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

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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.

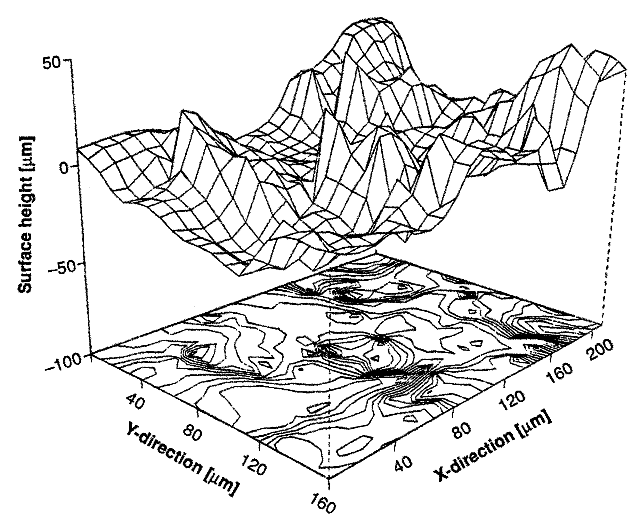
Carter uses a scanning electron microscope to take two pictures of an object from slightly different angles. After one electron micrograph is done, the object is turned a small amount—usually about 8°—and a second micrograph is taken. The pictures are converted to digital form and entered into a computer. 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



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

Los Alamos National Laboratory