3D/4D MODELLING, VISUALIZATION AND INFORMATION FRAMEWORKS: CURRENT U.S. GEOLOGICAL SURVEY PRACTICE AND NEEDS

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Abstract

Progress is being made in the ability to visualize and model geologic data and information in 3 spatial dimensions (3D) and sometimes adding time for 4 dimensions (4D). These abilities are enriching the conceptual models and process simulations constructed by geologists and hydrogeologists. Computer technology is also enhancing the visualization and modeling of landscapes and the hydrodynamic simulations of surface waters. Progress needs to be made in visualizing and coupling geologic, hydrologic, atmospheric, and biologic processes together into 3D/4D information frameworks that encompass and integrate observations and simulations across a diversity of spatial and temporal scales and data types. Achieving progress in these areas will also enhance the relevance and effective communication of USGS science to policy makers and to the lay public.

1. INTRODUCTION

We need to gain abilities to visualize and model our dynamic multi-dimensional earth. Natural processes are 3D/4D in character, yet many people increasingly access the natural world through 2D screens and visualize and simulate reality through 2D or 1D representations. Current 3D modelling and visualization efforts often consist of 2D map/GIS overlays stacked in 3D space that only provide a limited extension of the geological realities perceived by Nicholas Steno in 1669. Static block diagrams and other 2D visuals do not allow efficient exploration of the rich multi-dimensional datasets and knowledge that they portray. Why should we, and how can we, advance our visualization and modelling of information frameworks to a new level of perceived reality? Plato described this need in his allegory of the cave, referring to the "philosopher" as someone who was able to escape a 2D world of shadows. Current capabilities and practice in using 3D/4D visualization/modelling tools vary widely across the U.S. Geological Survey (USGS). Our presentation (1) considers different types of 3D/4D visualization and modelling efforts currently conducted in the USGS, (2) highlights some interdisciplinary possibilities for future efforts and science applications, including the more effective communication of USGS science and the implications of alternative management scenarios to policy makers and to the lay public and finally (3) comments on desired software capabilities of a general information framework for 3D/4D modeling and visualization.

2. 3D/4D GEOLOGIC APPLICATIONS

Current USGS geologic applications for 3D/4D visualization and modelling include:

- Paleoseismic frameworks and tectonic models to assess past tectonic displacements, earthquake potential, and fault-slip scenarios;
- Geologic models to define, assess, and bound resources and/or lithologic properties (water, oil, gas, minerals, porosity, rock chemistry...);
- Geophysical inverse models to visualize/characterize anomalous properties in the earth's crust;
- Volcanic models to describe magmatically driven bulging or to predict eruption types and timing;
- Deformation models showing landform subsidence or rebound caused by removal or addition of resources;
- Geomorphic analyses to detect/quantify landscape changes and structural features (e.g., faults, landslides, debris flows, paleo-floods, glaciers, impact craters).

Recently published USGS 3D geologic maps and databases (e.g. Phelps et al., 2008; Faith et al., 2010; Pantea et al., 2011) go beyond traditional geologic mapping. They provide a more complete characterization of features (e.g., units, faults, unconformities, structures, physical and chemical properties) and also describe the methods and techniques used. The descriptions are needed because 3D geologic mapping updates and adds to the conventional scientific methods for 2D mapping. 3D maps and models also define some features solely on geophysical expressions and include a discussion of the data and model(s) used in constructing the map.

3. 3D/4D SURFACE-MAPPING APPLICATIONS

3D and 4D analyses and visualization of LiDAR (**Li**ght **D**etection **A**nd **R**anging) imagery are frequently used in the USGS. LiDAR data are displayed, checked and corrected in immersive, virtual-reality, environments that comprise hardware 3D display technology (e.g., Keck[1] Caves) and LiDAR viewing softtware. LiDAR and remote-sensing measurements and analyses can help determine the impact, frequency of occurrence and the future impacts of earthquakes, debris flows, fires, floods and other disturbances that have modified, or could modify, the land surface, its vegetative cover, water resources, and/or human infrastructure. For example, repeat ultra-high resolution (sub-centimeter) 3D ground-based LiDAR imagery was collected in the days and months following the magnitude 6.0 Parkfield earthquake in central California. Immersive, virtual reality 4D analysis (Kreylos et al., 2006, Kellogg et al., 2008) of the land surface and engineered structures illuminated small active tectonic geomorphic features that would have been overlooked in a 2D analysis.

Airborne and ground-based LiDAR are also commonly used in the detection of potentially hazardous faults and to assess structure and surface stability after landslides, rockslides, and debris flows. Detailed 3D/4D analyses are used to characterize these events, understand their driving mechanisms, and provide rapid feedback to local authorities regarding post-event stability of the land surface. Visualization tools, coupled with “before and after” landscape surveys, through remote sensing or LiDAR, are being used to benchmark current landscape conditions and help characterize and model the magnitude and extent of atmospheric events in terms of natural hazards, water availability, ecosystem response, and long-term climatic variability. At local scales, these technologies are used with biomorphic imaging of trees, roots or forest canopies to improve understanding of subsurface and surface relations between species, soils, geomorphic changes, solar fluxes and ecological productivity.

4. SURFACE HYDROLOGY APPLICATIONS

The USGS conducts work visualizing and predicting the impacts of sea level rise and salinity intrusion on coastal habitats. Although fixed-level 3D flood maps provide a first cut interpretation of the consequences of floods or sea level rise, 4D renderings are used to describe/model flood waves, storm surges, tsunamis, tidal surges, and outflows. Deterministic, predictive models based on mathematical descriptions of both, the operative physical processes and mass and energy conservation relations, are often displayed using advanced visualization systems to enhance dynamic patterns that would not otherwise be apparent. These models are vital to understanding the effects of storm surges on coastal wetlands or in predicting the potential impact and movement of hazardous spills or biomass (e.g., red tides). Numerical simulation models, often with associated 3D/4D visualization tools, have also been used to understand the dynamics of contaminant transport in Boston Harbor and Massachusetts Bay (Blumberg et al., 1993); and to simulate and understand water transport, nutrient cycling and ecological responses in the San Francisco Bay/Delta estuary (Lucas et al., 1999, 2009; http://cascade.wr.usgs.gov/index.shtm), in Upper Klamath Lake (Wood et al., 2008), and in the Florida Everglades (e.g., Larsen and Harvey, 2010).

The dynamically changing cryosphere presents complex environments, including permafrost and surging glaciers, with significant challenges to our understanding. The rapidly changing landforms, vegetation, and hydrology of arctic landscapes with warming temperatures and disappearing permafrost offers an example of the need for more integrated 3D/4D modeling, visualization and interpretations across traditional disciplines in the physical and

[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

biological sciences and also coupling surface and subsurface processes. As the areal distribution of permafrost decreases, there is increased hydrologic connectivity between surface water and groundwater that in turn changes the landscape, the distribution of vegetation, and the fluxes of nutrients and carbon to the rivers, sea, and atmosphere. The USGS also has a long-standing study of the Bering Glacier, which surges approximately every 20 years (e.g. Molnia and Post, 2010). Repeat 4D ground-based Tripod-LiDAR imagery of pressure ridges and on the glacier toe were collected to help understand and show the dynamic processes of the 2011 Bering Glacier surge.

5. GROUNDWATER APPLICATIONS

The USGS extensively uses 3D/4D visualization (e.g., Model Viewer: Hsieh and Winston, 2002) and modelling tools to simulate subsurface flow and contaminant transport. These tools are essential in:

- Representing and checking the primary data and information in a geologic context;
- Visualizing lithologic units and the spatial distribution and temporal evolution of hydrogeologic and chemical properties associated with lithologic properties (e.g. primary and secondary porosities, permeability, mineralogy) and/or with structural features such as active faults, fractures, joints, channels, and folds;
- Integrating hydrologic, chemical, or geophysical response information to help determine the spatial distribution of hydrogeologic or lithologic properties in various subsurface zones through “inverse modelling” numerical simulations;
- Using predictive or “forward” modelling to numerically simulate the potential movement of water, solutes, contaminants, colloids, viruses, or bacteria in the subsurface, and the coupled evolution of the hydrogeologic environment.

Both groundwater availability and groundwater contamination studies in the USGS focus mostly on the shallow subsurface, which is usually the source of groundwater resources for irrigation or drinking water. Hydrogeologic studies of deeper environments are mostly confined to sites that might be suitable for the disposal of nuclear wastes or the injection of other industrial wastes; however, this situation is rapidly changing. Developments in energy resource extraction increasingly necessitate geologic/hydrogeologic studies of the deep subsurface. These developments include: (1) the extraction of shale gas through the use of hydrofracking, (2) the potential development of oil shale resources through in-situ retorting, and (3) the deep-injection of waste fluids associated with energy resource extraction. There is also the potential for using deep geologic formations, specifically former oil and gas reservoirs, coal seams, and saline aquifers for geologic carbon sequestration. Finally, brackish and saline groundwater is increasingly recognized as a potential source of water, due to technical advances and cheaper costs of desalination technology (Alley, 2003).

There are a number of remote sensing approaches that are useful to assess groundwater fluctuations, water withdrawals, and their associated impacts at both global and local scales. At regional to global scales, terrestrial water storage-change observations from the NASA GRACE (Gravity Recovery and Climate Experiment) satellites have been used to estimate groundwater depletion in the US and in the Indian states of Rajasthan, Punjab and Haryana (Rodell et al, 2009). Groundwater withdrawals not only impact water sustainability in semi-arid environments but also can adversely impact surface water resources in humid climates, produce substantial land subsidence, damage infrastructure, and irreversibly decrease an aquifer’s ability to store water. At smaller regional scales, repeat satellite InSAR (Inferometric Synthetic Aperture Radar) imagery of active hydrocarbon fields shows how the land surface responds to hydrocarbon removal and CO_2 and water injection over time. At local scales, high resolution imagery from a suite of observational technologies including InSAR, airborne LiDAR, ground-based Tripod LiDAR, and GPS can be fused to characterize the surface deformation through time associated with pumping of groundwater at depth. In all these studies, 3D/4D visualization can help us understand what areas are at the greatest risk, what areas are being most depleted of groundwater or an energy resource, and can also be used in optimization modelling to more efficiently manage and distribute pumping and recharge in a given area. More generally, 3D/4D visualization tools can also be used to effectively communicate the implications of scientific research and assessments, and the potential results of alternative resource management scenarios, to policy makers and to the lay public.

6. OTHER APPLICATIONS OF 3D/4D MODELLING

Collaboration among scientists who often do not have the same scientific disciplinary backgrounds, and therefore lack a common scientific language, can be made easier through the use of advanced 4D immersive visualization systems. The USGS needs to extend its individual capabilities in 3D earth science modelling and visualization to provide greater understanding and integration of coupled processes for scientific research and assessments of natural resources and hazards. It also needs to consider and potentially include the 3D/4D visualization and simulation of atmospheric and biologic processes. For example, understanding orographic processes, their effects on precipitation intensity, duration and type (rain, hail, snow), and the interplay with vegetation and ecosystem dynamics with geomorphic processes, can help explain and/or predict the impacts of ecosystem disturbances (e.g., fire, drought, floods, debris flows). Communicating such understanding can help regulators and policy makers better manage landscapes and natural resources in the face of changing land use and climate. Visualizing, understanding, and predicting the storage and flows of water, nutrients, contaminants, and sediments and their biological feedbacks can help mitigate the damages caused by natural disturbances and can also help society make better decisions on how and where to exploit natural resources, where to place infrastructure, and how to minimize human impacts on the environment.

The interrelations of temperature and topography also affect our landscapes and associated ecosystems and their evolution in time. Visualizing and predicting temperature distributions across a mountainous landscape or watershed can help us understand biologic habitats and how they may change. Stream temperatures and their variability are extremely important to the health and population distribution of fish and other aquatic species. Such temperatures and their diurnal and seasonal variability are controlled by many factors that may include slope, slope aspect, shading, groundwater baseflows, stream flow, groundwater/spring temperatures, snowmelt contributions, albedo, air temperature, relative humidity, precipitation, microbial activity, and the number of animals crossing the stream or the extent of salmon spawning. Understanding and visualizing topographic and climatic drivers can help predict the movement and intensity of fires, the spread of pests or invasive species, and/or the migration or extinction of species. USGS scientists also routinely collect high-resolution 4D snow depth change data and combine the data with climate models to estimate daily snow melt runoff as a function of solar radiation and incident angle at various elevations. Climate forecast models using 4D climate data and different global warming scenarios help understand how ecosystems and water availability might change in the future.

7. SOFTWARE NEEDS FOR 3D/4D INFORMATION FRAMEWORKS

Emerging needs for 3D/4D modeling and visualization in the USGS include fundamental capabilities to represent geologic, hydrologic, physico-chemical, and biologic information. There is also a need to integrate information across spatial and temporal scales and to better represent a wider array of natural processes, source information, and modelled information. To be most useful, 3D/4D visualization and modelling tools of the future will help:

- Display and validate raw scientific data collected in multi-dimensional, spatial frameworks and perform mathematical and statistical operations on the data, in real time;
- Represent, interpret, and possibly reconcile data and primary information collected non-synoptically;
- Display temporal changes in scientific information in an "animated" 4D framework (e.g. energy or material fluxes, disruptions in 3D structures or boundaries, or changes in the intensities of distributed characteristic properties);
- Integrate diverse types (e.g., point, line, areal, volumetric) of primary spatial information through time for any given property (e.g. porosity, permeability, physicochemical properties) or function in a 3D/4D visual environment while displaying not only the information but also the associated uncertainties and the information gaps;
- Conduct inverse, statistical, geostatistical, stochastic, or other types of modelling to create 3D/4D realizations of natural phenomena;
- Interpolate and extrapolate spatial and temporal values from observed data using a variety of methods and using interpreted and modelled information to build 3D/4D information frameworks, such as geologic mapping frameworks, that maximize the use of the knowledge available for a given issue or given spatial system;

- Maximize the ability to use the information for interpretive or predictive studies, simulations, and assessments;

- Derive and tie results and conclusions tightly to underlying databases;
- Maintain all data in non-proprietary formats for future use;
- Provide the ability for external users to add their own data and interpretations to USGS derived interpretations and data sets with full traceability, information security, and privacy controls where needed;
- Provide animations, fly-throughs, and data-discovery tools that help researchers individually or collaboratively advance their scientific understanding and communicate their results;
- Allow scientists to communicate research, monitoring, and assessment findings and their implications, to each other, decision makers, and the greater public in a simple, cost effective, and timely manner.

8. FINAL COMMENTS

With greater capabilities and freedom in displaying, understanding, and extrapolating information come greater responsibilities in tracking, understanding, and evaluating the quality and uncertainties/biases of data and other primary information and of transformations that have been applied to that information. The technology to track, determine and evaluate information gaps, sources of error, and uncertainties needs to be integrated into the 3D/4D visualization and modelling tools of the future. At the same time, the assembly of information and the potential to efficiently examine and analyze large quantities of data will help provide QA/QC checks that were not available in the past and will help better manage and understand the data and primary information that are collected.

Improvements are needed in the integration of widely diverse information. Available data and observations often represent information integrated across very different spatial and temporal scales, and often across a different number of dimensions. Connecting these different scales and providing a consistent reconciliation of the information can only occur within a comprehensive encompassing framework, i.e., usually a 3D/4D information framework. Better techniques are also needed to construct coherent conceptual models from individual observations and from simulated or reconstructed information, process models, and intermediate scale models. Iterating among data collection, interpretation, and the application of forward, inverse, and statistical modeling tools is likely to provide progress in this area.

3D/4D visualization and modelling tools have the potential to display and discover information that will help (1) advance and communicate USGS science, (2) better manage natural geologic, hydrologic and biologic resources, (3) minimize undesired impacts in using those resources, (4) mitigate some of the consequences of natural hazards, and (5) make more informed decisions in societal planning (e.g. in the wise emplacement of human infrastructure).

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