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What's going on about geo-process modeling in virtual geographic environments (VGEs)

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ABSTRACT

Geography investigates changes in physical structures and distributions of objects in spatiotemporal world, which are shaped by geographic process (geo-process). With extensive simulation models used to study geo-process, this paper examines the status of geo-process modeling (namely model-based simulation) for multidisciplinary geo-processes across scales in virtual geographic environments (VGEs). The conceptual framework of integrated modeling in VGEs is proposed with a review of specific issues, including model sharing and management, collaborative modeling and uncertainty analysis. The contribution of a model base in model reusability and modeling management, concerning input data, parameterization, and simulation output, is detailed. Finally, this paper concludes with a discussion of future research directions for holistic geo-process modeling.

1. Introduction

In the geographic world, a vast amount of information is referenced by space and time. Space, time and processes are closely interconnected (Worboys, 1994), and changes in physical structures and distributions of objects in space are shaped by dynamic geographic processes (geo-processes) (Hofer, 2009). In the real world, these processes are three-dimensional, time-dependent and complex; they frequently involve nonlinearity, stochastic components, and feedback loops over multiple space-time scales (Bivand and Lucas, 2000). For example, landscape patterns are produced by a succession of states that evolve over a period of time, with enormous ecological impacts (Soares-Filho et al., 2002). Hence, to improve the understanding of the mechanisms and feedbacks of geo-processes, geographers have strived to gain additional knowledge about geo-processes.

Due to the limitation in data acquisition and information technology in previous decades, geographers usually focused on static expressions and relationships among multiple geographic variables by analyzing a series of snaps of geo-processes (Cho et al., 2011; Wu, 2004; Xu et al., 2011). Along with the accumulation of geographic knowledge and developments in Earth observation, database technology, and computer science, geographers and environmental modelers have recently designed massive models of geo-process to simulate dynamic geographic phenomena, such as land surface process modules for atmospheric models, water flow and contaminant transport modeling on a larger scale (Steyaert and Goodchild, 1994). As the next step in geographic data-based static expression of the geo-process, which is employed to explain the "what", a model-based dynamic analysis of the geo-process can also reveal the mechanisms of the "why" and "how" behind geographic phenomena (Xu et al., 2011). Thus, the development of dynamic models is attracting the interest of geographers in their investigation of geo-processes (Albrecht, 2005; Gogu et al., 2001; Mark, 2003).

In the context of the varying interests of geographers, the research tools for geographic study have also changed. Until the 1980s, geographic information system (GIS) has been extensively applied to assemble and manage large spatial databases, to perform spatial and statistical analyses, and to produce effective visual representations of geographic data (Steyaert and Goodchild, 1994). Interdisciplinary and multiscale modeling approaches have created new applications for GIS technology by integrating GIS and various

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dynamic models (Bivand and Lucas, 2000; Clarke and Gaydos, 1998; Goodchild, 1993; Gualtieri and Tartaglia, 1998; Lü, 2011; Rebolj and Sturm, 1999), such as the contemporary links between GIS and hydrological modeling (Maidment, 1993; Mccolm et al., 1990) and the use of GIS technology in regional air quality and tropospheric chemistry models (Novak and Dennis, 1993). Recently, simulation models are increasingly recognized as sophisticated tools for investigating and understanding geographic patterns and processes and estimating the effect of geographic change on local, regional, and global scales (Emery et al., 2012; Steyaert and Goodchild, 1994). In this context, with simulation models as a critical component in the study of geo-process, virtual geographic environments (VGEs) were proposed (Batty, 1997; Lin and Batty, 2009; Lin and Gong, 2001) as a new generation of geographic analysis tools that evolved from GIS (Lin et al., 2013a; Zhang et al., 2014a). Concerning complex geographic systems in the physical world, dynamic models in VGEs include not only air, land, water, animals and plants but also their interactions with non-natural systems, including constructed infrastructure and economic and social systems (Argent, 2004; Chen et al., 2013a).

This paper considers the problems in the development and application of geo-process modeling in VGEs and examines the advancements that have occurred over the last years. The remainder of the paper is organized into four sections. We discuss the background and scope of the paper concerning the theory of VGEs and the technical components of VGEs for dynamic geo-process modeling in Section 2. In Section 3, we propose a conceptual theoretical and technical framework that addresses geo-process modeling problems across a range of VGEs applications. Section 4 reviews integrated modeling in VGEs and corresponding critical issues, including model sharing and management, collaborative modeling and uncertainty in geo-process modeling. This paper culminates with the conclusions and a discussion of directions for future development.

2. Virtual geographic environments: Background

VGEs are constructed with the objective of providing open and digital windows into geographic environments based on two cores of geographic data and dynamic simulation models (Lin et al., 2013a; Xu et al., 2011). These VGEs are expected to correspond to the real world, in which human-environment interactions can be represented, simulated and analyzed (Chen et al., 2013a; Hu et al., 2011; Lin et al., 2013b), such as path planning with semantically-enhanced and geometrically-accurate VGEs (Mekni and Moulin, 2010a). In addition to replicating the real world, VGEs can help researchers reproduce the past and predict the future (Chen et al., 2013b; Lin and Batty, 2009). For example, based on land cover information about different stages of the urbanization process (for example, at 1995, 2005 and 2015) with air pollutant emission, meteorological and air quality models, the effect of urbanization on air quality can be simulated and recognized by multidisciplinary researchers with corresponding visualization functions in VGEs. Thus, VGEs make it possible to design and implement effective policies, which need to be informed by a holistic understanding of the systems (social and economic processes), their complex interactions, and how they respond to various changes (Kelly et al., 2013). In the near future, VGEs are expected to produce user-friendly modeling with less dependency on model specialist knowledge, because both VGEs software and aided hardware are expected to be more powerful and graphical, less expensive, and easier to use (Argent, 2004; Lin et al., 2013b).

According to the theories of VGEs, one completed VGEs consists of four types of components: data, modeling and simulation, interactive, and collaborative components (Fig. 1) (Lin et al., 2013a; Lü, 2011). The modeling and simulation component is the main component of VGEs as the fundamental goal of VGEs is to simulate dynamic processes by integrated models (Lü, 2011). Based on geo-process modeling theory and integration technologies, this component facilitates the exploration of occurrences in our real world and why and how it is evolving (Lin et al., 2013b). Meanwhile, this modeling component is extremely relevant to the remaining three components. First, diverse models (for processes of air, water, and land) require massive geographic data as an input to simulate geo-processes; the output from modeling is managed in the data component for additional modeling and application. Second, the interactive component provides multidimensional methods for both external and involved interactions to set modeling (Lin et al., 2013b). In this context, the general scientific model is embedded in a 'user-friendly' application to satisfy the needs of scientists, decision-makers and other participants who utilize VGEs. Third, users who conduct modeling may originate from different disciplines and spatially distribute; for example, both meteorologists and air quality experts need to work together to conduct air quality modeling. For a complex issue, participants of VGEs need to cooperate with each other not only to set modeling but also to analyze modeling results with visualization. Thus, the collaborative component is applied to support modeling and analysis. Considering the significance of the simulation component and its internal interaction with each component of VGEs, this paper examines the status of geo-process modeling.

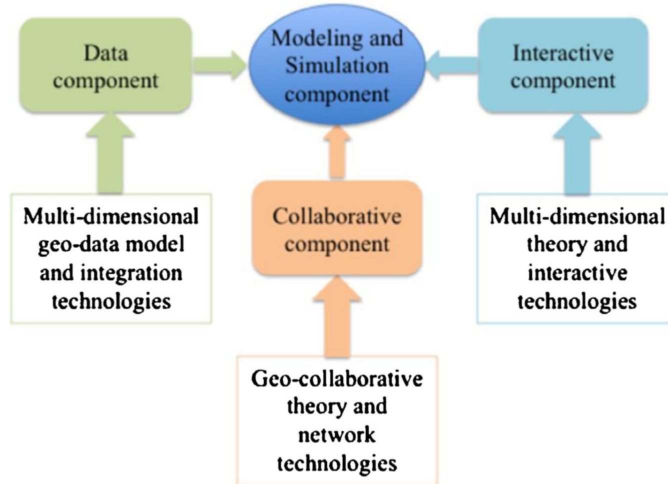

Fig. 1. Four components of VGEs.

3. A conceptual framework of modeling

3.1. Theoretical framework

To construct the modeling and simulation component of VGEs, a conceptual framework is proposed in this paper (Fig. 2). The main advantage of VGEs is integrated modeling, which has been considered to focus on multidisciplinary and cross-scale modeling, as demonstrated in the theoretical framework (Fig. 2 in green). The evolution of geographic processes is frequently and coherently influenced by interactions among several processes related to different fields. For example, the development of urbanization may affect river resources, air quality, landscape patterns, and populations (Chin, 2006; Wu et al., 2015). Thus, a comprehensive analysis of a geographic system, such as a catchment (Argent et al., 1999), can be conducted by integrating multidisciplinary models in a visual and formalized mode in VGEs (Haddad and Moulin, 2010; Chen et al., 2011). Concerning these interactions, the