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Complexity and Climate

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Complexity and Climate

D. Rind

The climate that we experience results from both ordered forcing and chaotic behavior; the result is a system with characteristics of each. In forecasting prospective climate changes for the next century, the focus has been on the ordered system's responses to anthropogenic forcing. The chaotic component may be much harder to predict, but at this point it is not known how important it will be.

Is the climate system "complex," and does it matter for long-range (decadal-scale) climate forecasts? The answer to the first question is definitely "yes"; the very concept of complexity originally arose in concert with atmospheric processes (*1*). To the second question, we have to answer "we don't know." If it is important, it will just make predictions of the anticipated climate change of the next century that much more difficult.

A complex system is literally one in which there are multiple interactions between many different components. This definition certainly fits the climate system. Consider how rain, falling on Earth, contributes to the growth of plants, which in the process of growing transpire the moisture back to the atmosphere. Once there, the atmospheric water vapor can form clouds, which affect the solar radiation that influences how plants grow. The atmospheric moisture also absorbs radiation from Earth (as a "greenhouse" gas), and this absorption, along with its cloud-generation capability, affects the temperature patterns. Temperature differences lead to pressure differences that generate wind and storms; the storms provide for the rainfall, and the wind helps produce the turbulence that enables transpiration to take place. The wind and rain also help govern the circulation of the oceans, with their further influence on temperature. Involved in this cycle are the components of cloud physics, land surface physics, biological processes, atmospheric radiation, atmospheric dynamics, and ocean dynamics, all with multiple interactions.

Dynamical Interactions and Oscillatory States

In addition, the richness of such interactions apparently allows complex systems to undergo spontaneous self-organization, in a sense producing order in the midst of chaos. A number of the components mentioned above are prime candidates for chaotic subsystems. The basic equations used to define atmospheric processes (the "Navier-Stokes" equations) are nonlinear, which is to say that the predicted variable (such as wind speed and direction or wind "velocity") appears in the equation raised to a power greater than one. For example, predicting the wind at your location tomorrow depends on where the air is coming from today (that is, the wind velocity) multiplied by how the wind at that location differs from the wind at your location (the wind gradient). This characteristic of the equations allows the system to be highly sensitive to small differences in the initial state: Change something slightly, and you can get a very different response.

The result of this tendency is to promote oscillations between a number of quasi-stationary states that can influence local weather and its variability and perhaps climate as well (*2*). A prime example is the so-called North Atlantic Oscillation (NAO), in which during one phase (the "high" phase), storms are strong near Iceland and warm air is advected over northern Europe, whereas in the other phase, storms are weak and northern Europe is much colder. Presumably, while in the midst of one state, a small change occurs and the system transitions to the other state. Were one phase to be maintained for some reason over a long enough period of time (say several decades), it would in effect lead to a "climate change" for the affected areas. In point of fact, the NAO has generally been in a high phase for the past several decades, as has another oscillation affecting the North Pacific and North America (the so-called "Pacific–North American Oscillation," or PNA). Together, these two phases have been associated with extensive warming over land in the Northern Hemisphere, with the oceans remaining relatively cool (Fig. 1).

Add to this the fact that the climate system consists of interactions between the atmosphere and ocean, which can again force a transition between very different states. The wind stress that drives the surface ocean is affected by temperature gradients within the ocean, which are altered by the wind forcing. Therefore, a particular state of the atmosphere and ocean may contain within it the "seeds of its own destruction," leading to an opposite state. A prime example of this process is the oscillation of El Niños and La Niñas, warm and cold water conditions in the eastern Pacific. Another example may be the ocean circulation in the North Atlantic, part of the so-called "conveyor belt" bringing warm water north at the surface and cold water south at depth; it is thought that this conveyor belt has varied in the past (*3*) and might do so again in the next century.

Physical Interactions: From Order to Chaos

In addition to these dynamical interactions, the physical components of the system run the gamut from order to randomness. Earth's climate is driven by solar forcing, which is pretty much the same from year to year. Regionally, climate and weather are associated with large atmospheric waves (whose surface expressions are the low- and high-pressure areas shown on weather maps), which are forced by the unchanging topography and land-ocean distribution. And it is known that the climate has maintained enough consistency over the past 4 billion years to allow life to survive. Hence, the temperatures must have maintained the range allowing for liquid water; the mean temperature has probably not varied more than ±5%. All of this argues for stability. However, the system also contains subcomponents, such as those referred to above, that number among the best known analytically intractable stochastic processes, namely, turbulence in the boundary layer and the movement of water through the soil. Even atmospheric water vapor, the chief greenhouse gas affecting the surface temperature, can be highly variable because of the exponential relation of water-holding capacity with temperature. A warming climate will evaporate more moisture into the air, which will increase the atmospheric greenhouse capacity, further warming the system and providing for more evaporation, an example of positive reinforcement that can drive the system away from a steady state.

Complexity and Climate Change: Is It Important?

So the atmosphere is not entirely stable but does not vary chaotically either; it self-organizes into states that show elements of quasi-stability. In this sense, it is much like other complex systems, ranging from economics to human organizations, as detailed in the other papers in this special issue. Of what advantage is it to know this? The very recognition of these oscillatory states can improve our predictions, as well as our understanding. It is clear that if you would like to forecast what the weather will be over Europe next winter that there is great advantage in predicting what the state of the NAO is going to be. Predicting El Niños is also quite useful for

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many regions of the globe; witness the generally successful forecast of rains in California during the winter of 1997–98, made possible by prediction of the continued intense El Niño. What is not clear is how important appreciation of complexity is for the most important long-range climate forecast, predicting what conditions will be like during the next century associated with projected greenhouse gas warming.

As exemplified by the most recent International Panel on Climate Change report (*4*), the most important climate change aspects are thought to be the radiative forcing variations. Increasing CO_2 and other trace gases will augment the greenhouse capacity of the atmosphere, allowing for additional radiative heating of Earth. The prime questions in that report, and in the discussions regarding future climate change in general, relate to the magnitude of the system's response (its "feedbacks") to those anthropogenic perturbations. Water vapor, cloud cover, and sea ice may respond when we start warming the planet, and they all affect the net radiation, that is, the available energy. Uncertainty in these issues gives rise to a range of possible global surface air temperature increases due to doubled atmospheric CO_2 from 1.5° to 4.5°C (*4*).

Where do the transitions from one quasi-steady state to another come in? The climate system has varied from one state to another (ice ages and interglacials), presumably driven by variations in Earth's orbit around the sun. Exactly how this relatively small forcing brings about ice ages is still somewhat uncertain (*5*), and perhaps the complex atmosphere-ocean-ice interactions help lead to these extremes. On a more local scale, suppose that in a warmer climate, there will also be a tendency for an increase in the phase of the NAO that advects warm air over northern Europe. Therefore, in addition to the radiative warming of the planet, there would also be an advective warming in that region. The projected magnitudes of these two effects could well be similar (locally), so for some regional climates it would be important to know how climate change may affect the phase of these oscillations. Has the recent warming over land (Fig. 1) been the result of high phases of the NAO and PNA being driven by global warming, or are they just unrelated "chaotic" coincidences? Another example would be El Niños. The frequency of El Niños (as opposed to La Niñas) has increased during the past 20 years; is this increase due to global warming?

Conversely, the phase of some of these oscillations might affect the radiative balance and hence overall warming of the planet. Sea-ice distributions are quite different in different phases of the NAO (*6*), and tropical moisture varies with the El Niño–La Niña phase (*7*). In this way, there would be an "up-scale" transfer of importance from the nonlinear effects to the major questions of climate change. Were the conveyor belt to change mode in response to changing atmospheric forcing, even greater global perturbations might be expected.

Complexity and Global Climate Models

To test the overall effect of nonlinearities in the full climate system, computer models are used. In various studies, the oceanic conveyor belt does seem to be affected next century, which could minimize warming over Europe (*4*, *8*). In addition, one can vary the initial atmospheric conditions in a model while keeping the radiative forcing, for example, CO_2 concentrations and solar intensity, unchanged; the differing solutions are then thought of as the "chaotic" component of climate variability (*9*). The primary conclusion of such a study was that chaotic fluctuations at midlatitudes altered the climate by up to ±0.5°C, which is twice as large as the greenhouse gas forcing over the past two decades but substantially smaller than the forecast change for the next century. However, whether the models can accurately assess this aspect is debatable; most have not been

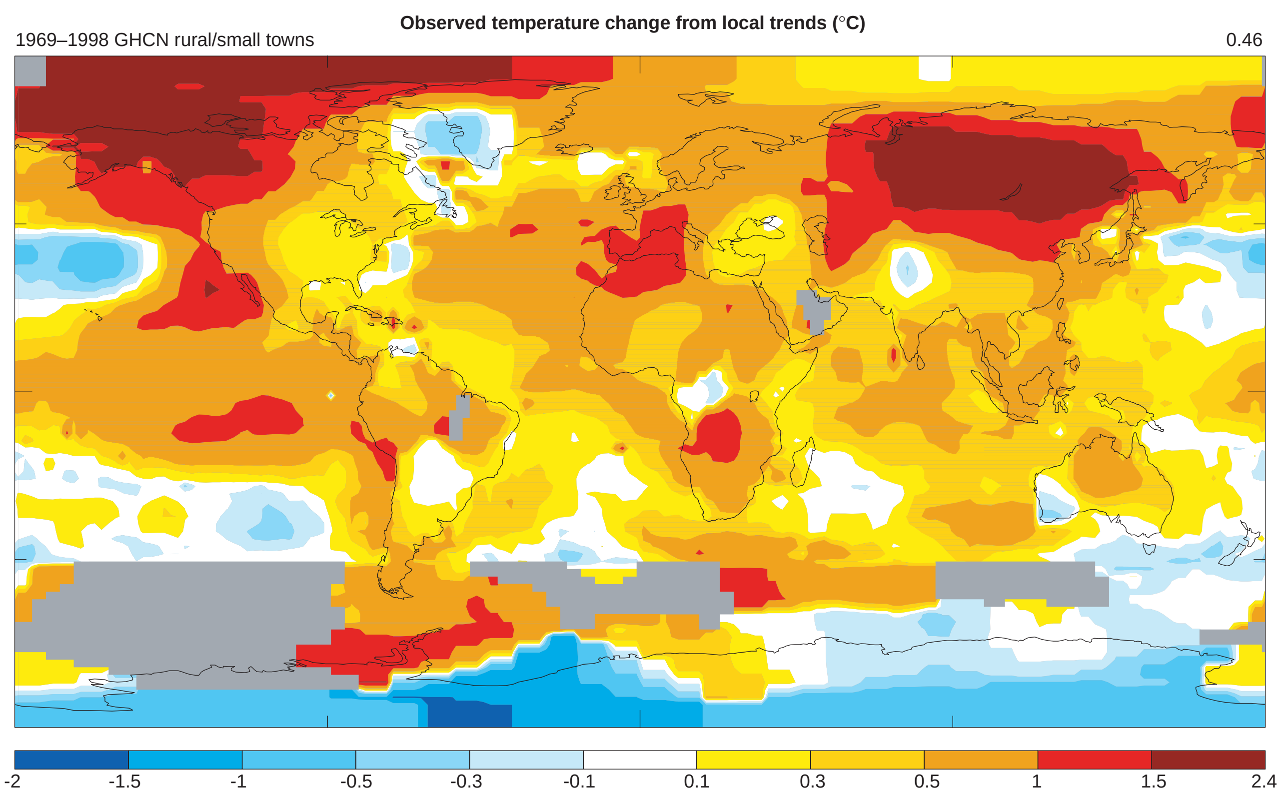

Fig. 1. Surface air temperature change between 1969 and 1998 based on land data from the Global Historical Climate Network (GHCN) and ocean temperature data. The gray areas in the figure indicate lack of data [courtesy of James Hansen]. The warming over land in the extratropical Northern Hemisphere is associated with consistently high phases of natural oscillations; the warming of the tropical Pacific is associated with increasing frequencies of El Niños. Whether these frequency changes are the product of global warming or simply chaotic variations is the subject of continued research (*13*, *14*).

rigorously tested for their ability to produce the oscillatory states usually associated with nonlinear effects. In addition, it can be argued, as by Deutsch (*10*), that the Navier-Stokes equations, although capable of simulating mean macroscopic characteristics, are inappropriate for determining sensitivities to initial conditions. Because all objects, including those in the climate system, really obey quantum theory not classical mechanics and quantum theory does not show such sensitivity to initial conditions, perhaps this modeling approach provides the wrong estimate of the real world sensitivity.

The uncertain importance of complexity in climate has implications for the resources needed to model the climate system and provide future forecasts. In practical terms, the questions become what spatial and temporal scales must be included in models, and how accurate must the depiction of the specific physical processes be? Depending on the perceived importance of the nonlinear effects, these questions may have very different answers.

From the point of view that focuses on the net radiation, detailed physics and fine scales are required only when necessary for modeling those processes that have the largest impact on the available energy. An appreciation of exactly what those scales must be awaits better understanding of some of the phenomena, for example, convection and cloud formation. Other scales and physical details are important primarily for localized impacts. For example, we probably need better understanding of how water moves through the soil, which includes both stochastic flow through a porous media and pipe flow through an irregular distribution of worm and root holes, if we truly want to be able to predict water availability in specific regions; a prime target would be forecasting the future recharge of the Ogallala aquifer, which provides much of the water for irrigation in the southwestern United States and is already being depleted (*11*).

If, on the other hand, there is a need to account for the various nonlinear effects and their up-scale potential, then the small scales acquire greater importance, as the key interactions that govern transitions from one state to the other may depend on local processes. Palmer (*12*, pp. 419–420) argues that "it may not be enough for climate models to have fluxes that are accurate to 4 W m^{-2} on global scales; they may also have to be accurate to 4 W m^{-2} in specific key sensitive regions, even if we are only interested in the hemispheric-mean response to imposed CO_2 doubling." Similarly, if the change in El Niño frequencies in the future is to be investigated, this imposes stringent requirements on modeling scales: None of the models used to simulate climate change seem to have sufficient resolution in the tropical oceans to induce realistic El Niños (*4*).

Conclusion: Limits to Forecasting?

Where does this leave us? Questions concerning the future climate in general will probably continue to be dominated by uncertainties in the radiative feedbacks. These feedbacks may be influenced by the system's nonlinearities and the future patterns of variability, but we do not know by how much. On the regional scale, the nonlinearities might play a larger role; they also might be extremely difficult to forecast. Climate, like weather, will likely always be complex: determinism in the midst of chaos, unpredictability in the midst of understanding.

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VIEWPOINT

Complexity and the Economy

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After two centuries of studying equilibria—static patterns that call for no further behavioral adjustments—economists are beginning to study the general emergence of structures and the unfolding of patterns in the economy. When viewed in out-of-equilibrium formation, economic patterns sometimes simplify into the simple static equilibria of standard economics. More often they are ever changing, showing perpetually novel behavior and emergent phenomena. Complexity portrays the economy not as deterministic, predictable, and mechanistic, but as process dependent, organic, and always evolving.

Common to all studies on complexity are systems with multiple elements adapting or reacting to the pattern these elements create. The elements might be cells in a cellular automaton, ions in a spin glass, or cells in an immune system, and they may react to neighboring cells' states, or local magnetic moments, or concentrations of B and T cells. Elements and the patterns they respond to vary from one context to another. But the elements adapt to the world—the aggregate pattern—they co-create. Time enters naturally here via the processes of adjustment and change: As the elements react, the aggregate changes; as the aggregate changes, elements react anew. Barring the reaching of some asymptotic state or equilibrium, complex systems are systems in process that constantly evolve and unfold over time.

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Such systems arise naturally in the economy. Economic agents, be they banks, consumers, firms, or investors, continually adjust their market moves, buying decisions, prices, and forecasts to the situation these moves or decisions or prices or forecasts together create. But unlike ions in a spin glass, which always react in a simple way to their local magnetic field, economic elements (human agents) react with strategy and foresight by considering outcomes that might result as a consequence of behavior they might undertake. This adds a layer of complication to economics that is not experienced in the natural sciences.

Conventional economic theory chooses not to study the unfolding of the patterns its agents create but rather to simplify its questions in order to seek analytical solutions. Thus it asks what behavioral elements (actions, strategies, and expectations) are consis-