Boundary-condition controls on pattern development in aeolian and fluvial dune fields

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ABSTRACT: Bedform patterns are self-organized by the interactions and behavior of the bedforms themselves. Interactions occur between bedforms, their faster migrating defects, and remotely. Interactions may be constructional, neutral or regenerative. Patterns emergent from the interactions alone, however, do not begin to approach the diversity seen in nature. The boundary conditions within which these complex systems evolve provide for the uniqueness of patterns in nature. Important boundary conditions for bedform patterns include flow depth, flow directionality, nature of the sediment supply, areal limits and antecedent topography.

1. INTRODUCTION

Fields of dunes in air and water form some of the most striking patterns in nature. It is now widely recognized that these patterns, along with much of the surface of the Earth, are self-organized. Self-organization refers to the spontaneous emergence of a pattern from a non-pattern state as a result of interactions between the elements of the system. With bedform fields it is the interactions between the bedforms themselves that gives rise to field-scale pattern coherence in space and time.

Models, remote sensing, field and lab evidence have now identified a number of bedform interactions and modes of behavior that contribute to pattern development. Two overriding aspects are evident from these works. First, the bedform interactions are much the same regardless of specific bedform type (i.e., ripples vs. dunes) or fluid (air vs. water). This supports the hypothesis that pattern ordering occurs at a hierarchical level above the fluid/grain and flow/bedform levels (Werner, 2003). Second, the emergent patterns resulting from bedform interactions alone do not begin to mimic the richness within and between bedform fields in nature. The hypothesis advanced here is that system boundary conditions, essentially unique to each case, accounts for the natural richness of bedform patterns.

2. THE COMPLEXITY OF BEDFORM-PATTERN DEVELOPMENT

2.1. *Approaches*

Initial insights into bedform patterns as self-organized development arose largely from cellular automaton (CA) models in the early 1990's (e.g., Forrest & Haff, 1992; Landry & Werner, 1994). In a CA model, system behavior emerges because of the interactions between neighboring cells on a grid in which cell behavior is defined by rules in an algorithm. For bedforms, the rules are designed to capture the abstracted dynamics of the bedform (e.g., lee deposition).

More recently various computational fluid dynamics (CFD) models have been introduced (e.g., Schwammle & Herrmann, 2004; Hersen et al., 2004). These models are not true computational simulations for flow over bedforms, but rather are simplifications that incorporate aspects of boundary-layer shear stress, a separation cell, and sediment flux.

Both model types have motivated lab and field observations and experiments, as well as casting into new light long-recognized bedform behavior (e.g., Allen, 1973).

2.2. Behavior with bedform streamwise approach

Five bedform modes of behavior have been recognized as migrating bedforms approach each other in the streamwise direction: (1) simple merging, (2) off-center collision, (3) repulsion, (4) cannibalization, and (5) bedform splitting. Simple merging, in which a smaller, faster bedform overtakes and merges with a larger, slower bedform, is seen with all bedforms and fluids. In experiments with barchans, off-center collision does result in merging, but also in the calving of a new bedform from the horn of the impacted bedform (Hersen & Douady, 2005). Repulsion occurs where a somewhat smaller upstream bedform approaches and overshadows a larger bedform such that it diminishes in size and, hence, increases its migration rate downstream Landry & Werner, 1994). Repulsion occurs between wind ripples, but its existence for bedforms with flow separation is highly questionable (Livingstone et al., 2005). Cannibalization is a more probable behavior with bedforms with flow separation. With cannibalization, the downstream bedform is effectively lost within the deepening trough of the upstream bedform. Bedform splitting is more exactly the emergence of a new bedform upon a stoss slope that is extending and decreasing in slope (Allen, 1973).

Simple merging and cannibalization are both pattern constructional in that they lead to fewer, larger, more widely spaced bedforms. Off-center collision and repulsion are neutral in the sense that they maintain the bedform number at the field scale. Bedform splitting is regenerative in the sense of increasing the number of bedforms in the field.

2.3. Defect dynamics

Defects are any irregularities in the pattern of continuous crestlines across the field, the most important of which are the crest terminations because these features can migrate significantly faster than the main body of the bedform. The identified modes of behavior that arise with defect dynamics are: (1) lateral linking, (2) repulsion, (3) defect creation, (4) calving, and (5) a less specific group of behavior associated with defect migration. The lateral linking of crests is constructional by increasing crest length. Repulsion, the primary mechanism by which defects are propagated through a field of wind ripples, maintains the status quo in bedform number. Calving is regenerative, as is defect creation, in which continuous crestlines break apart.

2.4. Remote transfer of sediment

The exchange of sediment between bedforms that are not otherwise undergoing any direct contact can be a mechanism of pattern development. For example, barchan dunes receive sediment all along the stoss slope but it is lost largely from the horns. Longer crest bedforms are, therefore, favored to grow at the expense of smaller dunes in this constructive process (Hersen et al., 2004).

2.5. Pattern emergence

Time-series profile surveys from the North Loup River, Nebraska, a LIDAR survey of the dune field at White Sands, New Mexico, and published field and lab studies readily show the suite of bedform interactions and behavior. In CA models, these interactions result in obvious pattern ordering over time. Interactions between bedform bodies decrease as these become more similar in size and migration speed, but defects continue to provide the field dynamics. Field stability ultimately rests upon defect density (terminations per unit crest length). This simple emergent pattern, however, is entirely generic. Boundary conditions are the external forcing that moves each system beyond this generic solution.

3. BOUNDARY CONDITIONS

3.1. Definition

Boundary conditions constitute the external environmental variables within which each bedform system evolves. Although only rarely explicitly addressed in sedimentology, other fields have invoked boundary conditions as the source of diversity within many complex systems. Viewed from the complex-system paradigm, boundary conditions shift the attractor in phase space (Werner, 2003). Because boundary conditions are likely to be different for each individual case, no two systems are likely to ever be exactly the same even when guided by the same interactions. Moreover, boundary conditions may favor one interaction over another, or define an overriding template to the pattern.

3.2. Some common boundary conditions

There are clearly a great many boundary conditions, many of which have already been demonstrated to impact pattern development, whereas others are newly proposed here. Flow directionality, unidirectional in fluvial systems but rarely so in aeolian dune fields, is the primary boundary condition that accounts for the diversity of aeolian dune types. Antecedent dune topography is common in aeolian systems and the impact of this boundary condition gives rise to a very rich array of complex dune patterns in nature. A similar boundary-condition control occurs in the Mississippi River with falling water stage. Areal limits to the bedform field, as defined by both the channel and bar shape, always exist for fluvial systems, but this boundary condition is also common to aeolian systems. Complex and spatially diverse dune field patterns in Mauritania (Lancaster, et al., 2002), the Gran Desierto in Mexico (Beveridge et al., 2006), and the Algodones, California (Derickson et al., in press) have been directly attributed to boundary conditions.

3.3. Flow depth

Subaqueous bedforms have long been known to scale with flow depth (van Rijn, 1984; Yalin, 1992).

Flow depth effectively imposes a "lid" on bedform growth, and this boundary condition is perhaps the most fundamental difference in pattern development between aeolian and shallow fluvial systems. Although there may exist some maximum height for aeolian dunes as defined by the wind, for a great many systems dune height is limited by only sand supply and time. Without an effective flow lid, dune interactions and behavior are constructional toward fewer, larger, more widely spaced dunes with progressively longer crestlines as a function of time. The evolution of these parameters is evident in CA models and natural fields, and inspired the concept of pattern dating for aeolian dunes (Ewing et al., 2006). In hindsight, the reason the CA models have so effectively modeled aeolian ripples and dunes, but would have completely failed if they had been applied to shallow fluvial systems, is that no boundary condition of flow depth exists in the CA models.

Time-series profile surveys from the North Loop River show that while constructional interactions and behavior occur, regenerative processes of bedform splitting and defect creation balance against these to produce a steady state that exists only statistically (Jerolmack & Mohrig, 2005). Moreover, attributes of individual bedforms exist on such an ephemeral scale that the bed configuration can only be characterized as field-scale statistical properties. In a comparison of plots of dune spacing, crest length and defect density over time for numerous aeolian systems to the North Loup River, the clear constructional trends evident for the aeolian dunes are not present in the North Loup.

3.4. Sediment source

Although limited sediment supply has long been recognized as favoring barchan over crescentic dunes in water and air, this same boundary condition favors a set of constructive (remote transfer of flux), neutral (off-center collision), and regenerative (calving) behavior that may be significant only for barchans and that act to maintain these fields (Hersen et al., 2004).

The shape of the sand source (line, point or plane) has been shown to result in different patterns for otherwise similar systems (Ewing & Kocurek, in rev.). For a line (beach) or point (wind gap) source, the pattern is constructional progressively downwind with bedform travel distance from the source area. With a plane source (reworked blanket sand) this spatial trend is not observed, but rather all parts of the field show a similar degree of pattern development.

4. CONCLUSIONS

Bedform interactions and behavior are the means by which patterns emerge in bedform fields. Most of these interactions are constructive toward fewer, larger, more continuous bedforms; but some are neutral, and yet others regenerative in creating new bedforms. The transcendence of bedform interactions and behavior across scales, bedform types and fluids argues that pattern ordering occurs at a high level of hierarchy largely decoupled from smaller-scale processes. Bedform interactions alone do not yield the richness of patterns in nature; rather this arises from the boundary conditions within which each system evolves. Important boundary conditions for bedforms are flow depth, flow directionality, the nature of the sediment supply, areal limits and antecedent topography.

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