Is Something Strange About the Weather?

Researchers are using a number of tools from the study of chaos, such as strange attractors, in attempts to increase their understanding of the atmosphere and to improve weather prediction

This is the fifth in a series of articles on chaos in various areas of science. The sixth and final article will look at how chaos theory has affected the way scientists and others view the world.

WHY IS IT THAT WE CAN put a man on the moon, but we cannot predict on Thursday whether it will rain on Sunday? Answer: Although it may seem contrary to common sense, it is actually much easier to fly 240,000 miles to the moon than to forecast the weather a few days in advance.

Predicting the weather means understanding the earth's atmosphere, an incredibly complex system of air and moisture. In essence, a weather forecast involves solving a problem in fluid dynamics with dozens or hundreds of equations. Even worse, chaos theory indicates that no matter how good one gets at solving such equations, the weather is inherently unpredictable more than 2 or 3 weeks in advance. But in return, chaos theory—the study of complicated, seemingly random behavior that appears in certain physical systems, including the weather—may also offer some consolation. Researchers using concepts and tools from the study of chaos claim to have new approaches to learning about the weather, some of which could lead to improved forecasting in the future.

At first glance, it seems reasonable that one should be able to predict the weather. One need only identify the important variables—temperature, humidity, pressure, wind velocity, and so on—and discover the equations that relate them. Next, measure the variables and put their values into a computer. Then it becomes a straightforward problem in fluid mechanics, a problem in physical calculation. In principle, it should be no different than figuring how to send a rocket to the moon. If the data are complete enough, the model good enough, and the computer powerful enough, one should be able to forecast the weather as far in advance as desired.

In 1963, Edward Lorenz shattered this hope. Lorenz, a meteorologist at the Massachusetts Institute of Technology, found a simple system of fluid mechanical equations whose long-term solution was inherently unpredictable. The lack of predictability arose from a "sensitivity to initial conditions," meaning the solution to the equations would change completely if the starting point were altered by even a tiny amount. The implication for weather forecasting has come to be called the butterfly effect—a butterfly flitting its wings in Honolulu may influence whether it rains in New York City a month later.

It was the early 1970s before scientists outside the meteorological community learned of Lorenz' results. Since then, the same type of unpredictable, seemingly random behavior Lorenz found in a simple fluid dynamical system has been discovered in many other areas—population biology, chemistry, astronomy, and medicine, to name a few. That behavior is now called chaos, a term coined by University of Maryland mathematician Jim Yorke.

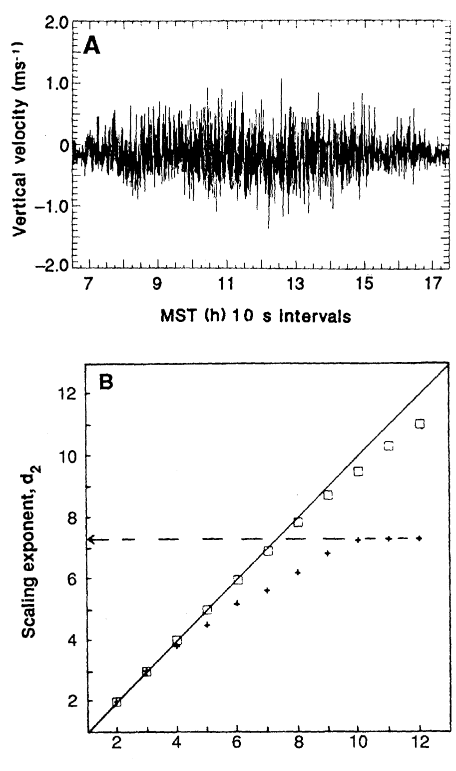
The message of chaos was that many things in nature, including the weather, do not act like a rocket flying to the moon. Burning a few extra ounces of fuel makes little difference in where the rocket ends up, but the difference of a tenth of a degree in the temperature can alter the course of the weather. This makes the weather unpredictable in the long run. Nonetheless, fluid dynamical systems do obey mathematical equations, so there is a certain regularity underneath the disorder.

Researchers have applied various tools from chaos theory to study this underlying order in the weather and, more generally, in fluid dynamics. Many have attempted, with varying degrees of success, to mimic complex physical systems with simple, chaotic models. Some have hunted for order in weather patterns and fluid flows by seeking strange attractors, a sort of footprint that is left behind when chaos stomps through a system (see box). Others use the idea of multiple attractors to explain why the weather shifts between a few distinct types of behavior. Some fluid dynamicists are attempting to use chaos theory to understand turbulence, one of the most intractable problems in any area of science.

Lorenz' work had two messages. The first—that the butterfly effect imposes fundamental limits on predictability—was rather pessimistic. Science will never know certain things. The second was more upbeat: Since much of the complicated, seemingly random behavior in the world may actually be simple in origin, it may be much easier to analyze this complexity than was previously thought.

This second message has generated great interest in model building as a way to understand complicated behavior. Take El Niño, for example. This climate pattern appears at irregular intervals and is signaled by the ocean off the coast of Peru becoming unusually warm, which does great damage to the fishing industry there. Although the timing of El Niño appears random, researchers have proposed models with as few as three equations that roughly mimic its behavior. The models have no immediate value in predicting El Niño, but researchers hope to gain insights into its behavior by understanding these simple models.

Some of the most striking modeling work has been done not on the earth's atmosphere but on the atmosphere of Jupiter. In the swirling turbulence of the Jovian atmosphere, a singular weather pattern has endured for more than 300 years—the vortex



A strange attractor *for an 11-hour record of wind velocity (A) has dimension 7.3 (B).*

known as the Great Red Spot. Last year, Philip Marcus of Berkeley showed that a simple model incorporating some of the basic features of Jupiter's atmosphere naturally settles into a pattern with a single large vortex similar to the Great Red Spot. Computer simulations of the model show, Marcus says, that a large vortex forms spontaneously out of the small-scale chaos of the atmosphere and that this chaos keeps the vortex going.

The model is simplistic, but Marcus says it offers insight into the basic question about the spot: "How does spatial structure form out of something that initially doesn't have spatial structure?"

Princeton's Gareth Williams downplays the Marcus model, saying it is less complete than work done earlier by others. "If you get into the Great Red Spot," Williams says, "you need to ask some hard questions. There are ten features that must be described, not just the uniqueness [that is, why there is just one vortex]." Williams has a model that explains nine of the ten features, he says, and computer simulations based on it produce a vortex very much like the Great Red Spot.

Model building is an intuitive approach to meteorology. A researcher decides which factors are likely to be most important, incorporates them into a mathematical model, runs that model on a computer to see how closely it mimics the real behavior, and then modifies the model to bring it more closely in line with reality. Because meteorological data are so complex, it is extremely difficult to discern any structure directly from observation. But a tool from chaos theory—the strange attractor—offers the potential for getting information about the structure of the weather directly from the data rather than indirectly from modeling.

Looking for strange attractors in weather patterns is the most controversial chaos-inspired technique among meteorologists. Proponents say it offers a new way to study the dynamics of the atmosphere. Various researchers have claimed to find low-dimensional strange attractors in the data, which would imply the weather has more structure—and thus more predictability—than thought. Doubters claim the weather data is too poor and too noisy to analyze by this method, and they say the "existence" of strange attractors owes more to sloppy math than to meteorological order.

The idea behind the mathematical concept of a strange attractor is that if a physical system, such as Earth's atmosphere, follows any type of pattern, that pattern can be discovered by the proper techniques, even if it is very complicated and looks random (see box). The most important quantity associated with a strange attractor is its dimension, which indicates how complicated the pattern is and gives a rough indication of how many variables it takes to describe the behavior of the system. If a strange attractor is low dimensional, it indicates that the weather under consideration is simple enough to model with only a few variables. Also, since the strange attractor contains the system's "preferences" for behavior, it is possible to use the strange attractor to predict the system's future actions.

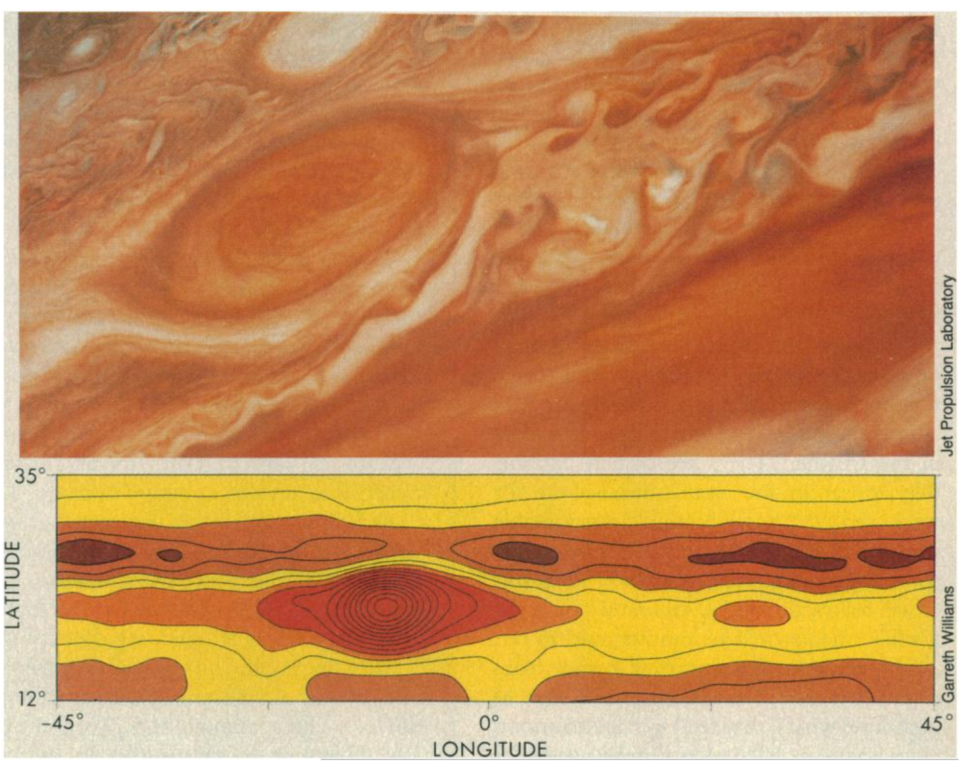
"We may be able to use ideas from chaos theory to actually predict the weather," says Anastasios Tsonis at the University of Wisconsin–Milwaukee. "We use weather data to reconstruct the attractor, and then we try to reconstruct the mapping [that describes the weather]." Theoretically, this technique works very well in uncovering underlying structure from experimental and observational data, he says.

A series of papers have claimed to find strange attractors in the earth's climate patterns. In 1984, Catherine Nicolis and Gregory Nicolis of Brussels analyzed percentages of oxygen-18 in the earth's atmosphere over the past million years, as calculated from measurements from deep-sea cores. (The amount of oxygen-18 in a layer of marine sediment provides an indication of total ice volume on the earth during the time the layer was deposited.) The two scientists claimed to detect a strange attractor with dimension about 3.1. This indicated, they said, that climatological models with only four variables could describe the essential features of the system.

Two years later, German meteorologist Klaus Fraedrich did a similar analysis, finding a climatic attractor with dimension 4.4. In addition, he analyzed daily records of air pressure and hours of sunlight over periods of 10 to 30 years. In each case, he found attractors with dimension between 3 and 5.

Then the German physicist Peter Grassberger, one of the leading chaos theorists, took aim at these two studies. Reexamining the same data that Nicolis and Nicolis analyzed plus additional core samples, he found no sign of a climate attractor over the past 2 million years. Although the existence of such an attractor could not be ruled out, he said, if one did exist, its dimension was much greater than 4. A similar analysis of tree-ring data over the past 7100 years showed that any climate attractor for that period must have dimension greater than 10. In assessing Fraedrich's work, Grassberger claimed there was a technical mistake that led to seeing greater structure than was really there.

That did not end the debate. In 1987, three Canadian mathematicians looked at 40 years of daily meteorological data and found an attractor with dimension slightly over 6. Last summer, Tsonis and James Elsner examined an 11-hour record of wind velocity



The Great Red Spot, *a vortex that has lived in the chaotic turbulence of Jupiter's atmosphere for more than 300 years, can be modeled very accurately on computer.*

taken in Boulder, Colorado. They reported a strange attractor of dimension 7.3.

A number of scientists, particularly those who study fluid mechanics, doubt the reliability of the dimension estimates. Harry Swinney of the University of Texas at Austin, who has studied chaos extensively in laboratory fluid flows, is "very skeptical about some calculations of dimensions. You need a lot of measurements with a lot of data points." The idea of calculating the dimension of strange attractors has "limited use in systems with many degrees of freedom [such as the weather]."

Tsonis argues dimension calculations do provide information about the weather. "If you want to estimate [the dimension] with an accuracy of 99%, then you need a tremendous amount of data," he says. "But if you estimate a dimension to be 7 or 8 and you have an error of 20%, then you still have shown a low-dimensional attractor."

Some meteorologists view these dimension calculations as useless exercises that do little to help predict the weather. "The people who have published them are really peripheral to the [meteorological] community," says Michael Ghil, a former mathematician and now chairman of the atmospheric sciences department at the University of California, Los Angeles. Ghil admits that low-dimensional attractors may exist in some limited cases, such as average climate patterns over the past million years, but adds that the calculations do not reveal much that was not known before. There are probably five to ten variables that determine physical processes on a scale of tens of thousands of years, he says, so an attractor with five to ten dimensions would be consistent with the known dynamics of climatic evolution.

As for finding a low-dimensional attractor that will help daily weather forecasts, forget it, Ghil says. "There's just no way you're going to come up with a number [for the dimension of a global weather attractor] that is less than 100."

But Ghil does believe attractors may prove valuable in improving long-range weather forecasts. He and other researchers are pursuing the idea of multiple attractors in the weather. There are certain patterns that appear in the earth's atmosphere for weeks at a time, and Ghil thinks it is valuable to think of each of these patterns as corresponding to a separate attractor. The weather will follow the outline of one attractor for a while, then switch to another, and so on.

The evidence for this view comes from certain features of the atmosphere, such as high-level winds, that tend to fall into anomalous patterns called blocks and wave trains which may last for weeks at a time. Although the specific behavior of the atmo-

Where Strange Attractors Lurk

The strange attractor is an imaginary beast that lives in an abstract mathematical space. Usually it is so big and so complex that it cannot be captured completely in a two-dimensional drawing. Scientists hunt this curious creature because of the company it keeps—where the strange attractor lurks, there also is order and structure.

In less metaphorical terms, looking for strange attractors is a mathematical technique used to get information about structure in complex physical data.

The strange attractor lives not in the physical world of space and time, but in phase space, where the dimensions can be any physical qualtities. For example, to describe the weather, one might work in a phase space with dimensions of temperature and wind velocity. To represent how the weather changes over time, one would draw a curve in phase space, where each point on the curve indicated the temperature and wind velocity at a particular time. A phase space can have as many dimensions as necessary to describe the behavior of the system, although it is difficult to visualize a space with more than three. A four-dimensional phase space might encompass temperature, pressure, wind velocity, and humidity.

An attractor—strange or otherwise—is the set of points in a phase space corresponding to all the different states of a system. For example, in the temperature-wind velocity phase space for Los Angeles, 70°F–10 miles per hour would be on the attractor, but 300°F–250 miles per hour would not. (It is called an attractor because the system is "pulled" toward it—the weather in Los Angeles, as represented in phase space, stays close to one attracting set.) In short, as Edward Lorenz puts it, a weather attractor basically is a mathematical representation of the climate.

If there were a place on the earth where the temperature and wind velocity were constant every day, the attractor would be a single point. If the temperature and wind changed in a simple cyclic pattern—perhaps starting at 50° at 5 a.m., rising steadily to 70° by 3 p.m., then falling gradually until the pattern started over again at 5 a.m.—the attractor would be a loop. Since weather is much more complicated than this, real weather attractors will not be as simple as points or loops.

To measure the complexity of an attractor, one calculates its dimension. Roughly speaking, the dimension of an attractor tells how many variables are needed to fully describe the system. For the point attractor, the dimension is 0—no variables are needed because the weather is always the same. The dimension of the loop attractor is 1—the only variable needed to describe this weather is the time of day.

More complicated attractors, such as for the weather, not only have larger dimensions, but their dimensions are usually not whole numbers. An attractor whose dimension is not an integer is called a "strange attractor" because it is unlike the normal physical objects of everyday experience, which have integer dimensions. A strange attractor is strange. But despite their mathematical complexity, strange attractors can be thought of simply as the points in a phase space that a given system will visit.

Proving that a strange attractor exists in a set of weather data and calculating its dimension is not easy. The first problem is that a researcher usually does not have a complete set of weather data with temperature, pressure, wind velocity, and so on; instead, he has a single time series—the average temperature each day for 10 years, for instance. Fortunately, a technical trick is available to turn a single time series such as daily temperature data into a form that serves the same role as daily data for several independent variables.

Searching for a strange attractor is done by looking at the data in more and more dimensions until a structure appears. To understand the mathematical technique, think of hunting for the loop attractor in a mass of weather data. If one looks at the data in one dimension, there is not enough room for the loop to show; one gets only a line. When one uses two dimensions, the loop becomes visible—structure has appeared. In three dimensions, the loop looks much as it did in two—it is still a loop—so one can stop adding dimensions.

After finding the number of dimensions needed to display a strange attractor, one calculates its dimension. This calculation is technical and very delicate, and if one does not have a great amount of data or if the dimension of the strange attractor is not very low, it is next to impossible. In the case of weather data, which are noisy and incomplete, the precise dimension of an attractor is often hard to pin down. ■ **R.P.**

sphere in a blocking pattern is complex and unpredictable, there is an obvious overall structure for each of the blocks. The atmosphere moves from one anomalous pattern to another with certain probabilities.

"We can not only predict the expected duration of one of these anomalies, but we can also predict what the next one is likely to be and how long it will take between them," Ghil says. Being able to predict these general large-scale patterns gives information about likely long-term weather patterns, he says. "We hope to get a practical long-range forecasting scheme out of it."

Other meteorologists question the value of chasing multiple attractors. "There are so many degrees of freedom in the atmosphere that it's hard to believe you have a probability distribution in phase space with multiple attractors," says Peter Stone, director of the Center for Meteorology and Oceanography at MIT. Strange attractors do tend to appear in systems with few degrees of freedom, he says, but they are rare in systems with many independent variables. "Over and over again someone has come up with a model [of the atmosphere] that shows attractors, but adding more details kills it [the attractor]." The more variables, the less the chance for an attractor, and the atmosphere has a lot of variables.

Hard problems remain. One of them is how to deal with turbulence in fluids (and thus in the atmosphere). Although turbulence is often given as an example of chaos, chaos theory actually has very little to say about such spatial disorder. Work on chaos has been concerned with *temporal* irregularities, such as appear in daily records of temperature or wind velocity. But turbulence is "chaotic" also in a *spatial* sense—the behavior of a turbulent fluid is random and unpredictable from point to point in the fluid. Charles Van Atta of the University of California at San Diego says, "An essential feature of real turbulence is a form, as yet not rigorously defined, of spatial chaos, perhaps in combination with a form of spatial chaos." To understand turbulence, he says, "may be a very difficult process, probably requiring additional discoveries, perhaps as revolutionary as those which have led to the interest in chaos." ■ ROBERT POOL

ADDITIONAL READING

C. Essex, T. Lookman, M. A. H. Nerenberg, "The climate attractor over short timescale," *Nature* **326**, 64 (1987).
P. Grassberger, "Do climatic attractors exist?" *ibid.* **323**, 609 (1986).
C. Nicolis and G. Nicolis, "Is there a climatic attractor?" *ibid.* **311**, 529 (1984).
A. A. Tsonis and J. B. Elsner, "Chaos, strange attractors, and weather," *Bull. Amer. Meteor. Soc.* **70**, 14 (1989).
G. K. Vallos, "El Niño: A chaotic dynamical system?" *Science* **232**, 243 (1986).

Seeing Cracks in Three Dimensions

A scientist at Los Alamos National Laboratory has developed a method to create three-dimensional microscopic images of surfaces. The technique should be valuable to researchers who investigate how cracks form on the surfaces of various materials in order to learn how to make stronger materials.

David Carter, a materials researcher at Los Alamos, modified an existing technique that extracts three-dimensional information from pairs of photographs and used it on electron micrographs of material surfaces. The so-called "stereopairs" technique works much like human vision—it compares two images of an object from slightly different angles and deduces the relative heights of the object's surface features.

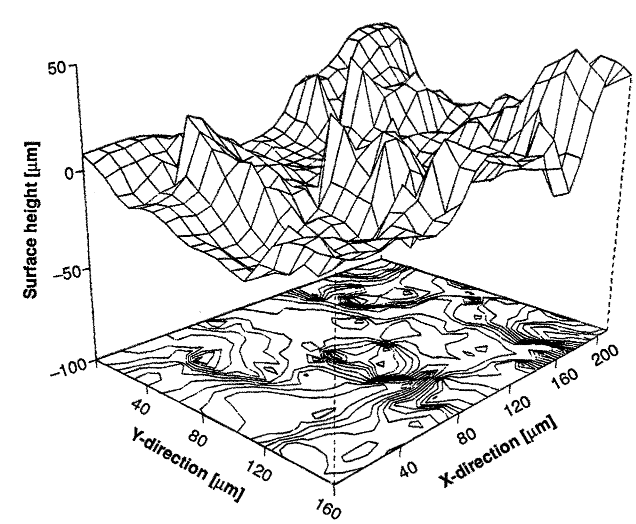
Carter uses a scanning electron microscope to take two pictures of an object from slightly different angles. After one electron micrograph is done, the object is turned a small amount—usually about 8°—and a second micrograph is taken. The pictures are converted to digital form and entered into a computer. By measuring the parallax—the difference in position when seen from two different angles—of the features in the two images, the computer calculates the height of each object with respect to a reference point. This height information is then used to generate a three-dimensional image of the surface and to calculate its roughness parameters.

Carter said his three-dimensional technique calculates the roughness of a surface much more accurately than the method most commonly used now, where a stylus is tracked across the surface of a material and its resulting up-and-down motion is recorded. With the electron microscope set for a magnification of from 500 to 1000 times, the three-dimensional pictures have a resolution of about 5 micrometers, he said, "much better than anything done with a stylus."

Carter developed the three-dimensional imaging system to analyze how fractures develop. "With this technique, you can tell exactly how a material breaks," he said, "and the more you know about how a material breaks, the better you can design it." By looking at cracks along surfaces and seeing what paths they are most likely to take, materials engineers can design substances that resist fracturing.

Carter has analyzed fractures in composites of molybdenum disilicide strengthened with "whiskers" of silicon carbide (SiC). These composites are being studied for use in such high-temperature environments as jet aircraft engines, and the cracks that Carter looked at were made at 1200° to 1400°C. The three-dimensional images enable one to see how fractures behave as they cross the whiskers. The break might go right across a fiber, for instance, or the fiber might become separated from the matrix material in which it is embedded. "You can tell these things quite easily with a three-dimensional picture of a fracture," he said.

The technique could be applied for uses besides fracture studies, Carter said. "If you can take a stereo picture of whatever it is, you can calculate its roughness. The accuracy is determined by the scale you're working on." ■ ROBERT POOL



Los Alamos National Laboratory

A roughness map *showing the fracture surface of a composite of molybdenum disilicide and silicon carbide whiskers.*