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Review papers

On the role of patterns in understanding the functioning of soil-vegetation-atmosphere systems

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ABSTRACT

In this paper, we review the role of patterns to improve our understanding of water, mass and energy exchange processes in soil-vegetationatmosphere systems. We explore the main mechanisms that lead to the formation of patterns in these systems and discuss different approaches to characterizing and quantifying patterns. Specific attention is given to the use of data-driven methods to detect patterns in spatial and temporal data that do not make assumptions about underlying statistical properties of patterns. These methods include e.g. decomposition methods, binning based methods, unsupervised classification and temporal stability analysis. We then analyze the value of considering patterns in evaluating model performance, reducing uncertainty in prediction of states and fluxes, as well as for upscaling and downscaling. Finally, we present ways forward to make better use of patterns in the description of flow and transport processes in soil-vegetationatmosphere systems.

Contents

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1. Introduction

There is a general awareness that some phenomena or properties *in Soil-Vegetation-Atmosphere (SVA) systems* tend to repeat and show up regularly in space, in time, or of both, and can be observed at different scales. Regularly appearing features are often termed patterns. In general, pattern is a vague term that has multiple connotations. Search for patterns and their formation is an omnipresent activity in a vast number of fields, from astronomy (Little and Ekers, 1971), cell biology (Basu et al., 2005) to criminology (Brantingham and Brantingham, 1981). In the field of geosciences, Goehring (2013) discussed pattern formation in e.g. desert andarid regions, wetlands, permafrost and cold regions, shorelines, river systems and rocks. In the field of ecology pattern formation was addressed by Lovett et al. (2005). Monitoring of patterns in the complete SVA systems and their potential use in more efficiently modeling the systems is currently studied in the Collaborative Research Centre TR-32 on pattern in Soil-Vegetation-Atmosphere Systems (Simmer et al., 2015), and first pattern-related results were already published by Vereecken et al. (2010). Pattern recognition is an essential part of machine learning (Bishop, 2006). The need in studying patterns increases as we enter the "big data" era and more and more data becomes available due to our increasing capacity in observing the Earth's surface and its ecosystems. Understanding on how to generalize such data to the large extent comes from identification of patterns in them (Fan et al., 2014).

The existence of patterns can be the consequence of systems' properties leading to self-organization as well as emergent properties including those appearing due to changes in scale, and presence of organization in systems controls. Patterns typically can be visualized and characterized using (1) images and maps, (2) notions, parameters, and statistics suitable to describe spatially distributed data, time series, and spatiotemporal data, and (3) models applicable to such data. Both patterns themselves and the systems' behavior need to be characterized and quantified when patterns are used to predict a systems' behavior. The objective of this work was to review methods and applications of pattern characterization in soil-vegetationatmosphere systems.

Different approaches have been used in literature to categorize patterns observed in nature, either from the perspective of pattern content (what is in the pattern) and from the perspective of pattern geometric features. Stevens (1974) distinguishes patterns in terms of geometric features of natural objects such as e.g. symmetry, trees, and waves amongst others. Formation of such patterns is the result of nonlinear non-equilibrium processes often controlled by strong feedback mechanisms. Lovett et al. (2005) identified three key characteristics of patterns which are widely used in ecosystem studies, namely, gradients, patches and networks. Gradients define the contrast of a property in space, while patches represent domains of property similarity. They are discrete areas where gradients diminish (based on certain cut-off values). A network defines a system of connected, hierarchically branching elements of structure and function and represents combinations of both continuous and discrete variation.

From the perspective of pattern content (or information), pattern characterization or categorization focuses on its statistical properties in terms of probability density distributions and their spatial and temporal dependencies. This approach is frequently used in meteorology, geology, hydrology and soil science. In these disciplines geostatistical and time series analysis approaches have been developed and applied to characterize different patterns in space and time.

We define in this study patterns as recurrent spatial or temporal features of system behavior across scales thereby comprising repeatability and predictability. The knowledge about patterns appears to be invaluable for diagnostics, monitoring, prediction and management of environmental, engineered, and social systems. The paper is organized in the following manner. In Section 2, we present different concepts used to understand and describe pattern formation including self-organization and emergence concepts. In Sections 3 and 4, we address methods for pattern detection and quantification. The utilities of using patterns in predicting water, energy and matter fluxes are addressed in Section 5. We conclude with an outlook on the use of patterns in SVA-systems. The aim of the paper is not to present a compendium of methods and concepts but to provoke and stimulate discussions and new developments.

2. Pattern formation

2.1. Theoretical concepts

Non-linear dynamic systems - such as the soil-vegetationatmosphere continuum – often exhibit macroscopic patterns generated as a result of organization and/or interaction on microscales of such systems. The idea that a complex chain of processes produce "order out of chaos" (Prigogine, 1984) has led to