Nonlinear Geophysics: Why We Need It

Few geoscientists would deny that effects are often sensitively dependent on causes, or that their amplification is commonly so strong as to give rise to qualitatively new "emergent" properties, or that geostructures are typically embedded one within another in a hierarchy. Starting in the 1980s, a growing number felt the need to underline the absolute importance of such nonlinearity through workshops and conferences. Building on this, the European Geosciences Union (EGU) organized a nonlinear processes (NP) section in 1990; AGU established a nonlinear geophysics (NG) focus group in 1997; and both unions began collaborating on an academic journal, *Nonlinear Processes in Geophysics,* in 1994.

The disciplines coalescing in the NG movement are united by the fact that many disparate phenomena show similar behaviors when seen in a proper nonlinear prism. This hints at some fundamental laws of self-organization and emergence that describe the real nature instead of linear, reductive paradigms that at best capture only small perturbations to a solved state or problem.

This article grew out of an open discussion, which followed an AGU/Canadian Geophysical Union session entitled "Geocomplexity," held at the Joint Assembly on 27 May 2009, and a linked workshop held at York University (28–29 May). At both meetings, participants recounted the difficulties encountered by nonlinear approaches in gaining the recognition they deserve. It is therefore timely to define and explain NG and its achievements. We also explain how—by allowing us to overcome long-standing obstacles—NG is important not only to the scientific community but also to society at large.

Studying NG Helps Science Disciplines Progress

The undeniable urgency of floods, hurricanes, earthquakes, or climate change (to name a few) has tended to reduce science to a system for the elaboration of "products" and "deliverables" with understanding as an incidental by-product. In comparison, concepts of nonlinear geophysics can provide a rational basis for the statistics and models of natural systems including hazards, which previously were treated by ad hoc methods.

NG has grown to respectable proportions. For example, the EGU 2009 general assembly had about 700 abstracts in 39 different NP-organized and -coorganized sessions, and the 2009 AGU Fall Meeting will have 10 NG sessions with about 160 abstracts. The term "nonlinear geophysics" has now evolved to the point where many recognize it as fundamental geophysics, the nonlinear sessions being typically interdisciplinary forums where participants compare the results of applying common theoretical concepts in sometimes radically different application areas.

NG must prove itself through successful applications. However, the meaning of "success" is not always straightforward and can sometimes be judged only over historical periods. Such successes that stand the test of time may ultimately be the most important to advancing science. Below are several examples of fundamental concepts in various fields that have been enhanced through NG.

Self-Organized Critical Behavior: Applications to Seismicity and Forest Fires

A major NG advance was the application of the concept of self-organized criticality (SOC) to the geosciences. SOC relates the emergence of scale-invariant and fractal structures to the underlying nonlinear dynamics. The simplest example is the forest fire model, which gives a robust power law relation between the size (area) of forest fires and their frequency of occurrence. Despite its simplicity, this model simulates the frequency-area statistics of actual fires in nature much better than classical alternatives [*Malamud et al.,* 1998].

Similarly, SOC models indicate that the Gutenberg-Richter frequency-magnitude statistics for earthquakes are a combined effect of the geometrical (fractal) structure of the fault network and the nonlinear dynamics of seismicity. The application of NG methods is thus indispensable for extreme phenomena and new hazard assessment techniques [e.g., *Rundle et al.,* 2003].

Geospace Complexity: Applications to Space Weather

Driven by the turbulent solar wind, geospace plasmas exhibit nonequilibrium intermittent space-time behavior with underlying processes ranging from small (kinetic) to large (magnetohydrodynamic) scales. The predictability of the global dynamical behavior, derived from the observational data using dynamical systems analysis, has provided a strong base for forecasting space weather [*Sharma,* 1995]. Recent contributions have led to a better understanding of its global and multiscale dynamics, particularly in resolving the controversy around the underlying physics of high-latitude geomagnetic activity with their colorful dancing auroras [*Uritsky et al.,* 2008].

Spatial Scaling: Applications to Floods

Spatial scaling (power law) relations have been found between observed peak flows and drainage areas. Scaling is an emergent property due to the combined effect of the fractal structure of river networks and nonlinear dynamics [*Gupta et al.,* 2007]. Such emergence is common to many nonlinear systems and provides a basis for developing a diagnostic framework to test physical parameterizations for floods.

For example, the catastrophic Iowa River basin flooding event in June 2008 showed scaling over 4 orders of magnitude variation in drainage area. Thus, applications of NG concepts are indispensable to developing new technology for improving real-time flood forecasting and predicting annual flood frequencies in basins without river flow data.

Pattern Formation: Applications to Columnar Joints and Geochemical Systems

Columnar joints are uncanny rock formations in which basalt outcroppings are mysteriously broken into nearly perfect hexagonal pillars all the same size. Using a combination of NG ideas, field observations, and lab analogue experiments using ordinary cornstarch, the mechanisms behind columnar jointing have been discovered [*Goehring et al.,* 2009].

Other familiar patterns in rocks include the beautiful colored bands seen in agates. By applying NG concepts of self-organization to reaction-diffusion systems in geochemical systems, many such patterns can be explained.

Singularities: Applications to Mineral Resources and the Environment

A significant advance in characterizing geophysical fields—including the concentration of minerals—was the concept of multifractals with its hierarchy of singularities. A simple model for mapping possibly anisotropic singularities is the density-area power law model, which identifies anomalies responding to mineralization and contamination processes. Such models are useful in mineral prospecting and environmental protection [*Cheng and Agterberg,* 2009].

Deterministic Chaos

The above examples are nice and tidy and are undoubtedly important, but a more difficult NG challenge has been to change our way of thinking about the world. For example, the paradigm of deterministic chaos, which due to sensitive dependence and hence limited predictability is popularly known as "the butterfly effect," did not live up to all of its initial promises. Nevertheless, by changing our view of science and the world, it achieved something even more important.

For example, as recently as the 1970s the predictable clockwork-like orbits of planetary bodies were purportedly typical features of natural systems. Today the solar system is recognized to be strongly nonlinear, even chaotic. Such sensitive dependence on initial conditions is now understood to be a commonplace feature of the real world. But the chaos revolution is far from over: The challenge remains of how to extend chaos notions to systems with huge numbers of degrees of freedom. "Spatiotemporal chaos," cascades, and multifractals are ongoing efforts in this direction.

Scaling and Fractals: Applications to Topography and Clouds

It has been nearly a century since Jean Perrin eloquently pointed out the nondifferentiable nature of the coast of Brittany, nearly 60 years since Hugo Steinhaus argued that Poland's Vistula River was nonintegrable, more than 50 years since Lewis Richardson demonstrated the scaling of coastlines, and 40 years since Benoît Mandelbrot's interpretation in terms of fractals. Today it is common knowledge that there is something fractal about coastlines. Yet paradoxically, resistance to this idea is still so strong that in many geoscience journals it remains virtually impossible to publish quantitative analyses on the subject!

Similarly, an educated layperson will spontaneously cite clouds and their "billows upon billows" as examples of fractals, yet meteorological models of clouds and their effects are still smooth and uniform—in spite of dozens of satellite-based studies showing that the layperson is correct! The systematic neglect of these resolution dependencies has

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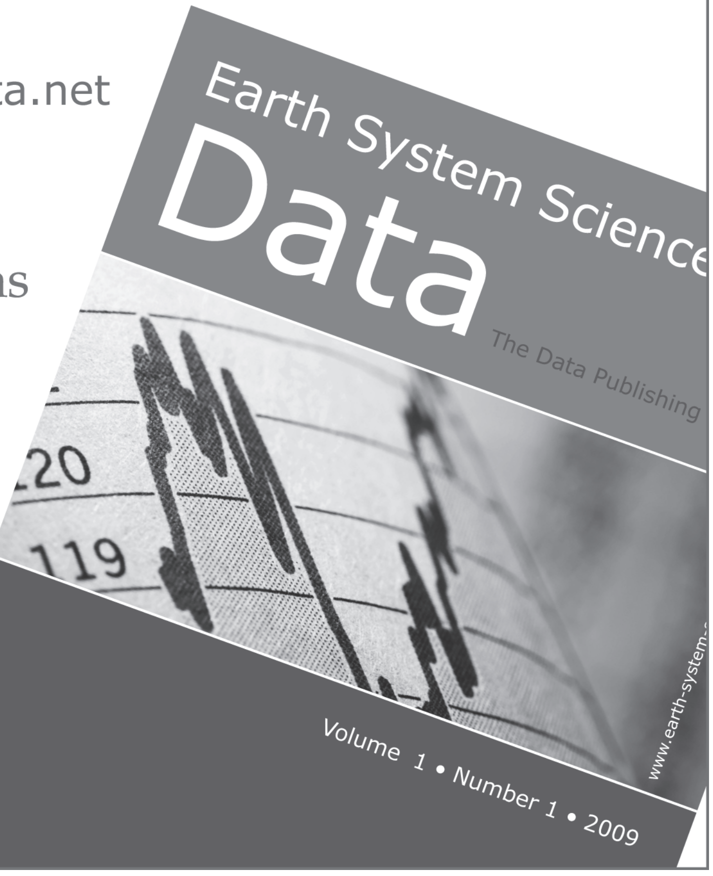

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many consequences including biases in estimating the Earth's energy budget with implications for climate feedbacks [e.g., *Lovejoy et al.,* 2009]. This is potentially significant because a negative instead of a positive feedback greatly reduces planetary warming due to greenhouse gases [*Spencer and Braswell,* 2009].

The Need for Broader Support of NG

Nonlinear ideas have shown how to tame fractal and other nonclassical "monsters," and these are important successes. Yet in the absence of societal support for very promising alternative nonlinear approaches, applications will continue to be deprived of this knowledge and resources will continue to be squandered on state-of the-art techniques informed by inappropriate theories. Thus, funding agencies, academic institutions, journal editors, and individual researchers need to see the future potential of nonlinear geophysics to solve science problems that have consistently been beyond the reach of traditional methods. NG methods thus make our understanding of the world more complete.

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