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Using natural archives to detect climate and environmental tipping points in the Earth System

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ABSTRACT

'Tipping points' in the Earth system are characterised by a nonlinear response to gradual forcing, and may have severe and wide-ranging impacts. Many abrupt events result from simple underlying system dynamics termed 'critical transitions' or 'bifurcations'. One of the best ways to identify and potentially predict threshold behaviour in the climate system is through analysis of natural ('palaeo') archives. Specifically, on the approach to a tipping point, early warning signals can be detected as characteristic fluctuations in a time series as a system loses stability. Testing whether these early warning signals can be detected in highly complex real systems is a key challenge, since much work is either theoretical or only tested with simple models. This is particularly problematic in palaeoclimate and palaeoenvironmental records with low resolution, non-equidistant data, which can limit accurate analysis. Here, a range of different datasets are examined to explore generic rules that can be used to detect such dramatic events. A number of key criteria are identified to be necessary for the reliable identification of early warning signals in natural archives, most crucially, the need for a low-noise record of sufficient data length, resolution and accuracy. A deeper understanding of the underlying system dynamics is required to inform the development of more robust system-specific indicators, or to indicate the temporal resolution required, given a known forcing. This review demonstrates that time series precursors from natural archives provide a powerful means of forewarning tipping points within the Earth System.

1. Introduction

Abrupt and extreme shifts in the climate and environment can impact the Earth and human systems on interannual to millennial timescales (Cooper et al., 2015; Hogg et al., 2016; Palmer et al., 2015; Turney et al., 2006). The passing of such 'tipping points' have been identified in the Earth's past (Dakos et al., 2008; Livina et al., 2011; Maslin and Brierley, 2015; Thomas et al., 2015; Turney et al., 2015), and analysis of these abrupt events can provide a deeper understanding of the underlying system dynamics, which is essential for understanding past and future mechanisms and impacts of change (Laurance et al., 2011; Lenton et al., 2012a; Lontzek et al., 2015). Though the methodological underpinnings of the analysis of abrupt events originate in field of ecology (Scheffer et al., 2001), there is an increasing focus on contemporary climate trends for anticipating (and ultimately managing) future abrupt and extreme events (Cai et al., 2016; Hughes et al., 2013; Lade and Gross, 2012; Lenton, 2014). Of particular importance is the analysis of natural archives, which are being increasingly applied for the identification of past and potential future threshold behaviour (Dakos et al., 2008; Thomas et al., 2015; Turney et al., 2015). In the case of palaeoclimate and palaeoenvironmental data, the tipping has already happened, thus the analysis is highly relevant as a tool for identifying the underlying dynamical mechanisms, as well as detecting and determining the impact of future changes.

This review specifically considers tipping points from a palaeoclimate and palaeoenvironmental perspective, summarising key methodological insights into abrupt and extreme change and identifying promising approaches to realise the full potential of natural archives of the Earth system. While these issues are also relevant to modern ecological/environmental change, these will not be discussed here (see Dakos et al. (2014) for discussion of early warnings of ecological regime shifts). Since palaeoclimate and palaeoenvironmental records often have different data characteristics, including length, resolution and density, to contemporary datasets (such as historical observations or model outputs), the appropriate data selection, pre-processing and analysis of these natural archives are imperative. Moreover, early theoretical work on early warning signals has primarily been tested with only simple models, and thus there is an urgent need

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for determining which approaches are most robust in highly complex real systems (Lenton et al., 2009).

The term ‘tipping point’ has recently been adopted and popularised by the climate community to describe certain types of abrupt climate change, defined as “*when a small change in forcing triggers a strongly nonlinear response in the internal dynamics of part of the climate system, qualitatively changing its future state*” (Lenton, 2011). It is this nonlinear response to forcing that characterises abrupt climate change, where shifts are the result of simple underlying system dynamics (Scheffer et al., 2009), termed ‘critical transitions’ or ‘bifurcations’. Even if there is not a thorough mechanistic understanding of complex systems, generic rules can be developed to identify the risk of such dramatic events. As a result, a suite of ‘early warning indicators’ can be applied to capture the characteristic fluctuations present in the data preceding a tipping point (Dakos et al., 2008). A growing number of studies have implemented these techniques on a range of systems, extending far beyond climate and environmental science, including ecology, social science, medicine, and financial systems. It is increasingly apparent that predicting non-linear events is not only more difficult but arguably more important than successfully simulating linear responses.

Abrupt climate and environmental changes often occur due to a non-linear response to forcing. These non-linear systems can take several different forms; Fig. 1a illustrates the stability structure of a non-linear system where only one equilibrium exists over the range of forcing. A non-linear system that is characterised by a bifurcation is one that has two or more stable equilibria separated by an unstable equilibrium (Fig. 1b). The tipping points referred to in this review focus on systems whose dynamics are assumed to be governed by an effective stochastic dynamics, where the presence of two or more quasi-stationary states, separated by an unstable equilibrium, can effect shifts between these states induced by natural fluctuations superimposed on a long-term forcing. However, some systems can be driven to tipping purely by noise alone, without the presence of a bifurcation and are not associated with any early warning indicators.

2. Concepts of critical slowing down

Tipping points that occur as a result of a bifurcation can be observed through a phenomenon called ‘critical slowing down’, whereby the climatic or environmental response to perturbations becomes increasingly slow as the threshold is approached (Dakos et al., 2008). From a dynamical perspective, the statistical properties of the data show the basin of attraction (as depicted in Fig. 1c, describing the stability of the system) becoming gradually wider and shallower before ‘tipping’ occurs. Thus when the climate system is perturbed by internal or external noise, it can travel further in the basin of attraction and take longer to return to its equilibrium state, which can be measured as a slowing of the rate of recovery.

2.1. Increasing memory

There have been various methods to exploit the changing return rate to equilibrium. Held and Kleinen (2004) and Dakos et al. (2008) discovered that critical slowing down leads to an increase in autocorrelation in the time series of fluctuations. Because critical slowing down causes the intrinsic rates of change in the system to decrease, the state of the system at any given moment becomes more and more like its past state, which is detected as an increase in the autocorrelation (and thus memory) of the time series (Ives, 1995). There are several methods used to measure this; the autocorrelation at lag-1 measures the similarity of each data point to the previous one, and detrended fluctuation analysis measures the short-term memory of the system (Livina and Lenton, 2007). Autocorrelation is regarded as the leading indicator of regime shifts and has been employed in a wide range of studies (Cimatoribus et al., 2013; Dakos et al., 2008; Lenton et al., 2012b; Thomas et al., 2015; Turney et al., 2015). Other metric-based indicators that exploit the rising memory of the system on the approach to a tipping point include the spectral density (Kleinen et al., 2003), spectral exponent (Biggs et al., 2009), and the spectral ratio (Dakos et al., 2012a).

2.2. Increasing variability

Variability may also increase on the approach to a bifurcation, associated with the widening and shallowing of the basin of attraction, allowing the system to travel further from its stable equilibrium (Lenton et al., 2012b). Variance and standard deviation are commonly used metrics to measure this increase in the variability of the system. Other metric-based indicators that exploit the rising variability of the system include conditional heteroskedasticity (Seekell et al., 2011), and the BDS test (Carpenter et al., 2011). However, it is important to note that it can be difficult to distinguish between increased variance due to critical slowing down and increased variance due to independent increases in stochastic noise.

2.3. Should autocorrelation and variance increase together?

The fluctuation-dissipation theorem (Kubo, 1966), suggests that both autocorrelation and variance depend upon the curvature of the basin of attraction. If affected by critical slowing down, the change in curvature of the basin of attraction would affect both autocorrelation and variance simultaneously. This indicates that

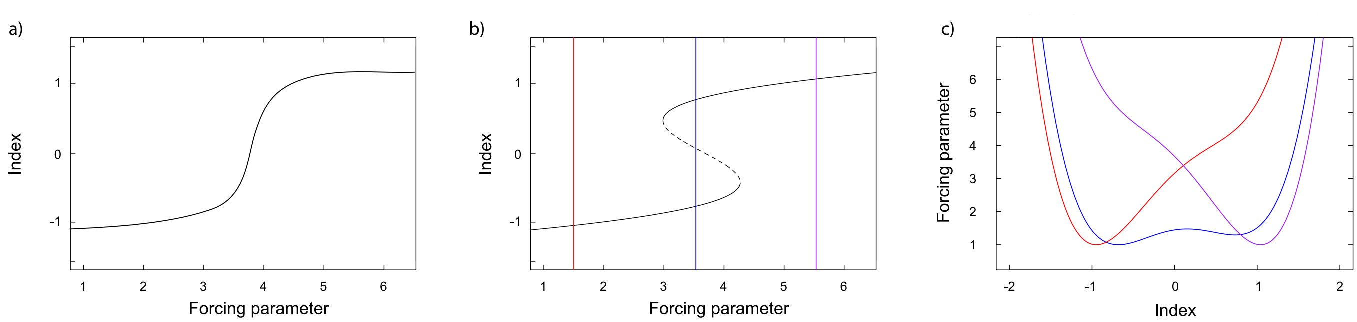

Fig. 1. Diagrams showing different representations of the stability structure of non-linear systems. a) Stability diagram showing a system where there is a non-linear response to forcing; b) Stability diagram, showing a non-linear system characterised by a bifurcation, where the stable states are denoted by the solid black lines, and the unstable state by the dashed black lines, and c) the changing shape of the basin of attraction for the system with bifurcation. The red, blue and purple solid lines depict the location in the stability diagram in (b) related to the shape of the basin of attraction in (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)