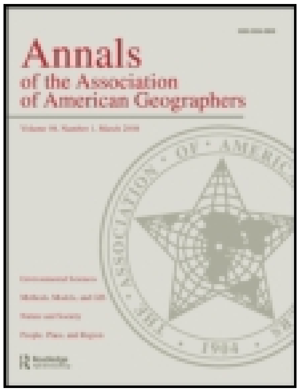

Annals of the Association of American Geographers
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/raag20

Virtual Geographic Environment: A Workspace for Computer-Aided Geographic Experiments

Hui Lin [a], Min Chen [a] & Guonian Lu [b]
[a] Institute of Space and Earth Information Science, The Chinese University of Hong Kong
[b] Key Laboratory of Virtual Geographic Environment, Ministry of Education of PRC, Nanjing Normal University
Published online: 05 Jul 2012.

Virtual Geographic Environment: A Workspace for Computer-Aided Geographic Experiments

Hui Lin,* Min Chen,* and Guonian Lu†

*Institute of Space and Earth Information Science, The Chinese University of Hong Kong
†Key Laboratory of Virtual Geographic Environment, Ministry of Education of PRC, Nanjing Normal University

A virtual geographic environment (VGE) is a type of workspace for computer-aided geographic experiments (CAGEs) and geographic analyses. By supporting geo-visualization, geo-simulation, geo-collaboration, and human participation, it provides open virtual environments that correspond to the real world to assist computer-aided geographic experiments involving both the physical and human dimensions. Based on a discussion of how VGEs can contribute to CAGEs and geographic analyses, this article proposes a clear, systematic framework for VGEs. Four subenvironments are discussed according to their different functions, pertinent issues, and corresponding solutions: (1) the data environment, (2) the modeling and simulation environment, (3) the interactive environment, and (4) the collaborative environment. Furthermore, a case on the simulation of air pollution and its analysis at different geographic scales is used to demonstrate VGEs' ability to facilitate computer-aided geographic experiments. *Key Words: subenvironments of VGE, systematic framework for VGE, virtual geographic environment (VGE).*

虚拟地理环境（VGE）是计算机辅助地理实验（CAGEs）的一种工作空间和地理分析类型。通过支持地理可视化，地理模拟，地理协作，和人类参与，它提供了对应于现实世界的开放的虚拟环境，来协助有关物质和人力方面的计算机辅助地理实验。本文基于一个有关 VGEs 如何能有助于 CAGEs 和地理分析的讨论，提出了一个明确的，系统化的 VGEs 框架。根据各自不同的功能，相关的问题，以及相应的解决方案讨论了四个子环境：（1）数据环境，（2）建模与仿真环境，（3）互动环境，和（4）合作环境。此外，本文使用一个空气污染的模拟，和对它在不同的地理尺度的分析，来演示 VGEs 促进计算机辅助地理实验的能力。*关键词：VGE 子环境，VGE 系统框架，虚拟地理环境（VGE）。*

Un entorno geográfico virtual (EGV) es un tipo de espacio de trabajo para experimentos geográficos apoyados en computador (EGAC) y para análisis geográficos. Al apoyar la geo-visualización, geo-simulación, geo-colaboración y la participación humana, tal espacio de trabajo provee entornos virtuales abiertos que corresponden al mundo real para ayudar en experimentos geográficos apoyados en computador que involucran las dimensiones tanto físicas como humanas. Con base en una discusión sobre cómo los EGV pueden contribuir a los EGAC y a los análisis geográficos, este artículo propone un marco claro y sistemático para los EGV. Se discuten cuatro sub-entornos a partir de sus diferentes funciones, asuntos pertinentes y soluciones correspondientes: (1) el entorno de los datos, (2) el entorno de la modelización y la simulación, (3) el entorno interactivo, y (4) el entorno colaborativo. Aun más, se utiliza un caso simulado de polución aérea y su análisis a diferentes escalas geográficas para demostrar la capacidad de los EGAC para facilitar los experimentos geográficos apoyados en computador. *Palabras clave: sub-entornos de EGV, marco sistemático para los EGAC, entorno geográfico virtual (EGV).*

Geography has traditionally been concerned with people, the physical environment, and their relationships (Murphey 1982). The spatiotemporal distribution of phenomena, processes, and features is studied by geographers to elucidate complex interactions between vast and closely interrelated human and environmental systems (Ackerman 1963; Renwick and Rubenstein 1995; Lin 1997; Armstrong 2000; Herbert and Matthews 2004). During this process, various theories, methodologies, and technologies have been employed to assist geographic research (Brunn, Cutter, and Harrington 2004; Clifford, French, and Valentine 2010; Gomez and Jones 2010), and computer-aided geographic experiments (CAGEs) have frequently been used to improve the analyses (Matthews and Herbert 2008).

Experiments and critical observations are important means for generating and validating scientific knowledge (Cohen 1985). Geographic experiments, which are known as a type of integrated research

Annals of the Association of American Geographers, 103(3) 2013, pp. 465–482
Initial submission, May 2011; revised submissions, September and November 2011; final acceptance, November 2011
Published by Taylor & Francis, LLC.

method, were proposed early in 1887 by Sir Halford John Mackinder, the first professor of geography at Oxford. The aim of these experiments was to simulate the natural and social worlds under one explanatory umbrella (Mackinder 1987; Matthews and Herbert 2008). Today, the content has been extended. With the development of computer science and environmental modeling, the traditional methods employed to investigate spatial distributions through samples and interpolation and to analyze the temporal patterns using snapshots have faced many challenges (Goodchild, Yuan, and Cova 2007; Konecny 2011). To overcome these challenges, researchers often devise CAGEs to simulate the geographic situations that constitute the complex world, test particular geographic theories, or analyze geographic phenomena and processes (Livingstone 1993; Lin, Huang, and Lu 2009). In this case, a suitable workspace with the special function of integrating both environmental simulation and human–environment interactions is necessary, and thus the virtual geographic environment (VGE) has become useful (Lin, Huang, et al. 2010).

VGEs were created to provide virtual environments that correspond to the real world to allow the conduct of open CAGEs, in which human–environment interactions can be represented, simulated, and analyzed. Furthermore, VGEs can help researchers to reproduce the past, replicate the current world, and predict the future (Batty 1997; Lin and Gong 2001; Lin, Huang, and Lu 2009). With a VGE, researchers from different areas and fields can collaboratively perform CAGEs. First, they can build virtual geographic scenes of different scales with integrated geographic data derived from various resources. Second, the distribution and dynamics of geographic features not only involve statistical relationships but also mechanisms driving the phenomenon in question (Goodchild, Yuan, and Cova 2007). A VGE allows researchers to simulate and explore those dynamic geographic phenomena and processes using geographic analysis models (e.g., the Fifth-Generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model or Gaussian Plume Model). Third, social factors can be subsequently incorporated into the virtual environment for geographic analysis and decision making. For example, emissions of polluted air caused by economic development and population expansion can be taken into account as negative impacts for experiments related to air quality management in the workspace. Public users can observe interactions between their activities and the resultant air quality change or directly participate in this virtual environment as avatars through multidimensional and multisense interactive interfaces, especially in microscenes, to experience and interact with the "real polluted world." They can improve or worsen the situation through their virtual activities. In this way, users not only feel the environments "in person," but they also "bring" their spatial knowledge and virtual spatial behaviors into the VGE. Fourth, based on the combined studies described earlier, multidisciplinary researchers can communicate and collaborate with corresponding tools to visually and interactively conduct and repeat comprehensive geographic experiments in a VGE. They can also verify the results, perform geographic analyses, and solve geographic issues.

Consequently, a VGE is different from a simple virtual reality (VR) system or virtual game system. The purposes of these environments are clearly different. Because a VGE supports geo-visualization, geo-simulation, geo-collaboration, and human participation, geography, which includes both physical and human dimensions, is the core of VGE. To build such a workspace, geographic data models, geographic analysis models, multichannel interactions, and distributed collaborative technologies that are based on a network and some other factors should be organically integrated in a VGE (Lin and Batty 2009).

Based on a short summary of research into the development of VGEs over the past decade, this article first proposes a systematic framework for the further development of VGEs. Four subenvironments (data environment, modeling and simulation environment, interactive environment, and collaborative environment) are then illustrated in detail to address questions such as "How can they contribute to a CAGE?," "What are their essential functions?," and "What are the key issues for developing such a subenvironment?" In addition, a case related to air pollution simulation and analysis at different geographic scales is discussed to demonstrate the ability of VGE to support CAGE. The article ends with a conclusion and ideas for the future direction of work on VGE.

The System Framework of a VGE

The term *VGE* has been used for nearly a decade and is still being developed. On one hand, some researchers have directly pursued the close theory and implementation of a VGE (Batty 1997; MacEachren et al. 1999; Lin and Gong 2001; Lin and Zhu 2006; Zhang et al. 2007; Zhu et al. 2007; Chen et al. 2008; Goodchild 2009b; Paris, Mekni, and Moulin 2009; Lin, Huang, et al. 2010; Lin, Zhu, et al. 2010). On the other hand, many researchers are absorbed in research that is indirectly related to building a VGE but can offer its references for the development of VGE, including multidimensional geographic data organization (Coors 2003; Shi, Yang, and Li 2003; Zlatanova, Rahman, and Shi 2004); geographical analysis model integration and sharing (Crosier et al. 2003; Hill et al. 2004; Redler, Valcke, and Ritzdorf 2009); geographic information visualization (Fabrikant 2005; Fabrikant, Montello, and Mark 2010); the construction of digital cities (Ishida 2002), virtual communities (Rheingold 2000), virtual worlds (Bartle 2003), and Digital Earth (Craglia et al. 2008); and human spatial behavior exploration using geo-tools (Kwan 2000, 2004; McLafferty 2005; Ren and Kwan 2007; Lee and Kwan 2011).

Previous studies have focused on theories, technologies, and implementations. To date, a unified systematic framework for the development of VGEs is still lacking. With a well-designed systematic framework, the concept of a VGE can be understood more precisely, prefabricated components and their functions can be clearly organized, technologies can be designed, and related contributions can be fully utilized directly based on the needs of the field.

Designing the Systematic Framework

The geographic environment, which is the core research subject for geographic experiments, consists of the surfaces on which human societies exist and develop (Matthews and Herbert 2008). This environment is a comprehensive system consisting of the natural, social, cultural, and economic factors and their interactions. To build a VGE that can represent and simulate this real geographic environment and assist in CAGE, four steps should be included. The first step is the exploration of effective technologies and methods for data acquisition and organization. Next, because simulation of various dynamic natural phenomena (e.g., precipitation, evaporation, storms, earthquakes, and volcanic eruptions) in modern CAGEs increasingly requires quantitative analysis and numerical simulation methods (Haidvogel et al. 2000; Francos et al. 2003), a corresponding VGE should be able to simulate these dynamic natural processes "naturally." After a "physical" virtual world has been built, the third step should be to search for strategies to encourage researchers and the public to interact with the virtual world more naturally. This step will put the public and their spatial knowledge on an equal footing with experts and decision makers to bridge the gap between users and the virtual workspace. After the integration of the physical phenomena and human interaction into one workspace, the last step should be to study collaborative modes and to develop suitable tools for experimental performance and the analysis of geographic issues to facilitate comprehensive research by multiple experts.

The VGE systematic framework is discussed in this article according to these four steps. The framework can be divided into four subenvironments. Figure 1 shows the framework and the subenvironments of a VGE.

Subenvironments

Data Environment

Geographic data provide the most critical foundation of any geographic research (Roman 1990), and these data are equally important for CAGE. The data environment in VGE is responsible for the integration, organization, and management of geographic data, which will further support geo-simulation, geovisualization, human-centered participation, and geocollaboration.

To build such a subenvironment, two key issues must be carefully addressed: the integration and sharing of multisource heterogeneous data and data model design for the representation and simulation of multidimensional geographic scenes. Figure 2 shows the relationships between these two elements and their functions.

Multisource Heterogeneous Data Integration and Sharing. The virtual environment to be built is usually comprehensive and complex, and therefore geographic data should often be acquired from different fields by different collection methods. Multisource data are generally heterogeneous in their structure, semantics, and metadata descriptions. Moreover, the simulation of complex phenomena must integrate multiple or even multidisciplinary analysis models. In addition, when these models are collaboratively implemented, heterogeneity between the input and output data among the different models often results in serious problems.

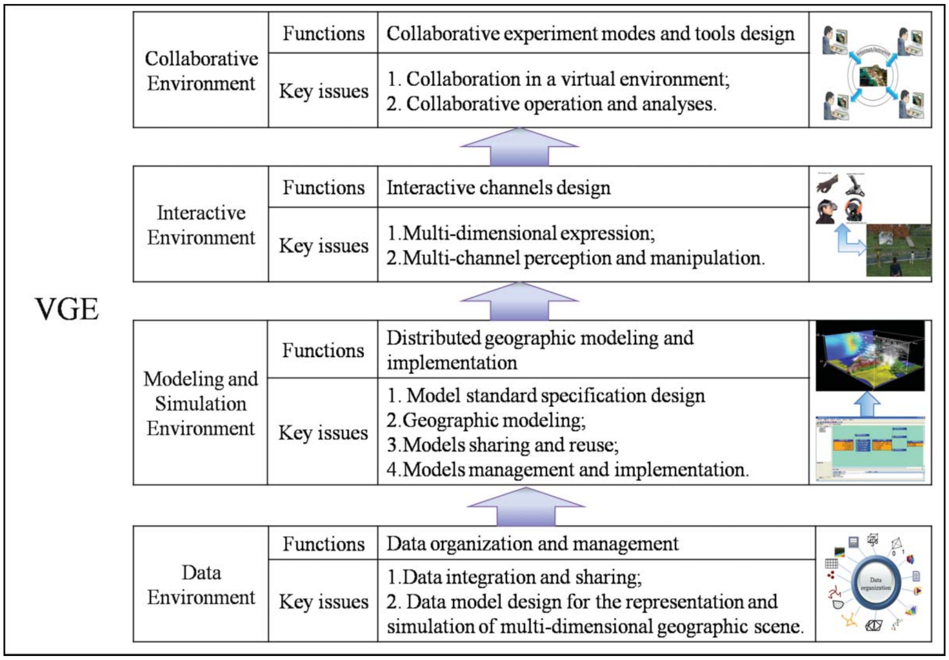

Figure 1. Framework and subenvironments of virtual geographic environments. (Color figure available online.)

To eliminate the heterogeneity of multisource data and search for effective data conversion strategies for multimodel collaborations, the most important step is to explore the different understandings of geographic data among different data providers and users from different fields. Because it is difficult to study every data model for integrating data in a VGE, initiatives of data sharing before data are integrated might be a useful method. In this mode, a unified representation mechanism is required for both the data owner and user to clearly describe the necessary characteristics of the geographic data that are provided or required, such as the data types and structures as well as the metadata, semantics, measurement unit, spatial reference, and spatial relationships. After the necessary characteristics of the geographic data are clearly expressed, the understanding of the geographic data can be shared. Next, through data customization methods, such as data extraction and data reconstruction, these geographic data can be integrated and reused by different users to build a VGE.

In this area, the Synthetic Environment Data Representation Interchange Specification (SEDRIS; James 1998; Foley, Mamaghani, and Birkel 1999), which provides methods to represent environmental data and promote the unambiguous interchange of environmental data, can be used as a good reference, although it primarily focuses on modeling an environment in a simulation field. Later, Su et al. (2008) proposed a geographic data representation model to solve data integration and sharing problems in VGEs.

Data Model Design for the Representation and Simulation of Multidimensional Geographic Scenes. The data model of a VGE should be an integrated data model that is distinguished by the following points. First, when simulating geographic phenomena, it is necessary to represent their spatiotemporal characteristics because they are continuous in time and space (Lin and Choi 1994). Thus, a VGE for CAGEs should be capable of building geographic scenes with different time stamps that can be used for spatiotemporal analysis and comparison of results. Therefore, the data model should be designed to account for the space–time dimension. Second, the physical environment consists of discrete entities that have clear boundaries and continuous spatial phenomena that lack clear-cut boundaries. To simulate such an environment, the data model should support object, field, surface, and volume modeling. Efficient conversion algorithms between these modeling methods should be realized in a unified theory to build an integrated data model.

In this aspect, algebraic theory, which can solve the multidimensional problems (Sibony 1976; Sunaga 2009), has been increasingly introduced into geographic data modeling and has proven to be particularly useful in VGE data. For instance, based on Clifford algebra, L. W. Yuan et al. (2010) built an integrated

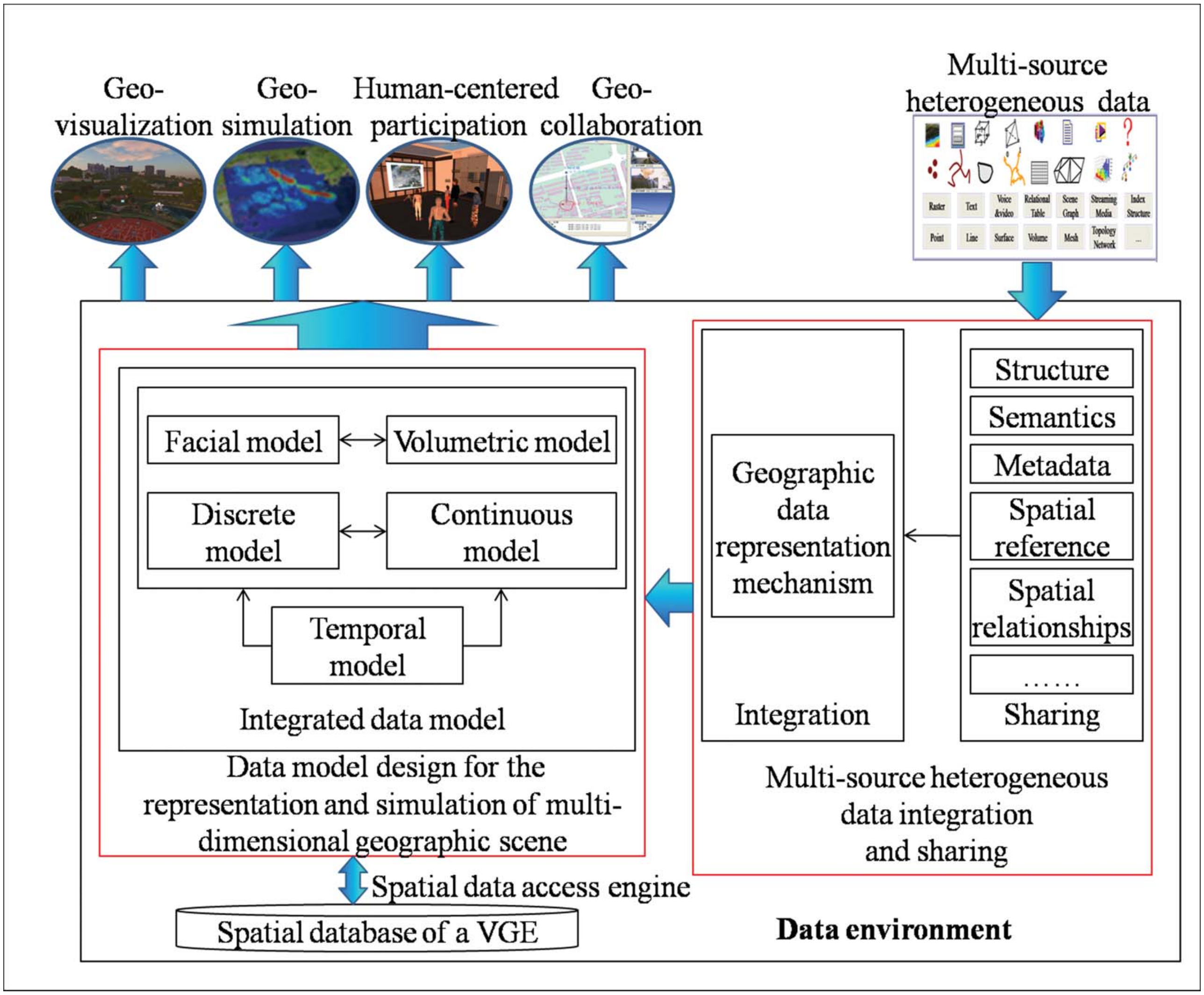

Figure 2. Relationships between the two parts of the data environment and their functions. (Color figure available online.)

spatiotemporal data model combined with a hierarchical spatiotemporal index. This model is capable of expressing and modeling time, space, and attribute information in an integrated manner. Wu, Shen, and Wen (2009) proposed the geometric algebra data model, which can model the above-ground and underground geospace in a comprehensive system, integrate geographic entities and fields using a 2D/3D Delaunay constraint algorithm, and provide conversion algorithms between the facial model and the volumetric model.

Modeling and Simulation Environment

The analysis and simulation of dynamic geographic phenomena are important in geographic research (Goodchild 2008; M. Yuan 2009) and of particular importance in CAGE (Peck 2004). Geographic analysis models are a common research practice in geography and can be used to facilitate communication among researchers in different disciplines and among the various stakeholders involved in geographic research (Perry 2009). In VGEs, these geographic analysis models are often employed as the main tools for the simulation of dynamic geographic phenomena. The modeling and simulation environment provides experts from different fields with an open workspace to create, share, reuse, and implement the distributed geographic analysis models. They can further simulate geographic processes in a convenient and collaborative manner. The simulation process in this subenvironment can be divided into four parts: model standard specification design, geographic modeling, model sharing and reuse, and model integration and implementation. Figure 3 shows the functional framework of this subenvironment.

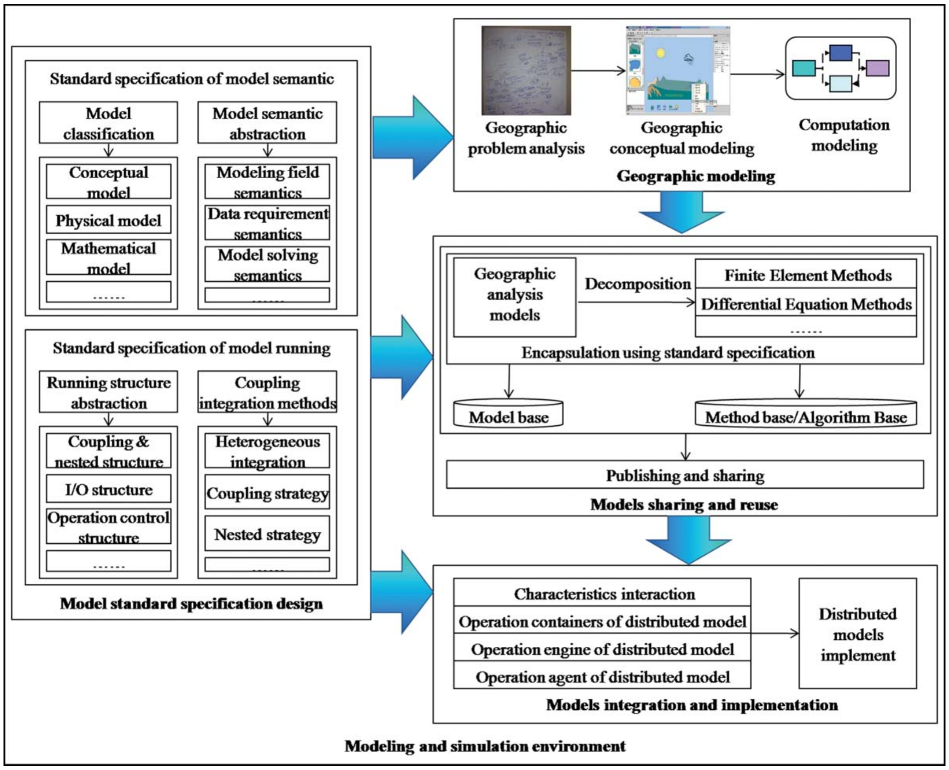

Figure 3. Functional framework of the modeling and simulation environments. (Color figure available online.)

Model Standard Specification Design. Geographic modeling and simulation of the complex world requires multidisciplinary perspectives. When researchers from different domains collaboratively create geographic analysis models, however, the primary challenge of communication is how to share their understanding of modeling ideas. Moreover, a standard and clear description is of crucial importance for other researchers who reuse or implement heterogeneous models. Therefore, the model standard specification design lays the critical foundation for the geographic modeling and simulation environment and will be used for the other parts.

Although many factors are related to model information (e.g., model classification, scope of the application, spatial reference, time range, spatial scope, model parameters, modeling principles, and solving methods), they can be generally classified into two types: model semantic information and model running information. The model semantic information includes descriptions about the model itself, such as model classification, model field semantics, and data requirements. The model running information includes the operational metadata of models, such as descriptions related to the running structures and coupling integrations. A standardized modeling and simulation environment can be built and collaborative work can be performed only if the model standard specifications are well designed.

Geographic Modeling. Geographic modeling establishes the basic geographic concept models and the computational models. During this step, multidisciplinary researchers can assemble geographic analysis models step by step by sharing their modeling knowledge, with the guidance of the well-designed model standard specifications.

Block diagrams and flow charts have been adopted by the Generic Modeling Environment (GME), Spatial Modeling Environment (SME), and GeoVista Studio to build models (Ledeczi et al. 2001; Takatsuka and Gahegan 2002; Costanza and Voinov 2004). A possible alternative method to this process is modeling by employing conceptual graphs. According to Thomas et al. (2006), visual conceptual graphs can facilitate effective communication for scientific research. The employment of conceptual graphs to build geographic conceptual models will greatly enhance the intelligibility and sharing of the modeling processes (Chen et al. 2010; Chen et al. 2011). In this mode, geographic conceptual entities will be represented by configurable conceptual icons, whereas relationships among entities will be represented by directed lines; finally, the geographic conceptual scenario will be built by dragging icons or directed lines into this visual scenario. Conceptual icons, which represent geographic conceptual entities and relationships, contain the meanings of geo-models, geo-semantics, and geo-data requirements, and the directed lines contain the meaning of the match rules between the models and data. During the modeling process, model standard specifications are used to obtain guidance and matching rules, and some constraint engines have been designed to guide the model matching and data matching processes. In this manner, geo-data, existing algorithms, and even submodels can be selected from the database, algorithm libraries, and model libraries to create a new geographical analysis model.

Model Sharing and Reuse. The sharing and reuse of models can make full use of model resources distributed throughout the network to reduce modeling costs and time spent by researchers on the creation of models, which leaves more time for geographic experiments. The crucial issue in this step is the organization of the model standard specifications in a standard way so that these models can be published online. Some successful models can be used as references for this procedure. Based on Structured Modeling Markup Language (SMML), EI-Gayar and Tandekar (2006) designed a distributed environment for model sharing. Kato, Yamaki, and Asai (2009) proposed a system named GPGCloud that consists of four components: the Content Management System (CMS), the Model Repository (MR), the Result Store (RS), and the Cloud, which helps users to share their simulation models with others. Feng et al. (2011) designed an online prototype for the integration and sharing of five disciplinary models using the Open Geospatial Consortium (OGC) Web Processing Service (WPS) standard.

Model Integration and Implementation. In recent years, theories and methodologies of model integration and implementation have become common concepts in geographic research (Argent 2004). Multiple models employed by researchers to conduct geographic simulations in VGEs have required integration and collaborative implementation via a network. The division of this step into four parts, which include the design of model containers, data exchange methods, operation workflow, and operation engine, will contribute to an effective operation. The design of the model containers is responsible for encapsulating running models. Data exchange methods are designed to solve data problems between heterogeneous models that are collaboratively implemented, such as when the output data of a model are not suitable to serve as input data for another model. Operation workflows are designed to implement the simulation in steps, whereas the actual implementations can be undertaken by the operation engine. Some previous work in this area can be used as references, such as the methods that were proposed by Ogle and Barber (2008) and Wen et al. (2011).

Interactive Environment

Generally, there are two ways to involve humans in CAGE: One involves related data collected by third parties and integrated into the system, and the other involves individuals who participate in the virtual environment individually to contribute their knowledge and personal experiences. In the first method, data can be abstracted and integrated in the data environment. For the second method, effective interactive methods and tools must be designed to facilitate the convenient participation of public users and to convey a sense of satisfaction to these users. The interactive environment is designed to provide such interactive channels between users and the VGE, and it includes both externally and internally observable tools.

Multidimensional Expression. A VGE can involve two types of users: geographic researchers who primarily participate in using analytical tools and windows and the public who participate as avatars. Therefore, different forms of interaction and navigation will be required. For example, when a hydrologist and a pedologist conduct collaborative simulation experiments, they might be eager to see familiar operator interfaces that often appear in their own domain tools. Another example is related to the second method of participation. When avatars walk around in the virtual environment, point to objects in the scene, and ask for information from the VGE's database, more intelligent and understandable methods of data querying and presentation might be required.

Therefore, according to Lin and Zhu (2006), multidimensional expression might be an ideal VGE interface to satisfy different types of users. The multidimensional expression mentioned here refers to multiple dimensions and multiple styles. Multiple dimensions means that 2D, 3D, or even 4D (which includes the time dimension) visualization should be used for generating more realistic renderings of phenomena or effects, whereas multiple styles means that different display styles (e.g., VR style, computer-aided design style, or the visualization in scientific computing style) should be used to meet the needs and expectations of users from different fields. Some related technologies have been described previously by Germs et al. (1999); Jacobson, Kitchin, and Golledge (2002); and Peuquet (2009).

Multichannel Perception and Manipulation. Humans and their spatial behaviors are often important elements in geographic analysis (Kwan 2004; McLafferty 2004). The study of human–environment interactions will make geographic experiments two-faceted—with a physical and a human dimension—research method. To "bring" humans "naturally" into the virtual environment to assist CAGE, the senses of vision, hearing, touch, smell, and taste are necessary for the perception of geographic phenomena. Furthermore, manipulations through language, gestures, and drawing are more flexible than traditional methods (e.g., using a mouse; Rodaway 1994; Rauschert, Agrawal, et al. 2002). Multichannel perception (e.g., through vision, touch, or gesticulation) and manipulation (e.g., through language, gestures, or drawing) will greatly improve the service capability of VGE and significantly reduce the gap between VGE and the real world (Lin and Zhu 2006).

To date, researchers have made significant progress in the field of multichannel perception (Loomis, Golledge, and Klatzky 1998; Wall and Brewster 2004; Jansson and Pedersen 2005). Specifically, some immersion systems have been developed, such as the Cave Automatic Virtual Environment (CAVE; Cruz-Neira et al. 1992), ImmersaDesk (Czernuszenko et al. 1997), and IWall (CAVE 2002), which were invented by the Electronic Visualization Lab at the University of Illinois, and GeoWall, which was invented by Johnson et al. (2006). Moreover, recent technologies proposed for 4D movies (Shin et al. 2010) also offer potential reference value.

Some platforms that are related to multichannel manipulations have been developed and applied to emergency management and crisis management scenarios. These studies have been summarized in the literature (Rauschert, Agrawal, et al. 2002; Rauschert, Sharma, et al. 2002; Agrawal et al. 2004). Recently, the development of Kinect and similar interfaces has also greatly advanced this field (Giles 2010; Mark 2010).

Collaborative Environment

Collaboration is a critical aspect of scientific research that often involves complex problems, rapidly changing technology, dynamic knowledge growth, and highly specialized areas of expertise (Hara et al. 2003). In an open VGE, collaboration enables a group of geographers and the public who are interested in certain geographic problems to work together to conduct complex CAGEs to explore processes of geographic phenomena. These experiments can be performed locally or remotely and simultaneously or asynchronously. According to the participation modes, collaboration can be divided into collaboration in the virtual environment and collaborative operation and analysis.

Collaboration in a Virtual Environment. A VGE can provide a virtual environment for multiple users to "live in" as avatars that mimic living in the real world, and it can also help users overcome space, time, and performance constraints (Lin, Huang, et al. 2010). The problem of implementing this type of environment is how to live in it collaboratively. For example, how can users communicate with each other and interact with geographic entities? This problem indicates that an efficient collaboration mode in a virtual environment is necessary.

Collaboration modes in a virtual environment can be divided into three types:

1. Human-to-human collaboration; for example, two avatars talk with each other and then go to work together.
2. Geographic entity to geographic entity collaboration; for example, a virtual rainfall with blowing wind that affects the virtual environment.
3. Collaboration between human and geographic entities; for example, avatars can plant various virtual trees.

Before these modes can be realized, key issues should be addressed. These collaboration modes must also integrate human behavior and geographical mechanisms into the virtual environment with some applied engines (e.g., a physics engine) and then track these interactions into a database for further experiments. Some technologies that are related to collaboration in a virtual environment have been applied in several 3D virtual world communities, such as Second Life (Boulos, Hetherington, and Wheeler 2007) and multiuser virtual environments (Dieterle and Clarke 2005).

Collaborative Operations and Analyses. Collaborative operations and analyses will provide the research results of a CAGE in a VGE. This mode does not require user immersion, but it will provide corresponding tools to facilitate collaborative work. For example, a virtual conference system can be provided in a VGE to permit face-to-face communication through audio and video calls, and this system can include text communication, whiteboard use, document transmission and distribution, and application sharing.

MacEachren and colleagues (2003; MacEachren and Brewer 2004) have made significant contributions in this area. They observed that collaborative operations toward graphic problems have been meaningful for geographic collaboration. A conceptual framework for visually enabled geo-collaboration was developed in which the choice of the decision-making mode, the management of collaborative processing, and the conflict detection in geographic operations were considered in great detail. Other applications can be acquired from Lin's silt dam planning system (Lin, Zhu, et al. 2010). In this prototype system, the collaborative workflow and application mode were studied, a dynamic adaptive method of workflow instance was explored, and a message-based synchronized collaborative workspace was proposed.

Case Implementation

This section presents a VGE built for the simulation and analysis of air pollution at multiple geographic scales and illustrates its ability to facilitate CAGE.

Background

Air pollution associated with economic growth is a global problem. Scientists, government officials, and the public are focusing on improving the ability to accurately predict and efficiently control air pollution. CAGEs can be used to effectively simulate and analyze this complex phenomenon. The creation of a VGE for this type of experiment will facilitate scientific research into air pollution and provide opportunities for all of the participants to experience the "polluted world" and understand the impact of human behavior.

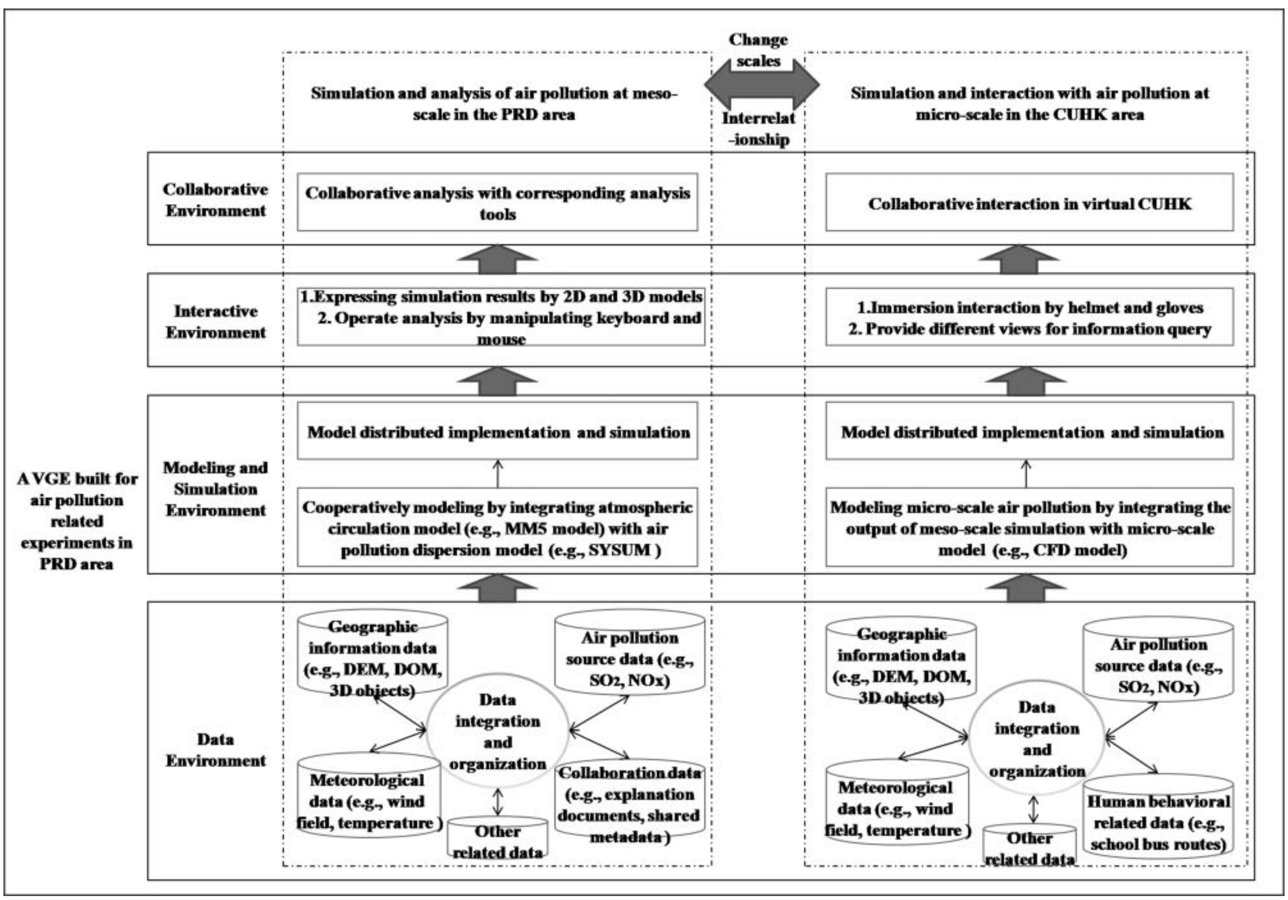

Figure 4. Architecture of a virtual geographic environment built for simulation and analysis of air pollution in the Pearl River Delta area.

The experimental area was chosen to be the Pearl River Delta (PRD), which pioneered reform and was the first area to open up when China's economic liberalization program began in the late 1970s. The area covers nine prefectures of Guangdong Province and the special administration regions of Hong Kong and Macao. In recent years, the air quality of this region has worsened with economic development and population expansion (Chan and Yao 2008).

The experiment was designed to simulate air pollution at a regional scale (the whole PRD area) for geographic analysis and research at a local scale (the whole campus of the Chinese University of Hong Kong (CUHK), which is located in the southeast of the PRD) to help humans understand their behaviors and their impact on nature. It is noteworthy that geographic phenomena in the two focus areas are inherently interrelated, although they exist at different scales. For example, the air quality at the local scale can be influenced by local pollutants and the spread of pollutants on a larger scale. Conversely, local air quality can also affect air quality on a larger scale. Therefore, in this article, the simulation and analysis of air pollution at the regional scale in the PRD area and the simulation and interaction with air pollution at the local scale in the CUHK area were implemented in the same VGE workspace.

Architecture of the Workspace

According to the systematic framework and to perform the simulation at different scales in the VGE, the architecture has four parts, which are shown in Figure 4.

Implementation of Each Subenvironment

The data environment is located at the bottom of the workspace and is responsible for organizing and managing the data for the next three steps. For the regional-scale experiments, data collection primarily includes geographic information data (e.g., digital elevation model, digital orthophoto map, and 3D geographic entities data), air pollution source data (e.g., sulfur dioxide and nitroglycerin), meteorological data (e.g., wind field, temperature, and air pressure), and collaborative data (e.g., explanation documents and shared metadata). For local-scale experiments, human behavioral data (e.g., the daily bus routes) were collected by means of survey data as well as users' self-participation, in addition to these data from the real world and the virtual environment. Human behavioral data collected from the real world would contribute to a more realistic simulation of the geographic scenes, whereas the data collected from the virtual environment involve virtual events that might not have happened in the real world but can be provided in the experiments. Because data were collected from different resources, a standard metadata description has been designed for data sharing and integration. The regional-scale data were integrated based on the layer management method; local-scale data were integrated based on object-oriented data models, and the two types of data were integrated by referencing their locations. Figure 5 demonstrates the geographic scenes created by data integration.

Above the data environment is the modeling and simulation environment. On the regional scale, for the air pollution modeling in the PRD area,

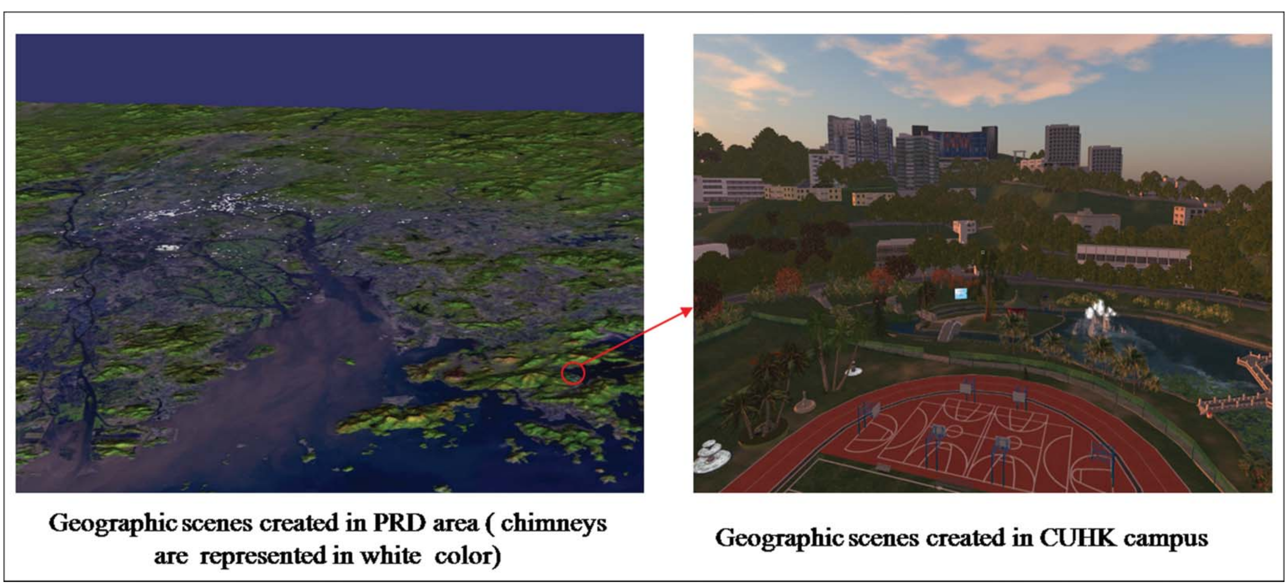

Figure 5. The geographic scenes created based on data integration. (Color figure available online.)

the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5; Grell, Dudhia, and Stauffer 1994; Dudhia et al. 2005) was selected as the atmospheric circulation model, and the Eulerian model based on the modified mesoscale atmospheric model (SYSUM; Xu et al. 2011) was selected as the air pollution dispersion model. The computational fluid dynamics model was employed for the local-scale simulation. A model specification was designed to assist participants, such as meteorologists, geographers, and computer

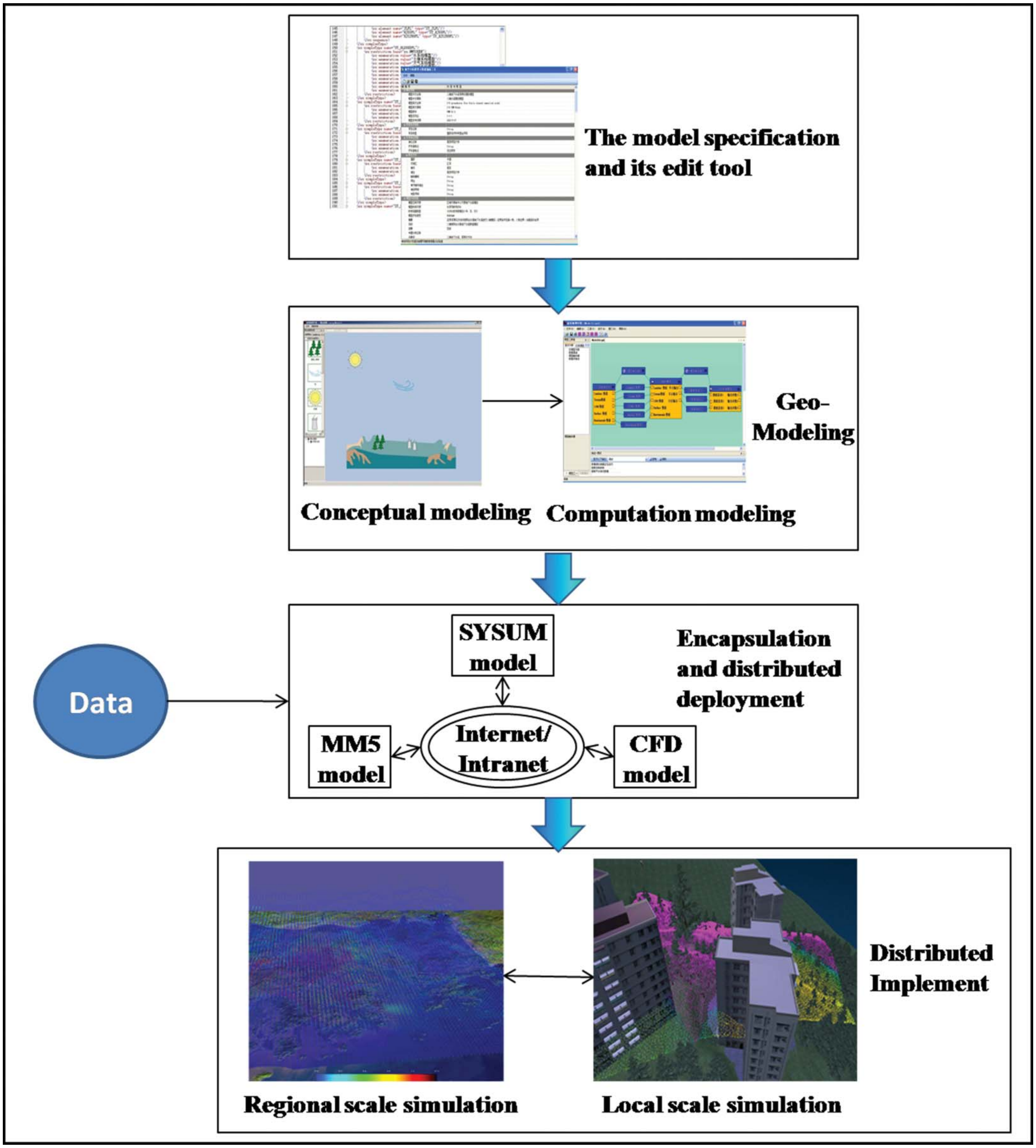

Figure 6. Model building and implementation processes for the air pollution simulation. (Color figure available online.)

scientists, in sharing their knowledge for collaborative modeling. Next, the conceptual scenes and computation workflow were designed: The output of MM5 and the emission source data served as the input for SYSUM for a regional-scale simulation, and the output of SYSUM in the CUHK area was selected and integrated with local pollution data to initiate the local-scale simulation. A data exchanging tool was designed to assist in the transformation of data among different models. Moreover, because model calculation often requires high resource consumption, the models were encapsulated and deployed in different services. Regarding the process of simulation, according to the conceptual workflow described earlier, the models were invoked from different services for their collaborative computation. Figure 6 shows the entire process for this step.

Following the air pollution simulation, the results were represented visually and users interacted with the virtual environment. For the regional-scale simulation, the users had no need to participate in the polluted region and the results were displayed on a screen or a display wall. To realize the 3D stereo display, each frame was acquired as an image in the memory by capturing the image data when they were transmitted from the software to the display card. Next, the image was be processed via matrix transformation and, finally, a new frame suitable for binocular vision was displayed in the stereoscopic mode; this frame was accessed by users only via polarization glasses, which did not require

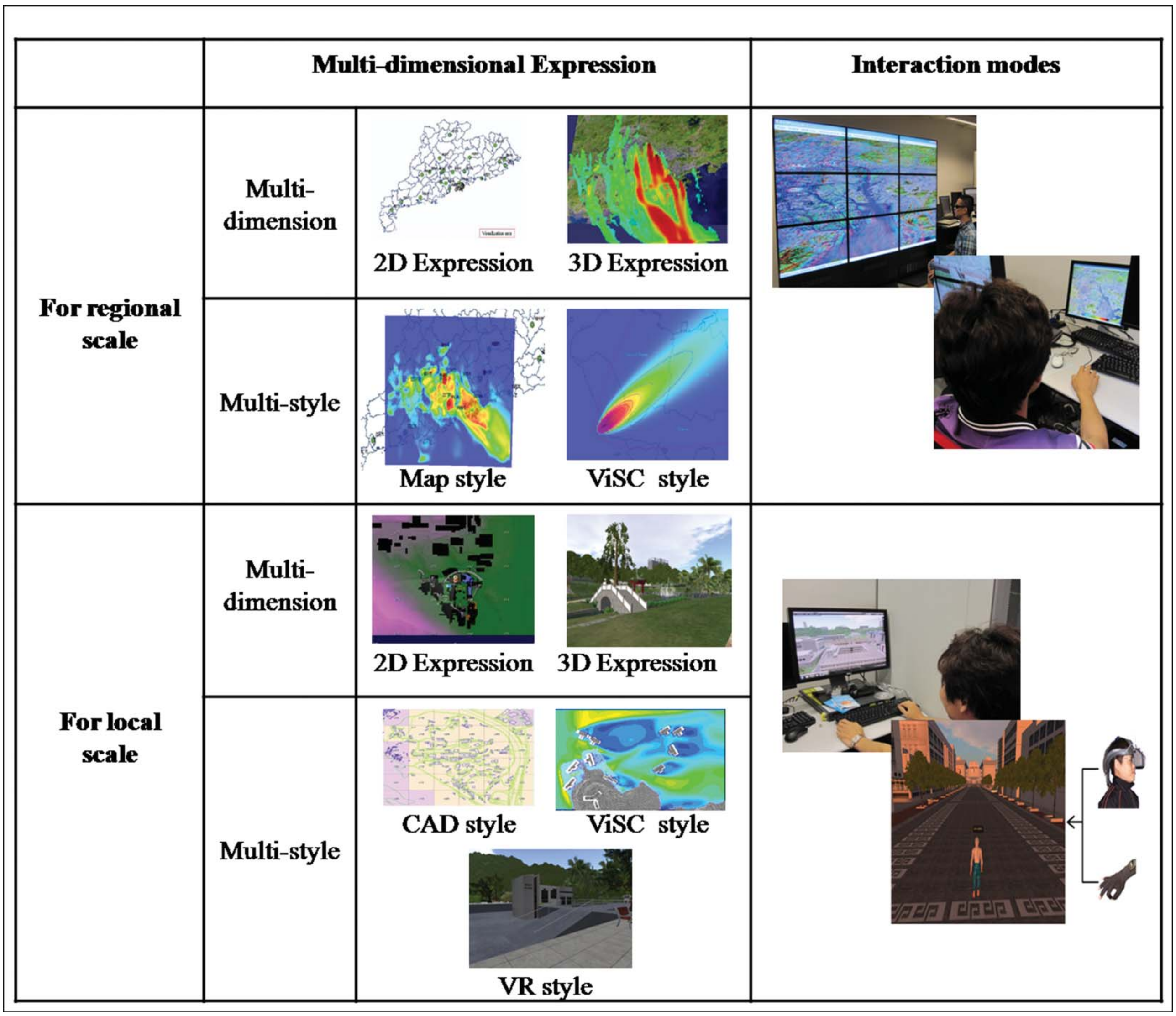

Figure 7. Interactive environment built for the air pollution experiments. (Color figure available online.)

any change in the visualization system program. In addition, the users manipulated the spatial analysis with keyboards and mice to access the desktop tools. For the local-scale expression and interaction, virtual reality helmets and gloves were integrated in the system so that users were able to participate as avatars to "naturally" experience the "local environment." The construction results of this subenvironment are shown in Figure 7.

The last step was the design of the collaborative modes and tools. Collaborative modes that are used in the 3D virtual world community were introduced into this workspace to facilitate participants' collaboration in virtual CUHK. The avatars were then able to collaboratively design buildings in the virtual campus that could significantly affect the diffusion path of air pollution, and they could then collaboratively communicate with others by actions, voices, and text. Because collaborative operations and analyses are important for the exploration of geographic processes through experiments, collaborative tools were designed accordingly. Based on a geographic consultation supported by cooperative document workflow, the collaborative workflow and application mode were studied. A dynamic, adaptive method of workflow instance was explored, and a message-based synchronized collaborative workspace was proposed. In addition, the geographic data and the parameters of geographic models could be edited collaboratively in these prototype systems using classified geographic operations and conflict-detecting strategies. Figure 8 shows the results of this step.

Based on the developed VGE, various experiments can be conducted accordingly. For example, more virtual factories and their chimneys can be placed in greenbelt areas of the virtual environment. After the computation, the increase in air pollution can be calculated and the dynamic phenomenon can be visually represented. At the local scale, additional local experiments can be conducted. For example, a virtual school bus can be designed to travel through the virtual campus so that the local and regional impacts can be simulated and tested. These scenarios can also be experienced by avatars in the local environment. The results of these experiments are shown in Figure 9. In this manner, physical and human factors can be integrated into the workspace together to permit geographic research, which will facilitate geographic experiments.

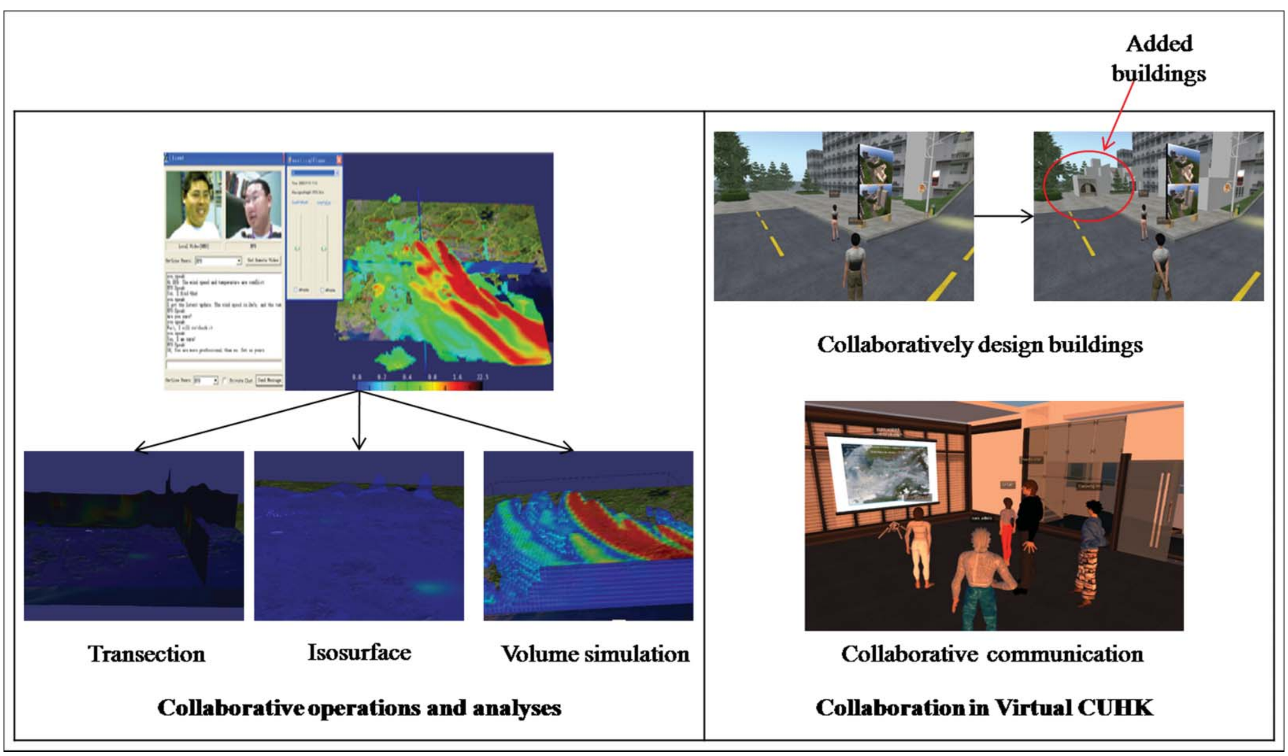

Figure 8. Collaboration in the virtual geographic environment. (Color figure available online.)

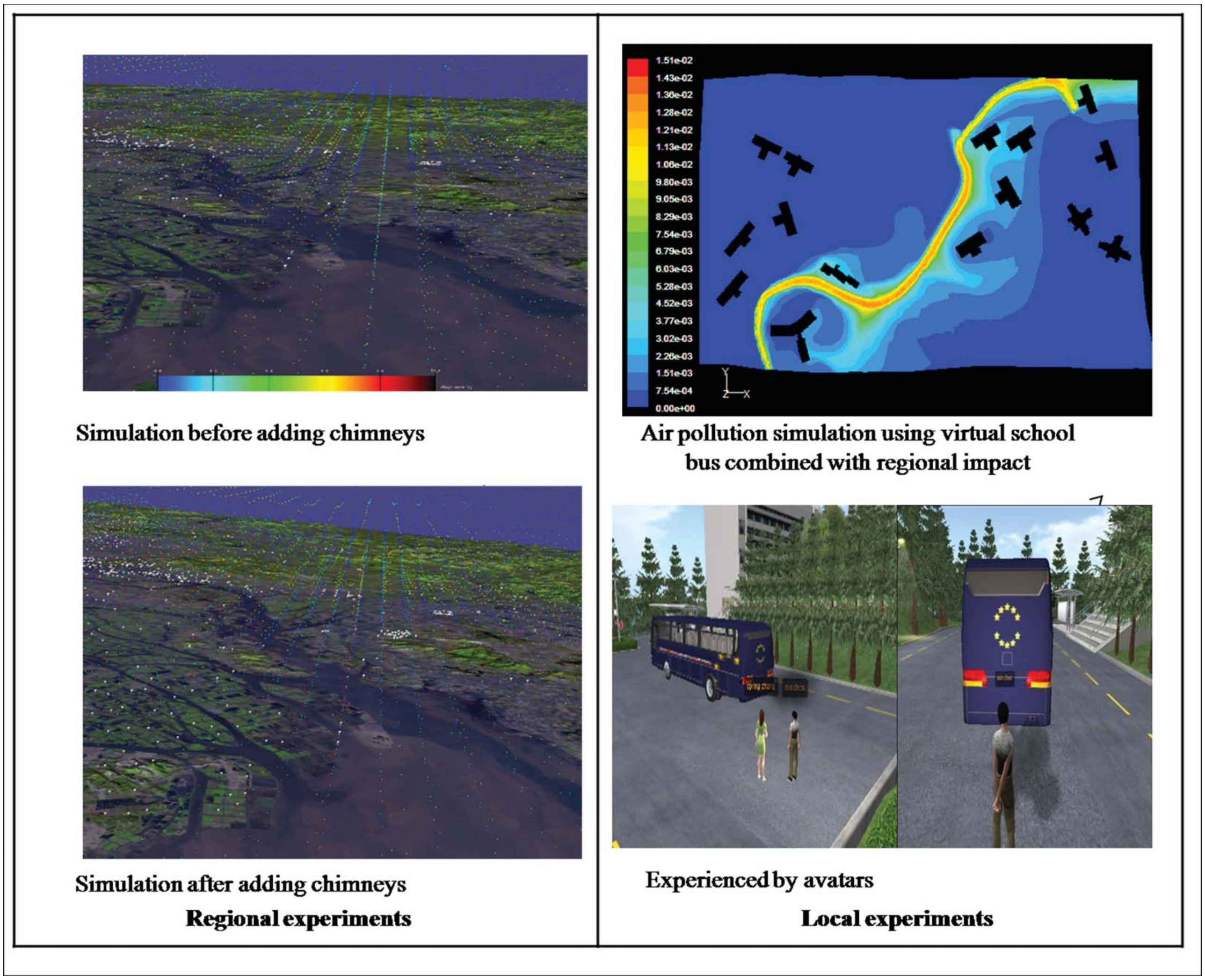

Figure 9. Computer-aided geographic experiments conducted in the virtual geographic environment. (Color figure available online.)

Conclusion and Future Work

With the development of computer and information science, geography, and network science, a workspace for modern CAGE should be built that includes the functions of geographic data integration, geographic knowledge modeling, multichannel interaction, and collaborative work support. Because of their ability to support geo-visualization, geo-simulation, geo-collaboration, and human participation, VGEs are products that can meet these demands. This article explored the systematic framework of VGEs and divided this framework into the four subenvironments: the data environment, the modeling and simulation environment, the interactive environment, and the collaborative environment. Each subenvironment was designed with functions for different steps of CAGEs. A case of air pollution simulation and analysis was designed to demonstrate the ability of a VGE to support CAGEs, and the simulation further provided us with the opportunity to explore the world more efficiently.

Although remarkable progress has been made, further work should be undertaken to improve VGE. Future research should be concentrate on the following aspects of each subenvironment.

Data Environment

Data integration ability remains limited. Although designing a standard data representation mechanism might solve some of the problems, the representation itself should be constantly supplied and updated. Currently, heterogeneous geographic data can be acquired in real time by sensors and other equipment, especially after Goodchild suggested that humans can be regarded as new types of sensors that contribute spatial informational content (Goodchild 2009a, 2009b, 2010). A suitable method for the effective integration of these data should be further explored, however. Moreover, the design of a data model that can organize data of complex geographic phenomena and entities to provide dynamic simulations and analyses is favorable.

Modeling and Simulation Environment

The integration problem is also the key primary problem in this subenvironment. Simulation of the complex world requires increasing interdisciplinary collaboration. The collaborative nature of heterogeneous interdisciplinary models requires continued studies and related key technologies, such as the design of standard and comprehensive languages for modeling and simulation, and the encapsulation methods of models should be optimized to interoperate simulations across disciplinary boundaries. In addition, it is important to understand how to make full use of current cloud computing technologies (Yang et al. 2011) to improve the ability of VGEs to model resource sharing and parallel computing for simulation.

Interactive Environment

When the number of participants increases, social experiments can be implemented more meaningfully. The desirability of the current participation modes of VGE is still low, however, and multisensory equipment that can support greater public participation is expensive and difficult to popularize. Therefore, the future exploration of civilian-oriented multisensory modes and equipment will be critical and might generate great interest from the general population.

Collaborative Environment

Collaboration modes and the design of related tools are critical for the support of comprehensive analyses in a VGE. Improvement of the customizable workflow and virtual scenario experiences as well as the introduction of multimedia assistance tools will greatly enhance the collaborative ability of the VGE, which will further contribute to collaborative CAGEs in the workspace.

Acknowledgments

We thank Dr. Bingli Xu, Dr. Mingyuan Hu, and other colleagues for their hard work in case development. We express our gratitude to Professor Michael F. Goodchild and Professor Michael Batty for their valuable suggestions. We also appreciate the detailed suggestions and comments from the editor and the anonymous reviewers. The work described in this article was supported by the Key Program of National Natural Science Foundation of China (Grant No. 40730527), the National High Technology Research and Development Program of China (Key "863" Grant No. 2010AA122202), the National Natural Science Foundation of China (Grant No. 41171146, Grant No. 41001223, and Grant No. 41101439), and the Research Grants Council of HKSAR, China (405608, 447807). Finally, the corresponding author of this article is Dr. Min Chen.

References

Ackerman, E. A. 1963. Where is a research frontier? *Annals of the Association of American Geographers* 53:435.

Agrawal, P., I. Rauschert, K. Inochanon, L. Bolelli, S. Fuhrmann, I. Brewer, G. R. Cai, A. MacEachren, and R. Sharma. 2004. Multimodal interface platform for geographical information systems (GeoMIP) in crisis management. http://www.geovista.psu.edu/publications/2004/agrawal_ICMI_04.pdf (last accessed 21 May 2012).

Argent, R. M. 2004. An overview of model integration for environmental applications—Components, frameworks and semantics. *Environmental Modelling & Software* 19 (3): 219–34.

Armstrong, M. P. 2000. Geography and computational science. *Annals of the Association of American Geographers* 90 (1): 146–56.

Bartle, R. 2003. *Designing virtual worlds*. Berkeley, CA: New Riders Games.

Batty, M. 1997. Virtual geography. *Futures* 29 (45): 337–52.

Boulos, M. N. K., L. Hetherington, and S. Wheeler. 2007. Second Life: An overview of the potential of 3-D virtual worlds in medical and health education. *Health Information & Libraries Journal* 24 (4): 233–45.

Brunn, S. D., S. L. Cutter, and J. W. Harrington, eds. 2004. *Geography and technology*. Dordrecht, The Netherlands: Kluwer.

CAVE. 2002. Electronic visualization laboratory. http://www.evl.uic.edu/pape/CAVE (last accessed 13 August 2011).

Chan, C. K., and X. H. Yao. 2008. Air pollution in mega cities in China. *Atmospheric Environment* 42 (1): 1–42.

Chen, M., H. Lin, Y. N. Wen, G. N. Lu, and H. Tao. 2010. Semantic driven geographic conceptual modeling environment based on icons. In *3rd International Conference on Cartography & GIS*. Nessebar, Bulgaria. http://www.cartography-gis.com/pdf/83_Min_Chen_China_paper.pdf (last accessed 13 August 2011).

Chen, M., Y. H. Sheng, Y. N. Wen, J. W. Sheng, and H. J. Su. 2008. Virtual geographic environments oriented 3D visualization system. *Journal of System Simulation* 20 (19): 17–24.

Chen, M., H. Tao, H. Lin, and Y. N. Wen. 2011. Study on a visual geographic conceptual modelling method. *Annals of GIS* 17 (1): 15–29.

Clifford, N., S. French, and G. Valentine, eds. 2010. *Key methods in geography*. 2nd ed. Thousand Oaks, CA: Sage.

Cohen, I. B. 1985. *Revolution in science*. Cambridge, MA: Harvard University Press.

Coors, V. 2003. 3D-GIS in networking environments. *Computers, Environment and Urban Systems* 27:345–57.

Costanza, R., and A. Voinov. 2004. *Landscape simulation modelling: A spatially explicit, dynamic approach*. Berlin: Springer-Verlag.

Craglia, M., M. F. Goodchild, A. Annoni, G. Camara, M. Gould, W. Kuhn, D. Mark, et al. 2008. Next-Generation Digital Earth—A position paper from the Vespucci Initiative for the Advancement of Geographic Information Science. *International Journal of Spatial Data Infrastructures Research* 3:146–67.

Crosier, S. J., M. F. Goodchild, L. L. Hill, and T. R. Smith. 2003. Developing an infrastructure for sharing environmental models. *Environment and Planning B: Planning and Design* 30:487–501.

Cruz-Neira, C., D. J. Sandin, T. A. DeFanti, R. V. Kenyon, and J. C. Hart. 1992. The CAVE: Audio visual experience automatic virtual environment. *Communications of the ACM* 35 (6): 64–72.

Czernuszenko, M., D. Pape, D. Sandin, T. DeFanti, G. L. Dawe, and M. D Brown. 1997. The ImmersaDesk and Infinity Wall projection-based virtual reality displays. *ACM SIGGRAPH Computer Graphics* 31 (2): 46–49.

Dieterle, E., and J. Clarke. 2005. Multi-user virtual environments for teaching and learning. In *Encyclopedia of multimedia technology and networking*, 2nd ed., ed. M. Pagani, 1033–41. Hershey, PA: Idea Group.

Dudhia, J., D. Gill, K. Manning, W. Wang, and C. Bruyere. 2005. *PSU/NCAR Mesoscale Modeling System tutorial class notes and users' guide* (MM5 Modeling System Version 3). http://www.mmm.ucar.edu/mm5/documents/tutorial-v3-notes.html (last accessed 16 August 2011).

El-Gayar, O., and K. Tandekar. 2006. An XML-based schema definition for model sharing and reuse in a distributed environment. *Decision Support Systems* 43 (3): 791–808.

Fabrikant, S. I. 2005. Towards an understanding of geovisualization with dynamic displays: Issues and prospects. http://www.geog.ucsb.edu/∼sara/html/research/pubs/SS805FabrikantS.pdf (last accessed 21 May 2012).

Fabrikant, S. I., D. R. Montello, and D. M. Mark. 2010. The natural landscape metaphor in information visualization: The role of commonsense geomorphology. *Journal of the American Society for Information Science and Technology* 61 (2): 253–70.

Feng, M., S. G. Liu, N. H. Euliss, Jr., C. Young, and D. M. Mushet. 2011. Prototyping an online wetland ecosystem services model using open model sharing standards. *Environmental Modelling & Software* 26:458–68.

Foley, P. G., F. Mamaghani, and P. A. Birkel. 1999. *The Synthetic Environment Data Representation Interchange Specification (SEDRIS) development project*. http://www.sedris.org/download/documentation/it103a60.pdf (last accessed 12 August 2011).

Francos, A., F. J. Elorza, F. Bouraoui, G. Bidoglio, and L. Galbiati. 2003. Sensitivity analysis of distributed environmental simulation models: Understanding the model behaviour in hydrological studies at the catchment scale. *Reliability Engineering & System Safety* 79 (2): 205–18.

Germs, R., G. V. Maren, E. Verbree, and F. W. Jansen. 1999. A multi-view VR interface for 3D GIS. *Computers & Graphics* 23 (4): 497–506.

Giles, J. 2010. Inside the race to hack the Kinect. *The New Scientist* 208 (2789): 22–23.

Gomez, B., and J. P. Jones, III, eds. 2010. *Research methods in geography: A critical introduction*. Oxford, UK: Blackwell.

Goodchild, M. F. 2008. Representation and computation of geographic dynamics. In *Understanding dynamics of geographic domains*, ed. K. S. Hornsby and M. Yuan, 13–30. Boca Raton, FL: CRC Press.

———. 2009a. Geographic information systems and science: Today and tomorrow. *Annals of GIS* 15 (1): 3–9.

———. 2009b. Virtual geographic environments as collective constructions. In *Virtual geographic environments*, ed. H. Lin and M. Batty, 15–24. Beijing, China: Science Press.

———. 2010. Twenty years of progress: GIScience in 2010. *Journal of Spatial Information Science* 1:3–20.

Goodchild, M. F., M. Yuan, and T. J. Cova. 2007. Towards a general theory of geographic representation in GIS. *International Journal of Geographical Information Science* 21 (3): 239–60.

Grell, G. A., J. Dudhia, and D. R. Stauffer. 1994. A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). http://nldr.library.ucar.edu/repository/assets/technotes/asset-000-000-000-214.pdf (last accessed 16 August 2011).

Haidvogel, D. B., H. G. Arango, K. Hedstrom, A. Beckmann, P. Malanotte-Rizzoli, and F. Shchepetkin. 2000. Model evaluation experiments in the North Atlantic basin: simulations in nonlinear terrain-following coordinates. *Dynamics of Atmospheres and Oceans* 32 (3–4): 239–81.

Hara, N., P. Solomon, S. L. Kim, and D. H. Sonnenwald. 2003. An emerging view of scientific collaboration: Scientists' perspectives on collaboration and factors that impact collaboration. *Journal of the American Society for Information Science and Technology* 54 (10): 952–65.

Herbert, D. T., and J. A. Matthews. 2004. Geography: Roots and continuities. In *Unifying geography: Common heritage, shared future*, ed. J. A. Matthews and D. T. Herbert, 3–20. London and New York: Routledge.

Hill, C., C. Deluca, BaLaJi, M. Suarez, and A. Da Silva. 2004. The architecture of the Earth System Modeling Framework. *Computing in Science & Engineering* 6 (1): 18–28.

Ishida, T. 2002. Digital city Kyoto. *Communications of the ACM* 45 (7): 76–81.

Jacobson, R. D., R. Kitchin, and R. Golledge. 2002. Multimodal virtual reality for presenting geographic information. In *Virtual reality in geography*, ed. P. Fisher and D. Unwin, 382–400. Boca Raton, FL: CRC Press.

James, R. H. 1998. *SEDRIS data model*. http://www.sedris.org/download/documentation/datmodel.pdf (last accessed 12 August 2011).

Jansson, G., and P. Pedersen. 2005. Obtaining geographical information from a virtual map with a haptic mouse. Paper presented at the International Cartographic Conference, La Coruna, Spain. http://micole.cs.uta.fi/copy_of_publications/publication_files/Haptic_mouse.pdf (last accessed 14 August 2011).

Johnson, A., J. Leigh, P. Morin, and P. V. Keken. 2006. GeoWall: Stereoscopic visualization for geoscience research and education. *IEEE Computer Graphics and Applications* 26 (6): 10–14.

Kato, Y., H. Yamaki, and Y. Asai. 2009. GPGCloud: Model sharing and execution environment service for simulation of international politics and economics. *Lecture Notes in Computer Science* 5925:616–23.

Konecny, M. 2011. Review cartography: Challenges and potential in the virtual geographic environments era. *Annals of GIS* 17 (3): 135–46.

Kwan, M.-P. 2000. Interactive geovisualization of activity-travel patterns using three-dimensional geographical information systems: A methodological exploration with a large data set. *Transportation Research C* 8:185–203.

———. 2004. GIS methods in time-geographic research: Geocomputation and geovisualization of human activity patterns. *Geografiska Annaler B* 86 (4): 267–80.

Ledeczi, A., M. Maroti, A. Bakay, G. Karsai, J. Garrett, C. Thomason, G. Nordstrom, J. Sprinkle, and P. Volgyesi. 2001. The generic modeling environment. http://www.cs.virginia.edu/~rp2h/home/research/ReadingList/gmepaper.pdf (last accessed 21 May 2012).

Lee, J. Y., and M.-P. Kwan. 2011. Visualization of socio-spatial isolation based on human activity patterns and social networks in space-time. *Tijdschrift voor Economische en Sociale Geografie* 102 (4): 468–85.

Lin, H. 1997. STIN operation: A study on searching for spatiotemporal measures. *Cartography* 26 (1): 27–36.

Lin, H., and M. Batty. 2009. Virtual geographic environments: A primer. In *Virtual geographic environments*, ed. H. Lin and M. Batty, 1–10. Beijing, China: Science Press.

Lin, H., and S. K. Choi. 1994. 3-D visualization of spatiotemporal intersection (STIN) operation: An approach to test spatiotemporal correlation. *Cartography* 23 (2): 13–21.

Lin, H., and J. H. Gong. 2001. Exploring virtual geographic environments. *Geographic Information Sciences* 7 (1): 1–7.

Lin, H., F. R. Huang, and G. N. Lu. 2009. Development of virtual geographic environments and the new initiative in experimental geography. *Acta Geographica Sinica* 64 (1): 7–20.

Lin, H., F. R. Huang, X. J. Lu, M. Y. Hu, B. L. Xu, and L. Wu. 2010. Preliminary study on virtual geographic environment cognition and representation. *Journal of Remote Sensing* 14 (4): 822–30.

Lin, H., J. Zhu, J. H. Gong, B. L. Xu, and H. Qi. 2010. A grid-based collaborative virtual geographic environment for the planning of silt dam systems. *International Journal of Geographical Information Science* 24 (4): 607–21.

Lin, H., and Q. Zhu. 2006. Virtual geographic environments. In *Large-scale 3D data integration: Challenges and opportunities*, ed. S. Zlatanova and D. Prosperi, 211–30. London and New York: Taylor & Francis.

Livingstone, D. N. 1993. *The geographical tradition: Episodes in the history of a contested enterprise*. Oxford, UK: Blackwell.

Loomis, J. M., R. G. Golledge, and R. L. Klatzky. 1998. Navigation system for the blind: Auditory display modes and guidance. *Presence: Teleoperators and Virtual Environments* 7 (2): 193–203.

MacEachren, A. M., and I. Brewer. 2004. Developing a conceptual framework for visually-enabled geocollaboration. *International Journal of Geographical Information Science* 18:1–34.

MacEachren, A. M., I. Brewer, G. Cai, and J. Chen. 2003. Visually-enabled geocollaboration to support data exploration and decision-making. http://www.geovista.psu.edu/publications/2003/MacEachren_ICA03.pdf (last accessed 21 May 2012).

MacEachren, A. M., R. Edsall, D. Haug, G. Otto, R. Masters, S. Fuhrmann, and L. J. Qian. 1999. Virtual environments for geographic visualization: Potential and challenges. http://www.geovista.psu.edu/publications/NPIVM99/ammNPIVM.pdf (last accessed 21 May 2012).

Mackinder, H. J. 1987. On the scope and methods of geography. *Proceedings of the Royal Geographical Society and Monthly Record of Geography* 9 (3): 141–74.

Mark, I. 2010. The brave new intelligent interface. *IEEE Intelligent Systems* 25 (4): 4–6.

Matthews, J. A., and D. T. Herbert. 2008. *Geography: A very short introduction*. New York: Oxford University Press.

McLafferty, S. 2004. The socialization of GIS. *Cartographica* 39 (2): 51–53.

———. 2005. Women and GIS: Geospatial technologies and feminist geographies. *Cartographica: The International Journal for Geographic Information and Geovisualization* 40 (4): 37–45.

Murphey, R. 1982. *The scope of geography*. 3rd ed. London: Methuen.

Ogle, K., and J. J. Barber. 2008. Bayesian data-model integration in plant physiological and ecosystem ecology. *Progress in Botany* 69 (4): 281–311.

Paris, S., M. Mekni, and B. Moulin. 2009. Informed virtual geographic environments: An accurate topological approach. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4782683 (last accessed 21 May 2012).

Peck, S. L. 2004. Simulation as experiments: A philosophical reassessment for biological modeling. *Trends in Ecology and Evolution* 19:314–37.

Perry, G. L. 2009. Modeling and simulation. In *A companion to environmental geography*, ed. N. Castree, D. David, D. Liverman, and B. Rhoads, 336–56. Oxford, UK: Blackwell.

Peuquet, D. J. 2009. Toward integrated space-time analysis environments. In *Virtual geographic environments*, ed. H. Lin and M. Batty, 37–48. Beijing, China: Science Press.

Rauschert, I., P. Agrawal, R. Sharma, I. Brewer, A. MacEachren, and G. Cai. 2002. Designing a human-centered, multimodal GIS interface to support emergency management. http://delivery.acm.org/10.1145/590000/585172/p119-rauschert.pdf?ip=137.189.162.186&acc=ACTIVE%20SERVICE&CFID=104369498&CFTOKEN=19914980&_acm_=1337584757_

8983fad5d15183d6e39ccbb5c66550b1 (last accessed 21 May 2012).
Rauschert, I., R. Sharma, S. Fuhrmann, I. Brewer, and A. MacEachren. 2002. Approaching a new multimodal GIS-interface. http://www.geovista.psu.edu/publications/2002/GIScience/Rauschert.pdf (last accessed 21 May 2012).
Redler, R., S. Valcke, and H. Ritzdorf. 2009. OASIS4: A coupling software for next generation earth system modeling. *Geoscientific Model Development Discussions* 2:797–843.
Ren, F., and M.-P. Kwan. 2007. Geovisualization of human hybrid activity-travel patterns. *Transactions in GIS* 11 (5): 721–44.
Renwick, W. H., and J. M. Rubenstein. 1995. *People, places, and environment: An introduction to geography*. Upper Saddle River, NJ: Prentice-Hall.
Rheingold, H. 2000. *The virtual communities: Homesteading on the electronic frontier*. London: MIT Press.
Rodaway, P. 1994. *Sensuous geographies: Body, sense, and place*. London and New York: Routledge.
Roman, G. C. 1990. Formal specification of geographic data processing requirements. *IEEE Transactions on Knowledge and Data Engineering* 2 (4): 370–80.
Shi, W. Z., B. S. Yang, and Q. Q. Li. 2003. An object-oriented data model for complex objects in three-dimensional geographical information systems. *International Journal of Geographical Information Science* 17 (5): 411–30.
Shin, S., Y. Ahn, J. Choi, and S. Han. 2010. Design of a framework for interoperable motion effects for 4D theaters using human-centered motion data. http://delivery.acm.org/10.1145/1980000/1971659/p96-shin.pdf?ip=137.189.162.186&CFID=35668475&CFTOKEN=92605037&_acm_=1313327788_9d8e0dbb6762fc0e0447aa52666f1a00 (last accessed 14 August 2011).
Sibony, N. 1976. Multi-dimensional analytic structure in the spectrum of a uniform algebra. *Lecture Notes in Mathematics* 512:139–65.
Su, H. J., Y. H. Sheng, Y. N. Wen, M. Chen, H. Tao, and J. W. Shen. 2008. Spatial data representation model oriented to geographical problem solving. http://www.isprs.org/proceedings/XXXVII/congress/2_pdf/5_WG-II-5/11.pdf (last accessed 21 May 2012).
Sunaga, T. 2009. Theory of an interval algebra and its application to numerical analysis. *Japan Journal of Industrial and Applied Mathematics* 26 (2–3): 125–43.
Takatsuka, M., and M. Gahegan. 2002. GeoVISTA Studio: A codeless visual programming environment for geoscientific data analysis and visualization. *Computers and Geosciences* 28 (10): 1131–44.
Thomas, J. E., T. A. Saxby, A. B. Jones, T. J. B. Carruthers, E. G. Abal, and W. C. Dennison. 2006. *Communicating science effectively: A practical handbook for integrating visual elements*. London: IWA.
Wall, S. A., and S. Brewster. 2004. Providing external memory aids in haptic visualisations for blind computer users. http://www.dcs.gla.ac.uk/~stephen/papers/IJDHD_wall.pdf (last accessed 21 May 2012).
Wen, Y. N., M. Chen, G. N. Lu, L. He, and H. Tao. 2011. Distributed sharing of geographical models. *International Journal of Information Processing and Management* 2 (1): 114–20.
Wu, M. G., J. W. Shen, and Y. N. Wen. 2009. A hybrid data structure for integrated modeling of geographic 3D data. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05455360 (last accessed 12 August 2011).
Xu, B. L., H. Lin, L. S. Chiu, Y. Hu, J. Zhu, M. Y. Hu, and W. N. Cui. 2011. Collaborative virtual geographic environments: A case study of air pollution simulation. *Information Science* 181 (11): 2231–46.
Yang, C. W., M. F. Goodchild, Q. Huang, D. Nebert, R. Raskin, Y. Xu, M. Bambacus, and D. Fay. 2011. Spatial cloud computing: How can geospatial sciences use and help to shape cloud computing. *International Journal of Digital Earth* 4 (4): 305–29.
Yuan, L. W., Z. Y. Yu, S. F. Chen, L. Wen, Y. J. Wang, and G. N. Lu. 2010. CAUSTA: Clifford algebra based unified spatial-temporal analysis. *Transactions in GIS* 14 (1): 59–83.
Yuan, M. 2009. Knowledge discovery of geographic dynamics in spatiotemporal data. In *Geographic data mining and knowledge discovery*. 2nd ed., ed. H. Miller and J. Han, 347–66. Boca Raton, FL: CRC.
Zhang, J. Q., J. H. Gong, H. Lin, G. Wang, J. L. Huang, J. Zhu, B. L. Xu, and J. Teng. 2007. Design and development of distributed virtual geographic environment system based on web services. *Information Science* 177 (19): 3968–80.
Zhu, J., J. H. Gong, W. G. Liu, T. Song, and J. Q. Zhang. 2007. A collaborative virtual geographic environment based on P2P and grid technologies. *Information Science* 177 (21): 4621–33.
Zlatanova, S., A. A. Rahman, and W. Z. Shi. 2004. Topological models and frameworks for 3D spatial objects. *Computers & Geosciences* 30 (4): 419–28.

Correspondence: Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Shatin Hong Kong, e-mail: huilin@cuhk.edu.hk (Lin); chenmin0902@cuhk.edu.hk (Chen); Key Laboratory of Virtual Geographic Environment (Ministry of Education of PRC), Nanjing Normal University, Nanjing, Jiangsu Province 210046, P. R. China, e-mail: gnlu@njnu.edu.cn (Lu).