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Edward N Lorenz's 1963 paper, "Deterministic nonperiodic flow", in *Journal of the Atmospheric Sciences*, Vol 20, pages 130–141: Its history and relevance to physical geography

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Abstract
Lorenz (1963) provided the foundation of chaos theory and inspired a fundamental reappraisal of systems' nonlinearity in many disciplines, including physical geography. I will provide a brief overview of chaos in nonlinear systems as documented in Lorenz (1963), including the major tenants of chaos theory, followed by a discussion of the effects of chaos theory within meteorology and climate sciences, geomorphology, and ecology and biogeography. In general, Lorenz (1963) provided the intellectual framework for reconsidering the predictability of many physical systems.

Keywords
classics revisited, chaos theory, Edward Lorenz, nonlinear dynamics, systems

I Introduction

The discipline of physical geography is composite in nature; its theory, principles, and methodologies are derived from the basic sciences (Malanson et al., 2014; Osterkamp and Hupp, 1996). As such, paradigm shifts that have occurred in its foundational disciplines of physics, chemistry, and biology have similarly sparked epistemological shifts within physical geography. A classic example is the impact of Darwinian evolutionary theory in models of landscape development, originally developed by William Morris Davis (Osterkamp and Hupp, 1996) but later replaced with time-independent models grounded in general systems theory.

In 1963 Edward Norton Lorenz (1917–2008, Figure 1), a meteorologist from the Massachusetts Institute of Technology, published a landmark paper, "Deterministic nonperiodic flow," in *Journal of the Atmospheric Sciences*, which currently has approximately 8000 citations, as reported on Web of Science. This paper revolutionized contemporaneous conceptions of systems' behavior and inspired a fundamental rethinking about the capacity of a given system to achieve stability, equilibrium, and

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Figure 1. Edward N Lorenz in 2003 hiking on Mt Battie near Camden, Maine. Photo by Kerry Emanuel. Used with permission.

predictability. Lorenz (1963) was the first paper to illustrate the concept of chaos by showing that some systems, governed by a simple set of rules, are capable of producing outputs that seem random, yet are ordered. This paper was foundational in the development of chaos theory, which states that order is hidden within apparent disorder, making simple deterministic systems seem random (Gleick, 1997). The discovery of chaos in physical and natural systems initiated a cross-disciplinary discussion on the behavior of nonlinear systems dynamics in nature.

The purpose here is to examine this first paper to make note of deterministic chaos in systems with a focus on its ontological contributions to systems thinking in physical geography. First, I will provide a brief overview of the discovery of chaos in nonlinear systems as documented in Lorenz (1963) including the major tenants of chaos theory. A discussion on the relevance of chaos theory within meteorology and climate sciences, geomorphology, and ecology and biogeography will follow.

II Lorenz (1963): Account of a serendipitous discovery that revolutionized systems thinking

Edward Lorenz was exploring the ongoing challenge of weather prediction when he serendipitously uncovered chaotic behavior in a numerical model of convection in a simulated atmosphere (detailed in Gleick (1997) and Lorenz (1995)). Lorenz (1963) presented a simplified mathematical model for atmospheric convection based on three ordinary differential equations (now known as the Lorenz equations) that would behaved chaotically when plotted. Possible solutions generated a diagram of a trajectory that never repeated or intersected itself (i.e. 'The Lorenz Attractor'); this diagram became the emblem of chaos theory because it revealed the fine structure hidden within an apparently random stream of data. Though earlier investigators (e.g. Henri Poincare) had uncovered similar behavior (Roulstone and Norbury, 2013), Lorenz was the first to recognize chaos for its scientific significance rather than dismissing it as noise (Gleick, 1997).

The importance of Lorenz (1963) to physical geography is threefold. First, it provided evidence that some simple deterministic systems (such as fluid behavior) are seldom predictable (Malanson et al., 1990). Second, Lorenz (1963) demonstrated that some systems exhibit sensitive dependence to initial conditions, meaning that small differences in a system's state at a given time may produce amplified differences in a subsequent state (e.g. May, 1974, 1976). Lorenz discovered that his modeled atmospheric system behaved radically differently when using minutely different initial model conditions (Gleick, 1997). This phenomenon was later termed the 'butterfly effect' (Lorenz, 1972) and reflects how small differences in initial conditions or small perturbations may have large scale effects on a system's output. The third attribute of chaotic systems is order within apparent randomness. Chaotic behavior, although fully deterministic, indistinguishably mimics a random process; solutions never repeat, do not establish equilibrium, and are often highly irregular, however, they appear ordered or portray self-similarity (Gleick, 1997).

III Relevance of Lorenz (1963) to physical geography and its major sub-disciplines

Chaos is a concept that has implications for the way earth and natural scientists approach the study of systems. In physical geography, the concept of deterministic chaos was initially slow to popularize, likely because of the tremendous challenges chaotic systems and nonlinearity represented for prediction. Nonlinearity was not fully accepted at first in physical geography and, before the discovery of chaos, few considered the possibility that seemingly random patterns may not actually be random (Malanson et al., 1990).

Though systems theory continues to be the dominant paradigm in physical geography, literature on chaos theory that was clearly inspired by Lorenz's work first emerged in physical geography journals in the 1980s—almost two decades after the publication of Lorenz (1963). Culling (1987) provided an early account of the implications of chaos theory for physical geography; this effort was followed by several papers in the 1990s by physical geographers who explored potential applications of chaos theory to the discipline (e.g. Malanson et al., 1990, 1992) and the search for deterministic chaos in real landscapes (e.g. Phillips, 1996; Phillips, 1999a). The discussion has expanded to include related concepts such as nonlinear dynamical systems (NDS) and complexity, and continues to evolve in physical geography, as in other disciplines, over 50 years after its original publication.

1 Meteorology and climate sciences

The development of chaos emerged from an attempt to solve the meteorological problem of long-term forecasting; thus, the relevance of Lorenz (1963) is perhaps most evident in meteorology and weather forecasting (e.g. Lorenz, 1995), though his work also advanced basic understandings of climate dynamics (Palmer 2009). Lorenz (1963) provided evidence that some systems could not be predicted with great accuracy—a revolutionary finding at a time when most meteorologists believed atmospheric behavior to be predictable (Gleick, 1997). Initially, weather forecasters were dismayed by the implications of chaos for forecasting, since deterministic non-periodicity has far-reaching consequences when the goal is long-term prediction (Lorenz, 1963; Schaffer and Kot, 1986; Gleick, 1997). However, beginning in the 1990s, forecast meteorologists began incorporating components of chaos into their models (Roulstone and Norbury, 2013; David Carroll, 2015, Personal Communication). This type of forecasting, known as ensemble forecasting, incorporates the purposeful adjustment of initial conditions to understand a range of possible outcomes. Ensemble forecasting is still used regularly to understand how chaotically the atmosphere is behaving at a given time and to gauge confidence levels in long range predictions of large scale weather systems (e.g. Toth and Kalnay, 1993, 1997; Shukla, 1998).

2 Geomorphology

Nonlinear dynamical models expressing chaotic behavior remain important in the philosophical underpinnings of geomorphology (Church, 1996). Beginning in the 1990s, a reconsideration of landscape evolutionary processes was clearly influenced by Lorenz (1963). The extensive body of work on the potential for chaos in landscape evolution (e.g. Malanson et al., 1992; Phillips, 1992, 1993a, 1993b, 1995, 1999a, 1999b; Qin et al., 2001, 2002) was undoubtedly inspired by Lorenz's work. Phillips (1993a) explored issues of stability in geomorphic systems, especially in the context of landscape evolution and sought out field-based examples of chaos to dampen its abstractness (e.g. Phillips, 1992, 1999b). Phillips (1995) questioned the existence of chaos in landscape development and revolutionized thinking of linearity of landscape evolution models originally proposed by William Morris Davis (1899), by suggesting that many landscapes are self-organizing and driven by autogenic processes that may result in divergent forms (Phillips 1995, 1999a). Malanson et al. (1992) similarly examined landscape development in hillslope models, noting that chaos is likely given the disequilibrium behavior exhibited by the system.

3 Ecology and biogeography

In the 1970s, shortly after the publication of Lorenz (1963), theoretical ecologists became interested in chaos and nonlinear dynamics as applied to natural systems, and the body of work that ensued has helped to redefine traditional ecological theory (e.g. DeAngelis and Waterhouse, 1987). Chaos caused reappraisal of core concepts from population and community ecology (Schaffer and Kot, 1986) that also tied into biogeographical thought.

Initially, the potential role of ecological chaos in species population models and its consequences for species survival became a pivotal question—why did some species become extinct while others persisted? What role did chaos play, if any, in extinction and persistence (Earn et al., 1998)? The work of May (1976) derived concepts from chaos theory to conclude that biotic feedback instability could eventually lead to extinction—a finding supporting the importance of intrinsic dynamics and systems divergence in natural systems. Conversely, Allen et al. (1993) proposed that chaotic oscillations, by creating asynchronous population dynamics, can reduce the likelihood of species extinctions. DeAngelis and Waterhouse (1987) broached the notions of ecosystem stability with a conceptual model that addressed chaos, divergence, and unpredictability as a possible outcome of ecological systems under scenarios where strong internal biotic feedbacks can force it to become unstable. The profusion of published literature on chaos in ecology (e.g. May, 1976; Schaffer and Kot, 1986; DeAngelis and Waterhouse, 1987; Suárez, 1999) and biology (Cavalieri and Koçak 1994, 1995; Earn et al., 1998; Patten, 1997) indicates that chaos has gained ample, although sometimes controversial, recognition as a means of explaining the complex behavior of natural systems. Intellectual underpinnings of this debate were clearly influenced by the work of Edward Lorenz.

As a whole, biogeographers have gravitated more toward nonlinear concepts such as complexity, fracticality, and self-organization, which have been coined under chaos (Lorenz, 1995). The integration of both space and place in biogeography (e.g. Malanson, 1999) allows for the consideration of chaos. As suggested by DeAngelis and Waterhouse (1987), under certain time and space scales, systems may be stable, chaotic, or somewhere in between along the gradient. For example, Malanson (1999) cited the edge of chaos as an important biogeographic region, using ecotones as an example. Ecotones may exist at the edge of chaos where systems are close to a threshold transition into chaos. Systems with balanced positive feedbacks can be particularly sensitive to change and exhibit positive feedback switches (Malanson, 1997, 1999). Undoubtedly, positive feedback processes generate pattern at alpine treelines that are highly autogenic (Zeng and Malanson, 2006; Smith-McKenna et al., 2014). Under such switches, patterns developed could be chaotic and nonlinear responses to climate change could result.

IV Conclusions

Though nonlinear systems, and certainly chaotic behavior, are not present or even relevant in all earth and life systems (e.g. Phillips, 1996), their consideration is essential for a comprehensive understanding of predictive outputs and methodological approaches to their study. Whether physical geographers will continue to seek out the spatial nature of chaos likely depends on the development of more mainstream ways to study and identify chaotic systems. In physical geography, an ongoing emphasis on prediction (especially in the context of climate change) makes attention to chaos particularly relevant. An understanding of chaotic systems that exhibit nonequilibrium dynamics at various spatial and temporal scales enables geographers to rethink the concept of dynamic equilibrium and question the very notion of randomness (DeAngelis and Waterhouse, 1987; Phillips, 1992; Renwick 1992; Schaffer and Kot, 1986). Growth of attention toward nonlinear dynamics, as reflected in the literature, has undoubtedly been inspired by the important concepts elucidated in Lorenz (1963).

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