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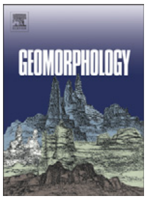

Geomorphology, complexity, and the emerging science of the Earth's surface

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ABSTRACT

The following is a white paper (adapted here for print) for the U.S. National Research Council's committee on Challenges and Opportunities in Earth Surface Processes, drafted at a National Science Foundation sponsored workshop associated with the 38th Binghamton Geomorphology Symposium, “Complexity in Geomorphology,” held at Duke University in October 2007.

1. State of the art

1.1. Motivation

Landscapes, and how they change over time, provide the template on which life must function and dictate the ecosystems and human activities that can exist in a given place. Rugged and steep landscapes, for example, tend to limit human development and agriculture; coastal landscapes support wetland nursery habitats crucial to the world's marine life and also sustain myriad human industrial, agricultural, and economic activities around major population centers.

Biological influences – especially human actions – in turn directly affect landscape-forming processes, helping steer landscape change. Wetland vegetation, for example, plays an essential role in determining how coastal morphology and ecosystems respond to sea-level rise, and land-use changes alter the feedbacks between biological and physical processes in such environments. In hilly regions, vegetation dictates the shape of the whole landscape; as humans alter vegetation cover (a typical effect of land use), the steepness and stability of the ground changes, which then affects humans.

Geomorphology, the study of landscape change, thus stands in the center of a newly emerging science of the Earth's surface, where strong couplings link human dynamics, biology, biochemistry, geochemistry, geology, hydrology, geomorphology, and atmospheric dynamics, including climate change (Fig. 1). We are now beginning to address the feedbacks between geomorphology and these linked disciplines. Adaptive environmental management on a changing globe requires rapid advancements in our understanding of Earth-surface dynamics; understanding these dynamics will allow us to influence our habitats in a purposeful manner. In this paper we emphasize novel investigative

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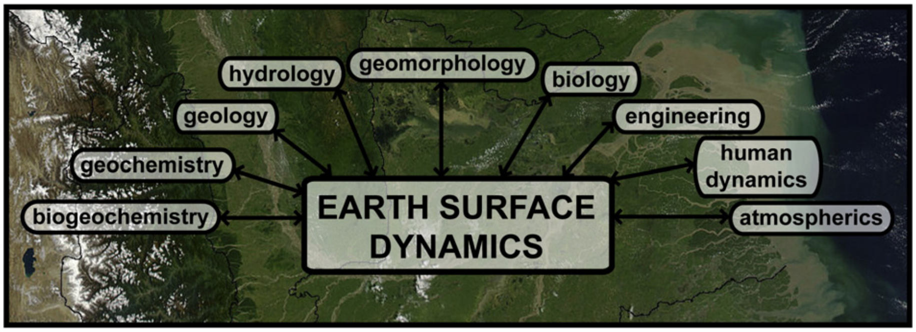

Fig. 1. The study of Earth-surface dynamics is inherently interdisciplinary. The cultivation of a new, unified Earth-surface science will catalyze otherwise disparate disciplines to interact and collaborate, increasing our understanding of landscape, ecosystem, and human behaviors and the complex couplings that connect them (in the background: a source-to-sink image of the Ganges River and related terranes, courtesy of the NASA Visible Earth image database, http://visibleearth.nasa.gov).

approaches being applied at the fast-expanding frontiers of Earth-surface science, address the principal challenges presently facing the geomorphologic research community, and look to what the future of Earth-surface science might hold.

1.2. Recent rapid advances

Geomorphologists today are employing a rapidly expanding, interdisciplinary set of tools that are revolutionizing how we understand Earth-surface processes. Historically, qualitative, descriptive modes dominated geomorphology. More recently, however, the discipline has turned the corner and is now accelerating along the leading edge of quantitative science. The wealth of data collected in the past, along with the development of an array of new quantitative techniques for characterizing landscapes and landscape change, has enabled a renaissance in theory and modeling; modern geomorphology is feeding off of its observation-rich history.

Many of the recent advances hinge on the ideas and quantitative tools of complex systems research. The umbrella of “complexity” encompasses several related theoretical approaches that originated in nonlinear dynamics. The Earth's surface exhibits some of the most striking examples of self-organized phenomena, with spontaneous spatial and temporal localizations, emergent patterns and structures, and fractal patterns and power-law scaling. Recognizing the possibility of each of these types of phenomenon recasts how we interpret much of what we observe and often what we forecast for the future. Many geomorphological studies today benefit from these complex systems perspectives and analyses, even when these influences are not explicitly mentioned; complexity-related concepts, listed below, permeate and are propelling the field:

(i) Chaos theory showed that rich, complicated, and perpetually dynamic behavior can arise from simple, nonlinear interactions. Recent geomorphological work is revealing many cases where local, deterministic interactions in a spatially distributed system can explain complicated behaviors that would previously have been ascribed to complicated (usually unknown) causes that defy holistic understanding.

(ii) An array of local nonlinear interactions can give rise to the self-organization of patterns with strong spatial gradients and localizations that had been attributed to hypothesized “forcing templates” (Fig. 2A). Knowledge and models of the interactions that create these localized structures facilitate explorations of how the landscape will change as climate or land-use forcing shifts (Fig. 2B).

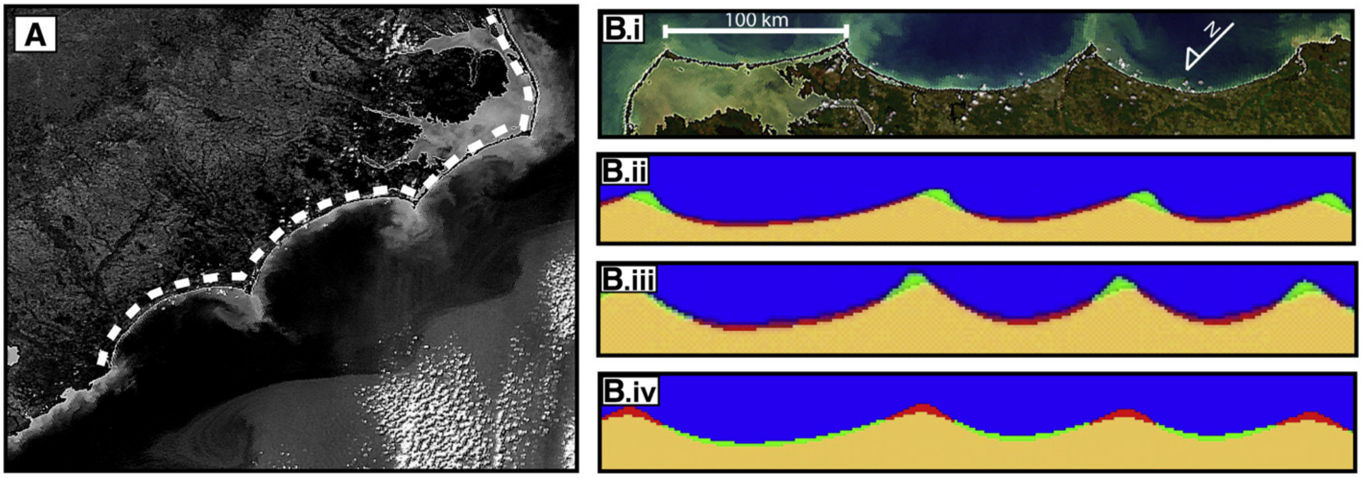

Fig. 2. (A) Satellite image of the sandy, cuspate Carolina Cape system (highlighted by the white dotted line); cape tips are ~100 km apart. The spatial regularity of the cuspate pattern was for decades assumed to be the result of peculiarities in the underlying geology, the classic argument of “template forcing.” Recent numerical modeling work, however, grounded in complexity theory, has shown that the capes could be self-organized, emergent features formed from fluxes of alongshore sediment transport, obviating the need to invoke a specific forcing template to explain their formation. (B) An extension of the same shoreline modeling examines how the coast might change under various hypothetical climate-change scenarios; the numerical model is not a direct representation of the Carolina cape system (B.i) nor intended to be, but is nevertheless analogous to it as an exploratory tool and illustrative of the large-scale, long-term processes driving changes in the landscape. The model output, in planview, shows that (B.ii) if stronger storms send larger waves from the left (NE), the cape tips will grow (shown in green) and shift to the right (SW) and the embayments will erode landward (shown in red); (B.iii) if more or larger storm waves arrive from the right (SW), the cape tips will grow and shift to the left (NE); and (B.iv) if stronger winds tend to direct waves straight onshore (to the NW), the cape tips will erode landward and the embayments will accrete seaward (adapted from Ashton et al., 2001; Slott et al., 2006).