

At the annual meeting of the Members of the University Corporation for Atmospheric Research (UCAR) on October 13 - 14, four new member universities were elected, bringing to 31 the number of universities participating in the management of the Corporation. The new members are:

Harvard University
University of Illinois
at Urbana-Champaign
State University of New York
at Albany
University of Toronto

UCAR membership is open to universities with continuing programs leading to the doctorate in the atmospheric sciences or closely related fields. The University of Toronto joined under a new provision of the UCAR by-laws establishing International Membership for institutions outside the United States.

Representatives of the Members discussed the scope of UCAR's objectives during the 1970s, how these objectives should be pursued, and particularly how UCAR can best stimulate cooperative atmospheric research programs related to the immediate needs of mankind. A report outlining UCAR goals for the decade will be published in 1971.

The Members' Representatives also elected five members to the UCAR Board of Trustees. Two Trustees-elect, Robert G. Fleagle (Uni-

versity of Wisconsin) and Robert R. Long (The Johns Hopkins University), will join the Board in January. Carl F. Floe (Massachusetts Institute of Technology), Kenneth M. Rae (University of Alaska), and Earl G. Droessler (Trustee-at-Large) were re-elected. John C. Calhoun (Texas A&M University), retiring Chairman of the Board, will be an ex-officio Trustee for the coming year.

NCAR Rocket Sampler

The flight of NCAR's second rocket-borne cryogenic air sampler, launched at White Sands Missile Range in late October, ended unsuccessfully. The cryogenic sampler did not operate because of a power failure. Apparently an electrical connector between the NASA-built telemetry section and the NCAR payload separated because of vibrational stresses during launch and ascent. The additional weight of the nose cone and the unused supply of liquid neon overtaxed the recovery parachute, and the sampler was damaged beyond repair when it hit the ground.

The sampler was to have collected air at altitudes between 40 and 50 km by condensation on coils cooled with liquid neon (see *NCAR Quarterly* No. 25, November 1969). A new liquid neon sampler will be constructed and tested for another rocket flight experiment next year.

Notes

Ascension Island Launches

In June and July NCAR's Global Atmospheric Measurements Program (GAMP) flew 13 GHOST balloons from Ascension Island. These were tracked by the NASA Nimbus 4 satellite, using the IRLS (Interrogation, Recording, and Location System) for balloon-satellite-ground communication. In October-November, 17 more flights were launched, bringing the total to 30. Of these, ten were at 30 mb, and twenty at 50 mb. The flights, which are expected to remain aloft for three to six months, support a study by

Richard J. Reed (University of Washington) and James K. Angell (National Oceanic and Atmospheric Administration) of quasi-biennial oscillations, 26-month fluctuations in equatorial stratospheric winds.

Five smaller GHOST balloons were launched in May-June to float at 150 mb, near the top of the tropical troposphere, to test balloon performance at this level for Paul Julian and Henry van de Boogaard of the NCAR staff. One of these balloons remained aloft for 118 days, drifting in or close to tropical latitudes during three circuits of the globe.

A 150 - mb GHOST balloon described a gently sinuous path defining winds in tropical latitudes. Although low-level winds at these latitudes are easterly, westerly winds predominate in the upper troposphere.

