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Visualizing and analyzing dynamic meteorological data with virtual globes: A case study of tropical cyclones

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ABSTRACT

Visualization is an important component of the evaluation of meteorological models, forecasting research, and other applications. With advances in computing power, the volume of meteorological data generated by geoscience and climate researchers has been steadily increasing. The emerging technique of virtual globes has been regarded as an ideal platform for visualizing larger geospatial data over the Internet. To visualize and analyze meteorological data with the new virtual globes, this paper proposes a systematic meteorological data visualization (MDV) framework in World Wind, an open-source virtual globe. The key technologies, including a hierarchical octree-based multiresolution data organization, data scheduling, level of detail (LOD) and rendering are described in detail. The framework is then applied to a practical tropical cyclone simulation, including flow vectors, particle tracking, cross-sectional analysis, streamlines, pathway animation, and volume rendering. The results show that virtual globes are effective tools for meteorological data visualization and analysis.

Software availability

Name of software: Virtual Globe based Meteorological Data Visualization and Analysis (VGMDV)
Contact address: State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, P.O. Box 9718, Beijing 100101, China. Tel./fax: +86 010 64849299
Year first available: 2014
Hardware required: tested on Lenovo PC and DELL PC
Software required: MS Windows (tested on Windows 7 and Xp)
Programming language: MS visual studio 2010.net C#, DirectX 3D
Program size: 45 MB
Availability and cost: Contact via e-mail
Maintenance: Contact via e-mail

1. Introduction

With advances in computing power, the static and dynamic meteorological volume of data generated by geoscience and climate researchers has been steadily increasing (Brovelli and Zamboni, 2012). Concurrently, enhanced observation techniques, such as satellite operations, have also contributed to the growth of climate-related data. These data are often in the form of multidimensional and multivariate volumetric datasets; thus, visualizing of these data is a computational- and data-intensive task (Shen, 2006).

When underlying properties are to be identified from simulations and observational data, visualization is the principal method for evaluating the reliability of conclusions based on these datasets. Many visualization techniques exist for different data classes, e.g., flow, volume, and multivariate visualizations (for overviews, see Nocke et al., 2007). Table 1 summarizes the technologies used in meteorological data visualization based on the spatial data dimensionality and the data type. The focus of the present work is on the visualization of regularly gridded meteorological data that are represented in their spatial reference frame.

Many studies have attempted to utilize meteorological data visualization for different application purposes. However, due to

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Table 1
Summary of technologies for spatial climate visualization (modified from Nocke et al., 2007).

	2D data	3D data
Scalar	Standard color and Isoline	Isosurface
	Images	Decomposition methods
	Height representation	Direct volume rendering
	Globe representation	Realistic rendering
Vector	Arrows or wind barbs	Icons
(& scalar)	Topology-based methods	Field lines
		Decomposition methods
		Texture-based/direct volume rendering

the large volume of data, it is difficult to visualize such data (e.g., for volume rendering) using a conventional computer in the network environment. Several specialized software packages, such as Paraview, SimVis, Vis5D, VAPOR, AVS/Express and Avizo Green (Hibbard et al., 1994; Vroom, 1997; Doleisch, 2007, Norton and Clyne, 2013; Cedilnik et al., 2006), have also been developed to support climate research. Although these software packages have achieved fairly good results, they lack collective interoperability for the public, and they are not ideal for large-scale dynamic volumetric data, especially in a network environment. The demand for new visualization tools always exists, even with innovations in hardware.

Beginning with the "Digital Earth" concept proposed by Gore (1998), different virtual globes have been developed, e.g., Google Earth (GE), and in the open-source world, the National Aeronautics and Space Administration's (NASA's) World Wind (Aurambout et al., 2008). The rapid development of virtual globe technologies provides an effective framework to efficiently demonstrate meteorological concepts not only to specialized meteorological scientists but also to the general public. The capabilities and characteristics of these virtual globe platforms vary greatly. For example, GE is one of the most notable globes. It can be freely downloaded from the web using geometric object data provided in keyhole markup language (KML) format (Wernecke, 2008). Researchers utilize GEto visualize large-scale geospatial datasets to support spatial analysis and decision making (Blenkinsop, 2012; De Paor and Whitmeyer, 2011; Chien and Keat Tan, 2011, Ballagh et al., 2011; Yamagishi et al., 2010; Wright et al., 2009; Webley et al., 2009; Chen et al., 2009). GE can also be used for meteorological data sharing and analysis (Sun et al., 2012; Turk et al., 2011). However, the visualization capability of the KML format remains limited for meteorological applications, as shown in Table 2. GE does not support advanced visualization technology (such as volume rendering, field lines, and the decomposition methods described in Table 1). Moreover, the user cannot freely modify the commercial software for special applications.

The capabilities and characteristics of these virtual globe platforms vary greatly. Other virtual globe frameworks have nearly the

Table 2
KML geometric object types (Wernecke, 2008).

Object	Description
Placemark	Indication of a specific location
Points	A point with a specific position (longitude, latitude, and altitude), where the altitude is optional
LineString	A list of points
LinearRing	Represents the outer or inner boundaries of polygons
Polygon	Comprises one or more outer boundaries (with or without inner boundaries)
MultiGeometry	A collection of geometries listed above
GroundOverlay	A 2D surface on the terrain

same capabilities as GE and continue to lack support for professional meteorological applications (Aurambout et al., 2008). Thus, it remains a challenge to combine climate visualization and virtual globes. World Wind (WW), an open source platform developed by NASA to demonstrate the capabilities of virtual globes as meteorological data visualizers, is used in this study. WW has the following three key features: 1) due to the open source nature of the software, the existing product can be reused and customized for enhanced virtual globe functionality; 2) large quantities of volumetric data can be rendered on a virtual globe using WW, such as volume rendering, which has been partly demonstrated by previous studies (Brovelli and Zamboni, 2012; Li et al., 2011); and 3) the most recent WW program is written in the Java language, which makes it platform-independent and accessible by simple web browsers without specific plugins. In this paper, we present a methodology for enhancing the capability of virtual globes to enable meteorological applications.

Gahegan (1999) identifies several typical challenges for geovisualization, e.g., issues involving the representation of natural phenomena with an increasing volume of data. Several of the challenges involved in realizing the interactive dynamic visualization of meteorological data in a virtual globe environment are addressed in this paper. This study has three main objectives: 1) to create a systematic framework for meteorological data visualization (MDV) on globes; 2) to describe the key MDV technologies, including data organization, scheduling and LOD, and rendering; and 3) to develop a practical system for a tropical cyclone Ultimately, simulated tropical cyclone (TC) data were used to evaluate the system.

The remainder of this paper is organized as follows: Section 2 provides a detailed description of the MDV architecture and the key technologies. Section 3 demonstrates the proposed framework using simulated tropical cyclone data. Section 4 presents a detailed evaluation of the software. Finally, Section 5 presents a brief discussion and conclusions.

2. Design of the MDV framework and its key technologies

The virtual globes are highly capable of supporting image, vector, and terrain data but have a limited capability for meteorological data visualization, especially in the case of large collections of time-varying volumetric data in a network environment. As shown in Fig. 1, an innovative MDV framework is proposed to visualize time-varying volumetric data for meteorological data analysis. The MDV system is composed of an MDV server and MDV WW-Client.

In the MDV server, a graphical user interface (GUI) allows users to preview the meteorological variables and filter for the variable in which they are interested. Presently, meteorological datasets are commonly organized in NetCDF and/or HDF5 formats, which are large gridded data files that contain multi-time and multi-variable data with metadata descriptions. The original data are parsed and pre-processed for rendering, including coordinate transformation, data bricking, and octree construction. After pre-processing, a collection of volumetric tiles is resampled from the original data. These tile data can be accessed on local servers or on remote web servers through the http protocol.

MDV WW-Client, the core of the MDV system, is the graphical 3-dimensional (3D)/4-dimensional (4D) interface that is implemented using the WW software development kit (SDK). The user can select the suitable variable and technologies to present the data in the interface. The client consists of two primary modules: data-scheduling modules (on the CPUs) and rendering modules (on the GPUs). The original data are scheduled from the server with a data-scheduling module. The data are then traversed and rendered using