Geological and Hydrological Visualization Models for Digital Earth Representation

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Abstract

This paper presents techniques and interactive models for multi-dimensional analyses and geospatial visualization in virtual globes based on three application examples: 1) earthquakes around the world, 2) groundwater well levels in Texas, and 3) geothermal subsurface heat indexes in Texas.

While studies are known that represent multi-dimensional geospatial data points, we develop and suggest multi-dimensional models for virtual globes using KML and KMZ (compressed KML files) with a complete and static time series data set. The benefit of this approach for the user is the ability to view and analyze time-based correlations interactively over the entire time span in one instance, which is not possible with animated (dynamic) models.

The methods embedded in our models include: a) depth layer cueing within subsurface Earth visualization for a better orientation when maneuvering below the ground, b) a technique with Ternary Visual Shape Logic (TVSL) as a quick indicator of change over time, and c) different visual representations of multiple dimensions for the addressed case study examples. The models can be applied to a variety of problems in different disciplines, especially to support decision-making processes.

Keywords: Multi-dimensional visualization, geospatial analysis, virtual globes, subsurface depth layer cueing, Ternary Visual Shape Logic (TVSL)

1 Introduction

In recent decades, computer graphics visualization and imaging have experienced a rapid growth and captured the interest of governments, scientists, and business representatives (Fox and Hendler, 2011). The idea of a virtual globe (a computer application allowing users to browse and search data projected on a cartographic representation of the Earth) emerged at the end of the last millennium (Bailey, 2010). The development of the XML-based markup language KML (Keyhole Markup Language) – open source, tag-based scripting language, interactive digital cartography became possible in all major virtual globes (NASA World Wind, Google Earth, Microsoft Virtual Earth, and ESRI's ArcGIS Explorer) (De Paor and Whitmeyer, 2011). Visualization techniques have been acknowledged to provide a powerful way to '*take advantage of human abilities to perceive visual patterns and to interpret them*' (Andrienko et al., 2003; see also: Costabile and Malerba, 2003; Kopanakis and Theodoulidis, 2003; Compagna et al., 2007). Nowadays, most research studies apply two- and three-dimensional (2D and 3D) models (Rowe and Frank, 2011; Xu et al., 2010; Mao and Ban, 2013), especially for satellite imagery (Zhang et al., 2007), 3D web graphics (Evans et al., 2014) or topography maps (Guo et al., 2009). Also, other multi-dimensional analyses using 4D models have been conducted over the years (Baum et al., 2007; Thomas et al., 1996; Li et al., 2011). However, most of those models and their standard spatial visualization in the existing geographical applications are not always adequate and sufficient for decision-support systems. New solutions are necessary that would include not only a static graphical view of the results, but that would also offer the possibility to interact with data

in a spatial and temporal view (Compieta et al., 2007; Dransch et al., 2010; Shneiderman, 2002; Van de Weghe et al., 2014).

The goal of this paper is to provide several geotemporal models that extend the current knowledge in the field and meet the scientific and visualization needs as specified above. We emphasize practical benefits of the models with three examples: earthquakes worldwide, groundwater well levels and geothermal subsurface heat indexes in Texas.

Several studies are known representing multidimensional visualization examples. For instance, Zhu et al. (2014a) developed a 3D KML model for visualizing borehole well information in virtual globes. Zhu's et al. model, though valuable for research purposes, presents only an above-the-surface perspective using height, size and color of the spheres to represent the same variable (4D models). Also, Postpischl et al. (2011) developed 3D and 4D visualization models, using KML beach balls for their earthquake visualization. However, also this study offers only a 3D or 4D perspective with a flat shape representation, not fully utilizing virtual globe environment.

The models presented here build upon and extend previous research in the field by: 1) presenting both the above-the-surface perspective and below-ground subsurface perspective, and 2) using the size of the sphere and color of the sphere independently of the geolocation, thus creating an additional 5th visualization dimension (5D model). The presented models can be used with different virtual globes and on smartphone or mobile devices, which has not been reported in the previous literature yet.

Nowadays, most 3D models are based on and apply specific visualization software that is not always freely accessible to everyone, requires specialized graphic cards or hardware and/or is difficult to use as it involves a long learning process. Virtual globe applications, used for this research, do not have any special technical requirements in this regard and are capable of loading

and rendering standard KML files. This feature allowed us to use KML files in a unique way to develop models that would be accessible to anyone with very few limitations if any at all. The interactive models overcome the current limitations in the field making visualization easily accessible and interactively applicable for all computer users with Internet access, and thus fostering scientific and educational learning.

Furthermore, the developed models can be classified as a visualization analytics tool that, according to Andrienko et al. (2011), benefits from combining the strengths of human and electronic data processing, and where *'by means of visualization and interactive visual interfaces, humans and computers can converse and cooperate'* (Keim et al. 2008). The models also provide an exploration tool that, as advocated by Fox and Hendler (2011), *'scientists can use throughout the research life cycle'* not only to represent the final research results, but to look for and interactively explore hidden patterns and relations that would not be detectable solely with raw data sets.

The benefits, unique features, and contributions of the presented models to the multi-dimensional visualization field can be summarized as follows:

1. They provide an interactive visualization platform that allows the user to adjust the input parameters and specify the research needs more accurately. The platform is defined as any virtual globe, e.g., Google Earth, NASA WorldWind, ArcGIS Explorer, ArcGIS Earth, and Cesium.
2. They offer a multi-dimensional perspective in a single KML framework
3. They allow for spatio-temporal analyses covering both geographical location and the time variable without animation.

4. They are freely accessible to the end user (open access models) and do not require advanced software or license access keys.
5. They can be used on any computer system: Windows, Linux, Apple, smartphones, or touch pads.
6. They can be easily transferred to and are compatible with other software packages like e.g. ArcGIS or QuantumGIS.

The models and an interactive data framework represent natural Earth measurements and human-induced changes across geospatial time frames, at the global, national, and state levels. The techniques used in this paper will allow other researchers to view subsurface data with existing virtual globes to interact and see patterns in earthquake events, geothermal heat indexes, and groundwater well levels over time. The outcomes can be useful for further research in the field and to stakeholders to support decision-making processes related to earthquake emergency management, geothermal energy extraction, and sustainable water planning and management.

2 Challenges for visual representation of complex data using static virtual globes

This research applies virtual globes as currently the most comprehensive platform to represent multi-dimensional data. Despite their benefits, virtual globes still face several technological and methodological challenges. While we acknowledge those limitations briefly pointing them out in this section, we also provide solutions for the presented models and research examples.

For many decades, the 3D dimension has always been (and still is) a natural human part of comprehending real world information represented with several dimensions in virtual globes. Therefore, representing information from multi-dimensional data sets becomes the more challenging, the more dimensions we add to the visualization model. Furthermore, if the data is

not grouped and/or categorized in a meaningful visual way, the usefulness of a model might be lost. In addition, tools for manipulating data are not always readily available for specific types of multi-dimensional data sets from different disciplines. Several programs are available for displaying or converting data, like e.g. COLLADA, but more options are needed to provide a comparison benchmark.

Another challenge is subsurface representation in virtual globes. Techniques of this kind are rather recent, and they were not originally developed with the purpose of representing data below the Earth's surface.

While 2D cross sections and pop-up planes or blocks that come above the surface of the Earth are common (Dobson, 2012), they display solely pieces of subsurface as pop-up blocks. The subsurface models presented with this paper represent the subsurface of the Earth as a whole and is interactive meaning that it allows the user to fly-through and navigate under the Earth subsurface.

Currently, when a user zooms into a highly populated cluster of data, orientation and location may be lost. In cases like this more information about the subsurface surroundings is needed to keep on track and better understand the information and orientation.

Moreover, currently animations are often used with temporal data in virtual globes. However, if the time intervals are not set correctly, subtle information might be missed. Another issue with animating large data sets arises when loading them into limited memory space, which may prohibit viewing any of the data at all. In order to overcome this limitation, intelligent clustering and reducing the size of the data is needed. Even the application of intelligent clustering comparisons within a time-based static cluster will not insure a proper understanding of the data.

Natural visual representation of the data as geometric shapes would considerably improve human understanding of complex data sets.

Another potential limitation might be difficulty to present level of detail and memory restrictions. However, using WebGL-based virtual globes like Cesium and OpenWebGlobe (open source platforms) can alleviate this impediment.

3 Methodology

3.1 Specifications of the KML/ KMZ models

This paper develops new application methods and presents four types of models from different scientific disciplines: geophysics, geology, and hydrology to represent earthquake events around the globe (with a subsurface and above-the-surface representation – two separate models), geothermal heat indexes, and groundwater well levels, respectively. Each model is stand-alone, as it has unique application properties and features, while at the same time all models have overlapping attributes. More specifically, all four models have two attributes in common: they are georeferenced and represented with multiple visual dimensions. The various overlapping shared attributes of the models are: the temporal dimension, application of depth layer cueing, Ternary Visual Shape Logic (TVSL), and multiple visual dimensions. Table 1 summarizes the model characteristics and applied functions.

[Table 1 here]

In addition to the new application methods presented here, this paper also builds upon several standard computer visualization techniques that were commonly applied in the past in older 3D

computer games. One of them is '*limited instances of a texture map*' that were reuse multiple times in the presented models to achieve higher memory efficiency. While this standard technique has been used for years, it has not been widely incorporated into KML, as we suggest in this paper for the applied geoscience examples. Furthermore, we also apply the '*natural billboard effect*' in virtual globes by using a 2D texture map of a sphere (Lawrol, 2005). This technique allows for creating the effect of a true 3D sphere when viewing it from any side or above and below. It also renders faster and uses less memory than representing a geometric 3D sphere. In order to make the texture spheres look even more realistic we made use of the inherent '*z clipping*' in virtual globes that avoids displaying pixelization when zooming in close to the texture map image.

To present practical application of those techniques and unique properties of the models, we created a user-friendly visualization platform capable of 3D fly-throughs (visually conveying meaningful information in a more comprehensive manner). This feature was facilitated by the virtual globes and the developed KML code as a delivery format via the World Wide Web. The 3D analysis space to output the results in the KML format was generated with the C++ computing language. In all models the size and color of each sphere (data point) were used to represent different data attributes. In some of the models an additional feature '*visual cues*' has been added to the environment (e.g., for the earthquake and geothermal models) to create a subsurface wireframe with metadata that helps orientate and navigate through the subsurface. For this purpose, depth-shaded vector outlines of counties and states at set intervals depths were incorporated in the models, with varying gray values indicating different depths of earthquake events or geothermal heat indexes. By clicking on any of the depth vector polygons, the object's depth and the county/state can be visually identified. In the earthquake model, also translucent

layers at set interval depths were added for depth layered cueing. Both the vector outlines layers and the depth translucent layers can be turned on or off giving the user more visual options, as needed.

3.2 Methodology for subsurface visualization using depth layered cueing

Depth layered cueing was used for subsurface visualization of the earthquake model and geothermal gradient model; both based on KMZ files. The visualization models for the earthquake events use USGS data and Earth imagery data from NASA. In the presented model, earthquakes are displayed at the global scale in the last 100 years (April 1914 - April 2014) with the magnitude range between 5.5 and 8.0 >, which generates a database with a total of 24,398 entries. Unlike previous studies on earthquake events, we represent the data set from the USGS in a virtual globe in two different ways that represent an added value to the methodology and literature in the field:

1) Subsurface visualization that applies two methods for depth layered cueing (providing the user with a visual feedback about the spatio-temporal location, especially when using fly-throughs):

a) Transparent Earth layers with changing transparency as a function of depth, and

b) Outline of countries at different depths intervals with each outline gray-scaled as a function of depth.

2) Above-the-surface visualization with elevation represented as a function of time (spatio-temporal analysis) and the earthquake depth represented as a color.

The presented visualization builds upon earthquake research presented by USGS (n.d.), while also extending methodological knowledge in the field. The USGS models represent only a 4D

perspective of earthquake events with flat circles on a flat globe surface. The models proposed with this paper offer a unique perspective as they use spheres in the virtual globe environment, and thus add another (5th) dimension to the earthquake visualization. This additional dimension conveys a new piece of information and provides a more comprehensive analysis of earthquakes compared to USGS models.

The multi-dimensional subsurface earthquake model in this paper combines the following parameters: 1) latitude and longitude (x and y axes), 2) depth of the earthquakes in km (z axis), and 3) magnitude of the earthquakes represented both as the size and the color of the spheres. In order to create the subsurface layer and present the multi-dimensional earthquake data below the Earth's surface, the height of the Earth's surface was extended by 750 km, which still allows for the deepest earthquake in this model (720 km) to be viewed within this range. Next, an image map of the Earth at an elevation of 750 km was set to be translucent, so that users could see through the surface of the Earth down to the earthquake hypocenters (figure 1). The true depth representation expressed through the z axis provides the user with a better understanding of earthquake clusters and structures.

[Figure 1 here]

In 2012, De Paor et al. (2012) developed a COLLADA model representing a subsurface of the Earth. Building upon De Paor et al.'s research, our models advance knowledge in this field as they allow for fly-throughs and examining the respective geological events from a close perspective and as a subsurface virtual Earth. The example KML models presented in this paper do not require a specific version of Google Earth and can be used in any virtual globe supporting

KML. To facilitate user orientation, outline vectors of all countries of the world were set up at 3 depths intervals for 3D fly-throughs. In addition, a semi-transparent image map of the Earth was created at the depth of 300 km down as a user visual depth reference. Finally, we covered the existing Google Earth with a blank black image to give the user more of a sense of depth, as similarly done by De Paor et al. (2011). In a next step, the USGS earthquake data was converted to KML for an interactive view in the virtual globe, while our compiled C++ code allows for representing the depth going down, starting at 750 km (simulated Earth's surface), and dropping below the Earth's surface to explore and view earthquakes in 3D. This subsurface feature of the model extends knowledge presented in the previous literature.

Other studies, e.g. by Zhu et al. (2016) and Zhu et al. (2014b) proposed volumetric subsurface representation and developed a VisualCrust application and the SolidEarth system, respectively. Our research uses a similar technique for the subsurface visualizations; however, we visualize points (earthquakes) in subsurface to be viewed with virtual globes (3D viewers), which is currently the most comprehensive way to view the models. The recent API depreciation (embedding Google Earth within a browser) will not affect our models that can run on 3D viewers independently of the browsers. We also chose to separate the subsurface representation and the above-the-surface earthquake model (presented in section 3.3) due to the nature of our data set visualized as points in the whole earth environment.

The geothermal indexes model uses the x and y variables to represent geolocation, while the depth has been specified in a similar way as in the subsurface earthquake model described above. This model uses color to represent heat gradient indexes curves across Texas and thus display an additional (fourth) visual dimension (figure 2). Also in this case depth layer cueing was applied

at three levels represented by vector outlines of the Texas counties. The vector layer color was assigned as a function of depth (the deeper the representation, the darker the layer). In addition, each county has assigned characteristics (e.g., the county name) and the depth of the geothermal heat curves at each layer represented with the same method as in the earthquake model (here we use counties instead of countries as in the earthquake model).

[Figure 2 here]

The combination of those techniques not only presents the user with visual depth layered cues, but also provides a base for a reality check to verify the true geothermal depth while exploring the model. The vector layers and translucent layers used for subsurface depth layered cueing can be turned off or on by the user giving more flexibility in maneuvering through subsurface data points.

The uniqueness of the subsurface earthquake and geothermal models results from the combination of the '*depth layered cueing*' technique with a subsurface KML model, making them usable in any virtual globe.

3.3 Methodology for above-the-surface visualization of earthquake events

To provide a comprehensive learning experience to the user and a different approach of understanding data clustering, we developed an additional above-the-surface model for the earthquake data set. For this visualization, the time of the earthquakes was incorporated as elevation (old earthquakes are close to the surface, while most recent earthquakes are higher up above the surface), thus adding one additional visual dimension to the previous subsurface

model. The following model categories were included: 1) latitude, 2) longitude, 3) time variable (date of the earthquake) represented with the height of the sphere above the Earth surface, 4) magnitude of the earthquake represented with the size of the sphere, and 5) depth represented with 10 color categories (the darker the color, the shallower the hypocenter of the earthquake; the lighter the color, the deeper the hypocenter). The spheres are connected to the surface of the Earth via a white vector line. This multi-dimensional earthquake model does not use depth layering cueing techniques; therefore, the data set runs faster than the subsurface model, though a longer rendering refresh time can be expected on low end computer systems (figure 3).

[Figure 3 here]

3.4 Methodology of Ternary Visual Shape Logic as quick indicators of change

For the groundwater well level model we invented the Ternary Visual Shape Logic (TVSL) method that refers to the Russian computer Setun and its storage logic which used three states: positive, negative, and neutral. The analogy of the three states from Setun represents three recognizable visual states of groundwater levels discussed with this method: 1) cone shape (groundwater level decrease), 2) inverted cone shape (groundwater level increase), and 3) no discernible shape (no visible increase or decrease in groundwater well levels) (figure 4).

[Figure 4 here]

It needs to be emphasized that the TVSL is a visualization concept describing ‘visual logic’, not a mathematical algorithm/ mathematical logic in the strict sense of the word. Through a visual

representation of changing spheres humans are able to ‘naturally’ recognize patterns and trends in data sets that would not be detectable instantly if Boolean algebra and operators were applied. Thus, the TVSL concept has the capacity to make model results easily accessible to any user with or without sophisticated knowledge in the computer and mathematical sciences. The approach of representing patterns with a shape of multi-dimensional objects has proved to be very successful for human recognition and data interpretation (Kourtzi et al., 2003; Jiang et al., 2008; Pizlo, 2007).

The TVSL has proven very useful in this study to visually detect statically relevant and discernible well water changes over time for 12 consecutive years using spheres for each data point representation and the height above the ground as the time variable, with the time intervals grouped into three different height categories. The model used data on water wells level samples in Texas with over 140,000 data points in 2003-2014. For the purpose of the anticipated statistical analyses and in order to insure data conformity, the data set was further reduced to data points from wells with at least one sample per year. The data was first grouped into three years sections (2003-2006, 2007-2010, and 2011-2014), while four statistically relevant subgroups within each of the three years sections were defined in a next step. This statistical subgrouping reduced the data set to a manageable size and facilitated a smoother visualization process. Each subgroup was color-coded, while also a sphere size was assigned to each of them in addition, representing the same variable (well water level). The lowest water levels were assigned a light blue color and a small sphere size, while the highest water levels were assigned a dark blue color and a large sphere size. The statistical intervals were set in a way that the four subgroups range from a small light blue sphere to a large dark blue sphere. If water levels were consistently going down over years, the three spheres stacked one on top of the other would create a visual shape of

a cone, with the highest sphere being the smallest one at the top of the cone (a witch's hat shape). If the water levels were consistently going up over years, the sphere stack would display a cone shape with the bigger sphere at the top of the cone (a frozen icicle shape). If water levels were going up and down over the three time intervals, a cone shape would not be discernible.

4 Results and discussion: Interactive geospatial multi-dimensional analysis of the three application examples

4.1 Interactive global multi-dimensional earthquake models with depth layer cueing

The subsurface layers can be easily recognized as translucent covers of the Earth. Earthquake points are located either close to the upper layer (Earth surface) representing the shallow earthquakes, or further down below the Earth's surface representing deeper earthquakes. The color and the size of the spheres represent the magnitude of the earthquakes. Figure 1 displays a screen shot of earthquakes in Central and South America. In this part of the Earth, the earthquakes have a higher magnitude and frequency as the Cocos plate and Nazca plate are subducted along the coast. The model is interactive and can be adjusted to the user's needs by turning on and off the model categories and features.

Figure 5 is another screen short of the subsurface model representing a view from the coast of Philippines looking towards Japan at a depth of about 530 kilometers. The white lines dropping from the surface of the Earth clearly substantiate the use of subsurface visualization and help to exactly locate the earthquakes events as well as their frequency and magnitude. This allows the end user to experience a true representation of the spatial distribution of earthquake events. Each sphere provides additional information about the individual earthquake events giving the user the option to view it interactively in a pop-up balloon window. Country layer outline vectors are also interactive, thus providing additional information and orientation in the pop-up balloon windows.

[Figure 5 here]

4.2 Interactive multi-dimensional model for geothermal heat indexes in Texas with depth layer cueing

The geothermal model presented here was derived from a data set with approximately 30,000 wells in Texas (figure 2), which represents only a small percentage of the total number of all wells in the state. The well selection was determined by the data availability on wells with the bottom hole temperatures. The spheres represent the geographical and approximate depth location of the wells, while different sphere colors reflect different geothermal heat indexes that are independent of the well depth. When clicking on the spheres, detailed information about the heat index and the well are displayed, while due to its multi-dimensional format, the model allows for fly-throughs at different depths. The presented geolocation of heat indexes can be helpful both for supporting regional and statewide decision making processes as well as educational curricula. Based on the cost of electricity, distance to larger cities (and demand for energy), and depth of the geothermal heat layer to the surface, the model can be useful with indicating a breakpoint for economic feasibility of building potential geothermal plants in the respective locations across the state.

4.3 Interactive multi-dimensional model for well water levels in Texas with ternary visual shape

Figure 6 shows a screenshot from the multi-dimensional groundwater well model in a neighborhood area of Lubbock in Texas. Each of the three spheres that are part of the Ternary Visual Shape Logic are clickable and bring up a balloon information window with statistical

information and includes a link to the original well data from the Texas Water Development Board.

[Figure 6 here]

Due to a large data set, the model is densely populated and allows for an extensive analysis of changes in the well water levels over time (figure 7). It is clear that in the analyzed time period between 2003 and 2014 different measurements have been taken at different wells, with some well water levels increasing and some decreasing over time. The model shows that water levels in most of the wells have been decreasing, which has a potential to indicate the recent droughts occurring in the state since 2011. The majority of the wells indicate a cone shape (witch's hat shape) denoting a decrease of well water data. However, a minority of the wells are either inconclusive to which direction the well water level changed over time. The number of wells with increasing water levels represents only a small number that is displayed with the frozen icicle cone shape. Due to the Ternary Visual Shape Logic, the model allows the user to comprehend the results at one glance and determine where well water levels increased, decreased, or remained unchanged. The model can be useful for educational purposes, but more specifically for research and decision-making support, facilitating planning and efficient water management, especially in times of drought.

[Figure 7 here]

All models presented in this paper, including the subsurface representation of the earthquake events and geothermal heat indexes can be viewed on any computer system and/or smartphone (ipad, iphones or Androids), thus providing tools to a broader audience (figure 7-8).

[Figure 8 here]

[Figure 9 here]

5 Conclusions and outlook

With the increasing computerization the quality and advancement of visualization techniques have been improving to better and more accurately describe real world problems. Yet, nowadays most techniques use 2D and 3D visualization models that are still limited in their visualization capabilities. Also, most multi-dimensional models use specialized licensed software that is not available to everyone on the web and requires time to learn and utilize it.

Enhancing visualization techniques by new dimension features and providing an open access model would help to make visualization broadly accessible and help solve relevant problems more accurately and in a timely manner. To facilitate this development we developed interactive multi-dimensional visualization models based on the virtual globes framework accessible freely to anyone on the World Wide Web and easy to use for a targeted problem analysis.

The models can be used not only for research and teaching purposes, but also for supporting decision-making processes. Interactive geospatial visual representation is crucial for the three examples: earthquake, geothermal, and groundwater well levels. The subsurface earthquake and geothermal visualization is unique by allowing an interactive view, while moving through earthquake data sets below the Earth's surface with depth layered cues as guides and 3D orientation. The Ternary Visual Shape Logic used in the model for Texas well water levels

simplifies complicated large data sets used for statistical analyses into quick visual recognition of geometric shapes. This method uses spheres to produce outlines of cones; however, other shapes can be used instead to quickly and visually understand other types of complex and entangled processes and data sets.

The presented techniques and models use multi-dimensional data and facilitate a better understanding of and comprehensive interaction with different data dimensions. The models are spatio-temporally oriented with the geographical location, color and size of the spheres representing different data components. This provides a unique visualization, although the current state of computer capacity can be limiting to a smooth and fast rendering process of extremely large data sets like the presented earthquake data. However, according to the Moore's law, computer capacity will improve in time along with advancements in graphic cards, thus allowing for handling larger and more complicated data sets without any delays.

The main benefit of the geospatial interactive models is to deliver complicated data sets and a dynamic rendering engine (here: a virtual globe) via the web and thus to make it available to anyone to use at no cost by means of any modern computer system application (Windows, Mac, Linux, and smartphones). Nowadays, virtual globes predominantly read KML and KMZ files and thus offer a 3D visualization platform. We believe that other and more precise 3D applications with the ability to read and render KML/ KMZ files will become available in the course of time. They could provide a future platform to deal with larger and more complicated data sets, create multi-dimensional stereographic displays and thus help the end user to understand the visual data more easily and comprehensively.

We also anticipate future work in the field to develop virtual globes as a client and provide dynamic processing on the server side computers. Similar work in this area has been done to

move KML geometry elements via a user interface by Zhu et al. (2014c), while we also appreciate promising features of Cesium for future work in this same area.

We propose the presented models to be used as an educational and research tool to better analyze, present, and display research and teaching results. The models extend the current state of knowledge in computer science and computer imaging and visualization. They can be transferred to and applied to many other disciplines like medicine, epidemiology, social sciences, engineering, and/or biology, to name just a few. They can also be used to extend the progress in the field even further as the technology develops and allows for more complicated models in the course of time.

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Model access:

The models and an example video fly-through can be found here:

http://hitechmex.org/kml_examples/

The website is initially designed for the Editor and Reviewers, and will be refined upon acceptance for publication. Thank you for your understanding.

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552 **Tables**

553

554 Table 1 Model specifications

Model	Georeferenced	Temporal	Depth Layer Cueing	Ternary Visual Shape	Multi- dimensional (# of dimensions)
Earthquakes (subsurface) – World	Yes	No	Yes	No	Yes (4)
Earthquakes (above-the- surface) – World	Yes	Yes	No	No	Yes (5)
Geothermal gradients – Texas	Yes	No	Yes	No	Yes (4)
Well water levels – Texas	Yes	Yes	No	Yes	Yes (4)

555 Source: Authors' presentation

556

557

Figures

Figure 1 Subsurface earthquake map from above with translucent depth layers of Earth and earthquakes events below, along Mexico, Central America and South America

Source: Authors' calculation and presentation

566 Figure 2 Subsurface perspective of geothermal heat indexes in Texas showing clusters in
567 red and magenta in ArcGIS Earth

568
569 Legend: Texas county lines are displayed at three different levels (white at surface, gray at
570 10,000 feet below surface, and dark gray at 20,000 feet below surface).

571 Source: Authors' calculation and presentation

572

573 Figure 3 Above-the-surface view of earthquakes off the coasts of Chile

574

575 Source: Authors' calculation and presentation

576

577 Figure 4 Ternary Visual Shape Logic diagram

578
579 Source: Authors' calculation and presentation

580

581

582 Figure 5 View of deep earthquakes below the surface off the coasts of the Philippines and
583 Japan at a depth of about 530 kilometers

585 Note: White vectors connect the earthquake epicenter on the Earth's surface with the hypocenter
586 spheres below the Earth's surface

587 Source: Authors' calculation and presentation

588

589 Figure 6 Groundwater well levels in a multiple-dimension model in the region of
590 Abernathy in Texas

591
592 Source: Authors' calculation and presentation

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594 Figure 7 Groundwater well levels in Texas in NASA World Wind KML Viewer

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596 Source: Authors' calculation and presentation

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598 Figure 8 Geothermal heat indexes mapped with multiple dimensions across Texas on an
599 iphone

600
601 Source: Authors' calculation and presentation

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603

604 Figure 9 Above-the-surface earthquakes on an Android tablet

605

606 Source: Authors' calculation and presentation

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608

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611 earthquakes events below, along Mexico, Central America and South America
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