VIEWPOINT

Complexity in Natural Landform Patterns

B. T. Werner

Patterns in nature, such as meandering rivers and sand dunes, display complex behavior seemingly at odds with their simplicity of form. Existing approaches to modeling natural landform patterns, reductionism and universality, are incompatible with the nonlinear, open nature of natural systems. An alternative modeling methodology based on the tendency of natural systems to self-organize in temporal hierarchies is described.

A river channel meanders in wide, sweeping loops through its floodplain. Sand dunes mantle vast expanses of arid regions with crescentic, linear, and star-shaped forms. Shorelines are molded into smooth arcuate bays interrupted by cuspate horns. Frozen soils throughout the Arctic are broken by a latticework of thermal contraction fractures filled with wedges of ice. A photographer's dream, these and other natural landform patterns exhibit complex behavior that belies their apparent simplicity of form.

Complicated behavior arising from a simple form is a classic symptom of a complex system. Complexity in natural landform patterns is a manifestation of two key characteristics (1). Natural patterns form from processes that are nonlinear, those that modify the properties of the environment in which they operate or that are strongly coupled; and natural patterns form in systems that are open, driven from equilibrium by the exchange of energy, momentum, material, or information across their boundaries. A surf zone, where waves break near the shoreline, exemplifies these characteristics. Wave propagation, generation of currents, turbulent fluid flow, and transport of sediment all are nonlinear processes. The energy and momentum for driving fluid and sediment motion is derived from waves, generated in deeper water, entering the open system. The surf zone and other open natural systems are subject to external forcing on a broad range of temporal scales, for example, 10-s waves to changes in sea level over thousands of years.

These properties can lead to complexity in natural patterns in two stages. First, development of collective behavior by self-organization (2) reduces the very large number of degrees of freedom (for example, those characterizing sand grains on a beach) to a much smaller number of independent dynamical variables (beach profile or shoreline position). Second, these vari-

ables evolve and interact nonlinearly to produce rich, potentially emergent behavior that is only weakly related to the original numerous degrees of freedom or the processes operating on them.

Most natural patterns exhibit some form of complex behavior. Bedforms, patterns in a sediment bed such as ripples and dunes in rivers, oceans, and deserts, generally start small and disorganized; they grow in spacing and become better organized through interactions and mergers between bedforms (3–5). Crescent-shaped wind-blown (barchan) dunes spawn new dunes from their downwind pointing horns, an emergent behavior (1). Sand bars on beaches undergo transitions between different shapes, such as linear and crescentic, based on a complicated combination of incident-wave conditions and their current state (6). River channel meander loops grow until they pinch off, short-circuiting the loop (7).

Existing Approaches to Modeling Natural Patterns

No consensus exists on how to model natural patterns nor, in many cases, the mechanisms by which particular patterns develop (8). The origin of even simple properties, such as the spacing and orientation of bedforms, remains in dispute (5, 9, 10). Two approaches have dominated attempts to model natural patterns and the environments in which they form: reductionism and universality. Any modeling approach for natural patterns must provide a means for selection of dynamical variables (degrees of freedom) to use in the model from the infinite number of degrees of freedom characterizing the natural system. It also must provide for treating the reaction of the system to changes in the environment external to the system. Reductionism and universality are inadequate for meeting these requirements. Here, an alternative is presented that is more compatible with the dynamics of the complex systems in which natural patterns form.

Reductionism. Reductionism is the modeling methodology whereby the development and behavior of large (pattern)-scale features are reduced entirely to their underlying fundamental processes. A dynamical

model is formulated with variables related by these fundamental processes, and this model is used to predict the existence and characteristics of the pattern. For reductionist modeling, constraints and approximations that decrease the number of operative degrees of freedom and simplify the processes include conservation laws, smoothing or averaging, an equilibrium constraint, or initial and boundary conditions; one example is the selection of the macroscopic variables pressure, temperature, and volume through momentum, energy, and mass conservation in an ideal gas. These constraints break down for nonlinear, open systems. Instead, long-time–scale variables and their dynamics can emerge through an interaction between variables at differing temporal scales (11, 12): for example, the crest line of a bedform is selected as a set of dynamical variables because of the reinforcing nature of the interaction between the bedform and the sand grains composing it (see below). Where the emergence of variables occurs through an interaction between scales, the dynamics cannot be reduced entirely to the fundamental scale. For this reason, reductionism does not provide a self-consistent methodology with which to model natural landform patterns.

Universality. Universality is the modeling methodology whereby the overall characteristics of behaviors and patterns are modeled with the simplest system within a class of systems sharing these same behaviors and characteristics, despite being composed of very different building blocks (13). For example, it has been proposed that drainage networks are in a state of self-organized criticality, with dynamics that can be modeled with an idealized sand pile (14). One difficulty with this and other universalist models is that their simplified, typically stationary representation of external forcing is at odds with the forcing and resulting response of natural systems. Forcing in natural systems occurs over a broad range of temporal scales, exciting fast dynamics that depends on some of the differing aspects of the systems within a single universality class. Quantifying the reaction of natural systems to external change is critical for nontrivial modeling and prediction, such as in the reaction of a beach to a storm or the reaction of a drainage network to a tectonic event or a change in climate. This difficulty is exacerbated by the observation that the evolution of pattern charac-

Complex Systems Laboratory, Cecil and Ida Green Institute of Geophysics and Planetary Physics, University of California-San Diego, La Jolla, CA 92093–0225, USA. E-mail: bwerner@ucsd.edu

teristics and type is very much a function of history, for example, for beaches (6) and even for reaction-diffusion systems (15).

Hierarchical Modeling

Two robust characteristics of nonlinear, open systems point the way toward developing new models of natural patterns. First, the most rapidly changing parts of the system tend to be localized in space. Familiar examples include localization of shear into narrow bands in turbulent fluids and in solid deformation or fracture. Patterns inherently involve localization, because they can be described with fewer spatial dimensions than the space in which they are embedded: lines for two-dimensional patterns and surfaces for three-dimensional patterns. In the surf zone, where wave motion is focused near breaking wave fronts, rip currents are a localized return flow of water brought onshore by breaking waves, and large-scale bathymetric change can be tracked through shoreline and sand bar position (Fig. 1). Localization operates to select a limited set of variables with which the dynamics of the system can be described.

Second, variables with disparate intrinsic time scales, when nonlinearly coupled, can develop an asymmetrical relationship: Fast variables become slaved to slow variables and lose their status as independent dynamical variables, as can be argued with a formal adiabatic elimination procedure (12, 16). Numerous examples of slaving in natural, pattern-forming systems include the fast motion of sand grains and fluid slaved either to the slower motion of sand dunes in a desert or of the shoreline and sand bar on a beach (Fig. 2).

The foregoing suggests that a model can be constructed across a broad range of temporal scales as a hierarchy of dynamically uncoupled models, ordered by characteristic time, at the top of which is a level composed of slowly changing variables describing the pattern and at the bottom of which is a level composed of the faster evolving fundamental degrees of freedom. For bedforms, variables at the top level include spacing between and orientation of crest lines and at the bottom level include sand grain positions and fluid velocities (Fig. 3). This idea has been developed for natural systems most completely in ecology (17, 18). Following the arguments given here and those developed for ecological modeling, a hierarchical modeling methodology can be constructed that is objective and testable and is based on properties of nonlinear, open systems, with no new principles introduced (19).

First, identify the internal dynamical variables, the corresponding external environmental parameters, and the boundary between the system and its environment at each level n in the temporal hierarchy. Boundaries should be drawn so that the dynamical interaction between the external environment and system is minimal.

Second, for each level n in the hierarchy, abstract the dynamics of faster variables at level $n - 1$ into a minimal set of rules that dynamically relate the variables at level n to each other and to the external environment. The state of the system at level $n + 1$ provides a slowly varying context (17, 18) for the variables at level n.

Third, test the theoretical consistency of the model by comparing the predictions made at level $n - 1$ for variables at level n with predictions made at level n.

Fourth, test the predictions of the models against measurements within a changing natural environment.

Observations play a key role in choosing the levels of the hierarchy and in abstracting dynamics from lower levels. The abstractions derive from considerations of the interaction between levels, not from approximations made entirely at lower levels, as in reductionism. Abstracting fast-scale dynamics to the greatest possible extent serves two related goals: first, to maximize the physical content of hypotheses regarding the dynamics by making the most restrictive statements possible (20); and second, to enhance predictability by minimizing extraneous dynamics (17).

The resulting hierarchy constitutes a hypothesis regarding the dynamics of the system, which can be tested objectively for theoretical consistency and against measurements. Although experience regarding how to construct hierarchical models is only beginning to accrue, and coupling models of a natural system across temporal scales appears to be intrinsically difficult, some progress has been made in developing hierarchical models for several natural landform patterns, including bedforms.

Although bedforms in differing environments display a significant range of behaviors and forms, many can be characterized with the following developmental sequence. Bedforms start as small bumps of sand and progressively increase in height to the development of a well-defined crest, downstream of which sand is retained in its lee. These small bedforms migrate, interacting and merging with other bedforms, and evolve toward larger forms within a well-organized pattern (4).

A hypothesized hierarchy for bedforms includes levels at temporal scales corresponding to each of these formative stages (Fig. 3). In one model for the morphology of wind-blown sand dunes, the principal abstractions of sand grain and fluid flow physics are that
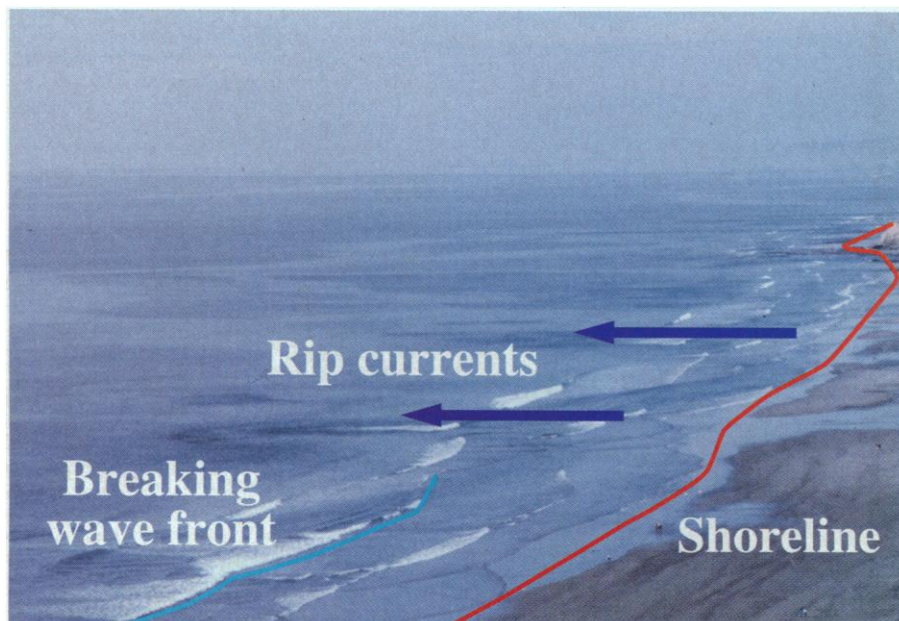

Fig. 1. Localization of dynamics in the surf zone: the mean shoreline, the steep front of breaking waves, and rip currents (the localized offshore return flow of water brought onshore by breaking waves).
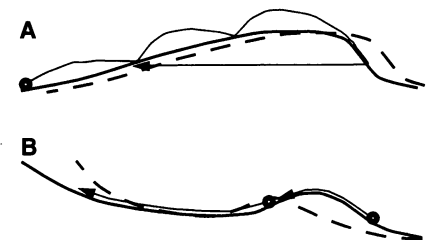

Fig. 2. Slaving in natural systems. The long-term motion of sand grains is slaved to the migration of (A) a sand dune or (B) a shoreline and a sand bar, despite the migration of these forms originating with the motion of many individual sand grains.

sand moves in uniform hops along the surface in the direction of the wind, sand tends to be deposited preferentially on sand surfaces, sand cannot pile up to an angle greater than the angle of repose, and sand is deposited and cannot be eroded in the lee of developing dunes (*1*). In models for spacing and orientation of bedforms, the dynamics of defects, ends of bedform crests, have been abstracted into rules describing how spacing and orientation evolve through time (*10*). Orientation can change only if oppositely facing defects migrate at different speeds (picture changing the orientation of long-crested bedforms) or if the pattern of crests is destroyed, for example, by a significant change in transport regime, and re-formed again, exciting faster scale processes. Some tests of the consistency of this hierarchy have been conducted between the pattern and morphology levels (*10*).

The focus of modeling natural landform patterns has been either on temporal scales analogous to the morphology scale for bedforms, with spatially distributed, cellular models (*21*) or on the pattern scale (*9, 10*). An impediment to progress in modeling natural patterns is the lack of treatment of structures at intermediate temporal scales as dynamical variables, such as bedform crest lines.

Viewed as possessing dynamical attributes, natural patterns are a simple end member of a continuum of complex systems. Regardless of the presence of prominent patterns, many natural physical systems dominated by nonlinearity and strong dissipation should be amenable to hierarchical modeling. The dynamical variables in the model correspond to the temporal scale of the phenomenon being modeled; variables and processes at faster scales are abstracted and those at slower scales provide context. For a surf zone, lifeguards want to predict currents, homeowners beach erosion during a storm, and geologists long-term shoreline change. All three currently are frustrated in these endeavors. By isolating dynamics at different temporal scales, better predictability might be achieved with hierarchical modeling than in reductionist models, in which temporal scales are dynamically mixed.

Many models for complex systems are simple and universalist. The advantage of these simple models is that it is often straightforward to understand how they work. Their disadvantage is that it can be difficult to conduct discriminating tests against natural systems. By providing a means of treating behavior both on the long time scales in which simple models might be appropriate and the faster scales that characterize much of the variability of nature, hierarchical modeling could constitute one step toward bridging the gap between complex systems models and the complexity of nature.

References and Notes
1. B. T. Werner, *Geology* **23**, 1107 (1995).
2. G. Nicolis and I. Prigogine, *Self-organization in Non-equilbrium Systems* (Wiley, New York, 1977).
3. R. P. Sharp, *J. Geol.* **71**, 617 (1963); R. A. Bagnold, *Proc. R. Soc. London Ser. A* **187**, 1 (1946).
4. G. Kocurek *et al.*, *J. Sediment. Petrol.* **62**, 622 (1992).
5. B. T. Werner and D. T. Gillespie, *Phys. Rev. Lett.* **71**, 3230 (1993).
6. T. C. Lippmann and R. A. Holman, *J. Geophys. Res.* **95**, 11575 (1990).
7. H.-H. Stolum, *Science* **271**, 1710 (1996).
8. Beach cusps: R. T. Guza and D. L. Inman, *J. Geophys. Res.* **80**, 2997 (1975); B. T. Werner and T. M. Fink, *Science* **260**, 968 (1993). Sand bars: A. J. Bowen and D. L. Inman, *J. Geophys. Res.* **76**, 8662 (1971); M. J. F. Stive, *Proc. 20th Coast. Eng. Conf. (Am. Soc. Civ. Eng.)*, p. 1550. Patterned ground: K. J. Gleason *et al.*, *Science* **232**, 216 (1986); M. A. Kessler *et al.*, *Eos* **78**, 270 (1997).
9. D. M. Rubin and R. E. Hunter, *Science* **237**, 276 (1987); P. Blondeaux, *J. Fluid Mech.* **218**, 1 (1990).
10. B. T. Werner and G. Kocurek, *Geology* **25**, 771 (1997); *ibid.*, in preparation.
11. K. R. Popper, in *The Self and Its Brain*, K. R. Popper and J. C. Eccles (Routledge, London, 1977), pp. 14–27.
12. H. Haken, *Synergetics* (Springer-Verlag, Berlin, 1983), pp. 191–200.
13. Universality in pattern formation: See, for example, M. C. Cross and P. C. Hohenberg, *Rev. Mod. Phys.* **65**, 851 (1993).
14. R. Rignon, A. Rinaldo, I. Rodriguez-Iturbe, *J. Geophys. Res.* **99**, 11971 (1994).
15. J. E. Pearson, *Science* **261**, 189 (1993).
16. The separation of time scales required for slaving can be achieved if behavior on longer temporal and larger spatial scales is generated by self-organization (*2*) or by competitive interactions between emergent structures, permitting only similar or disparate scales, such as leads to uniform-sized sand dunes mantled by much smaller wind ripples.
17. T. F. H. Allen and T. Hoekstra, *Toward a Unified Ecology* (Columbia Univ. Press, New York, 1992).
18. V. Ahl and T. F. H. Allen, *Hierarchy Theory* (Columbia Univ. Press, New York, 1996).
19. The hierarchical methodology presented here is objective, in that the levels and connections between levels are determined by dynamics and are testable, in contrast with a subjective, constructionist hierarchical framework previously proposed (*17, 18*).
20. K. R. Popper, *Conjectures and Refutations* (Routledge, London, ed. 5, 1989).
21. See, for example, A. B. Murray and C. Paola, *Nature* **371**, 54 (1994); R. S. Anderson and K. L. Bunas, *ibid.* **365**, 740 (1993); C. G. Chase, *Geomorphology* **5**, 39 (1992); B. T. Werner and B. Hallet, *Nature* **361**, 142 (1993).
22. H. E. Clifton, in *Beach and Wearshore Sedimentation*, R. A. Davis Jr. and R. L. Ethington, Eds., Society of Genomic Paleontologists and Mineralogists Special Publication 24 (SEPM Press, Tulsa, OK, 1976), pp. 126–148.
23. L. B. Clarke and B. T. Werner, *EOS* **78**, 352 (1997).
24. The top three images in Fig. 3 were acquired and processed by L. Clarke. Supported by a U.S. Navy–Office of Naval Research Scholar Award (N00014-97-1-0154) and the Andrew W. Mellon Foundation.
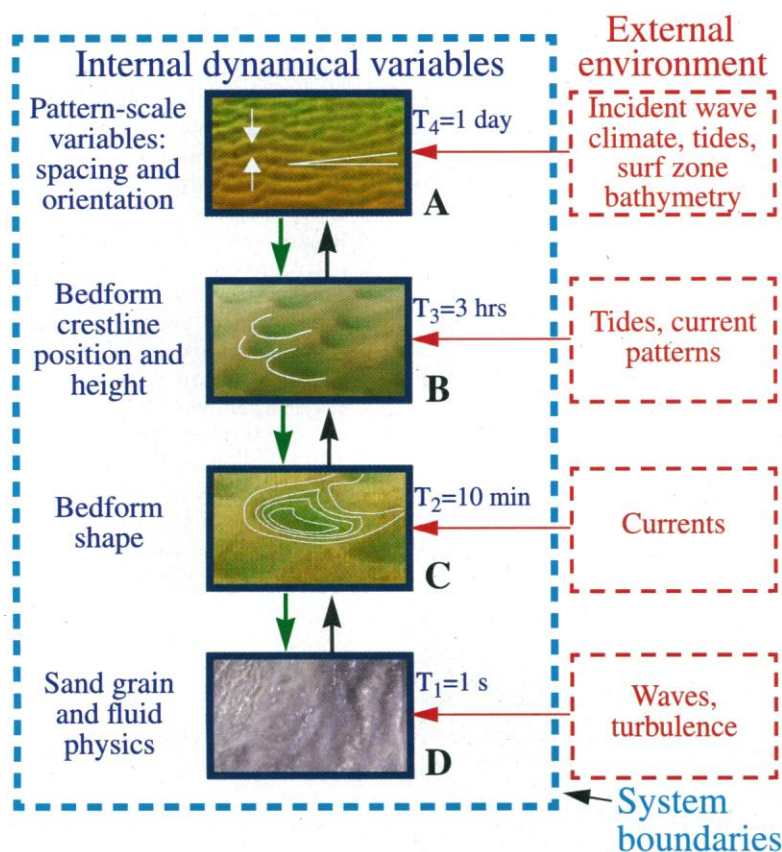
Fig. 3. Hypothesized hierarchy modeling methodology for surf zone megaripples (dunelike bedforms) (*22*). Variables characterizing the system dynamics are arranged by temporal scale T_n and related to faster (black arrows) and slower (green arrows) variables and the external environment (red arrows) as described in text. (**A** to **C**) False-colored, averaged, obliquely viewed images in ~1-m mean depth obtained with a new optical technique (*23*). (**D**) Plan view of suspended sediment plume in swash of 10-cm depth. Approximate top-to-bottom scale of images: (A) 20 m, (B) 10 m, (C) 5 m, and (D) 50 cm.