CARTOGRAPHIC METHODS FOR VISUALIZING SEA LEVEL RISE

John C. Kostelnick (1), Dave McDermott (2, 3, 4), Rex J. Rowley (2)
Department of Geography-Geology, Illinois State University, Normal, IL, U.S.A. 61790-4400.
Haskell Indian Nations University, Lawrence, KS, U.S.A. 66046.
Department of Geography, University of Kansas, Lawrence, KS, U.S.A. 66045.
Center for Remote Sensing of Ice Sheets, University of Kansas, Lawrence, KS, U.S.A. 66045.
Email: jkostelnick@ilstu.edu (Kostelnick); dmcdermo@ku.edu (McDermott);
rrowley@haskell.edu (Rowley)

ABSTRACT

Increased attention to global climate change in recent years has resulted in a wide array of maps and geovisualizations that forecast the anticipated consequences of climate change, including sea level rise in coastal areas. Since inundation from sea level rise is inherently geographic in nature, there is a need for effective cartographic representations at global, regional, and local scales that depict where the inundation is expected to occur as well as the magnitude of the projected inundation. The recent increase in production of maps and geovisualizations displaying the anticipated impacts of sea level rise calls attention to numerous cartographic issues that warrant consideration for such displays, including representation of various categories of uncertainty. Using examples from analyses of sea level rise at global, regional, and local scales, we provide a general framework of cartographic issues related to sea level rise as well as a collection of specific examples that demonstrate the challenges and limitations of sea level rise maps and geovisualizations. We draw our observations on the effectiveness and limitations of these displays through informal, qualitative feedback from scientists, educators, and other map users.

INTRODUCTION AND OBJECTIVES

Global climate change is perhaps one of the more significant hazards confronting the global society in the foreseeable future. The International Polar Year (IPY) has elevated climate change as a major issue that has received significant exposure in the recent scientific literature as well as the popular press. One potential consequence of global climate change is a gradual rise in sea level due to the increased melting of snow and ice pack from the world's temperate glaciers and the major ice sheets, Greenland and Antarctica. According to one estimate, global sea level would rise approximately 80 meters if the entirety of the Greenland and Antarctic ice sheets were to melt (USGS 2000). The Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007) report released in 2007 provides an upper-level estimate of 26-59 cm of sea level rise across the globe over the next century.

Cartographers and GIScientists have an important opportunity to contribute to the issue of global climate change through the production of maps and geovisualizations that depict the predicted consequences of sea level rise and may be used by scientists, policy makers, educators, and the general public. Given the great influence that such maps and geovisualizations may have for planning, public policy, education, and a range of other purposes, an important challenge to cartographers is the development of displays that communicate the critical issues associated with a forecasted event such as sea level rise in an effective, yet responsible manner. Despite the abundance of maps and geovisualizations that depict sea level rise in both the popular press and scientific literature, fewer studies have documented the specific cartographic issues that warrant consideration for such maps and displays. Such issues include depicting various types of uncertainty, displaying the temporal progression of sea level rise, and relating the geographic extent of predicted inundated areas to their impact on the natural and built environments.

The objective of this paper is to propose a general categorization of important issues that should be considered for maps and geovisualizations that display a speculative event such as sea level rise, and to propose cartographic strategies that may be utilized for addressing these issues on maps and geovisualizations. In particular, we focus our discussion on categories of uncertainty inherent in predicting inundation from sea level rise. Although the research presented here pertains to visualizing sea level rise, it may have relevance and applicability to hazards of unknown likelihood or phenomena of a speculative or ambiguous nature.

CARTOGRAPHIC REPRESENTATION OF HAZARDS

Maps and geovisualizations derived from GIS analyses serve several purposes for visualizing data related to hazards during the planning, mitigation, preparedness, response, and recovery stages (Greene 2002). Despite their potential, maps may be misleading and even controversial, such as in cases when they under- or over-predict the geographic extent of a risk or hazard zone. (Monmonier 1997). Effective representation of hazards and risks should consider several factors due to the critical role of maps in hazard situations. Cartographic studies have explored numerous issues related to hazard representation, including symbolization issues and considerations for maps utilized to support activities in areas such as emergency response (Dymon 2003) and humanitarian demining (Kostelnick et al. 2008). Citizen concern over industrial wastes has led to research on symbolization of risks associated with toxins, and called attention to the challenge of responsibly representing poorly understood relationships such as thresholds at which exposure to different toxins becomes an actual hazard to health (Scott and Cutler 1997). Representation of hazards must also consider that the scale requirements at which map users wish to evaluate risk may be very different from those at which the data are provided (Zerge 2002).

CATEGORIES OF UNCERTAINTY FOR SEA LEVEL RISE

All geographic phenomena are subject to various types of uncertainty, either inherent in the phenomenon itself or in the measurement of the data that represent the phenomenon (Couclelis 2003). Various categorizations of geographic uncertainty have been proposed to describe these types of uncertainty further in different contexts. MacEachren et al. (2005), for example, proposed a general typology of nine categories of uncertainty: accuracy/error, completeness, consistency, credibility, currency, interrelatedness, lineage, precision, and subjectivity. Plewe (2003) characterized uncertainty in historical GIS databases as composed of two primary elements: ambiguity and fuzziness. Some types of uncertainty can be symbolized quantitatively on maps and geovisualizations (e.g., Pang 2001; Slocum et al. 2003) while others are subject to the speculative or counterfactual nature of the phenomenon being represented and therefore are not easily represented by standard quantitative methods. Regardless of the type of uncertainty or method of cartographic representation, it is critical that map users comprehend the uncertain nature of the phenomenon. Level of expertise (such as domain and map use) may influence the assessment of risk for hazards such as flooding when uncertain information is presented on maps (Roth 2009).

Sea level rise is no different from many hazards or risks of a speculative nature: it is subject to inherent uncertainties regarding the magnitude, location, and temporal occurrence of the event when displayed on maps based on data inputs from GIS-based models. The primary challenge in mapping sea level rise deals with conveying three primary types of uncertainty--spatial, temporal, and process--to map users. Ultimately, the effectiveness of any map or geovisualization depicting sea level rise depends on how these categories of uncertainty are represented since they may not be apparent to naïve map users.

Spatial Uncertainty

Spatial uncertainty refers to the level of accuracy and precision of the predicted inundated areas displayed on a map or geovisualization as influenced by the scale, accuracy, and precision of the input data (e.g., elevation) utilized in the analysis. Gridded digital elevation models (DEMs) are available at several levels of horizontal and vertical accuracy and precision for use in GIS-based predictive models of sea level rise. Spatial uncertainty for predicting inundated areas is influenced, in part, by two important variables: the horizontal or spatial resolution of the DEM and the vertical accuracy and precision of the elevation values. For example, generalized DEMs often utilized for global or continental-scale analyses of sea level rise (e.g., CEGIS 2009; Li et al. 2009; Rowley et al. 2007; Weiss and Overpeck 2003) include the Global Land One-Kilometer Base Elevation (GLOBE) elevation dataset (Hastings and Dunbar 1998), which provides 30 arc-second horizontal or spatial resolution, and the Shuttle Radar Topography Mission (SRTM) with 3 arc-second spatial resolutions for much of the earth. DEMs may over or underestimate actual elevation values; SRTM, for example, has been found to overestimate elevation consistently with the error varying by land cover type (Shortridge 2006). For maps and geovisualizations at local scales, higher spatial resolution datasets are more appropriate such as 30-m DEMs provided by the U.S. Geological Survey (USGS). A limitation of all of these datasets is that elevation units typically are in whole meter integer values, which makes prediction of sub-meter levels of inundation unfeasible. Predicted inundation areas derived from Light Detection and Ranging (LiDAR) DEMs may portray sea level rise with the most confidence due to the finer spatial resolution (typically < 5 meters) and more precise vertical accuracy (typically submeter) (Figure 1).

In addition to uncertainty inherent to the horizontal and vertical resolutions, DEMs have other idiosyncrasies that can lead to spatial uncertainty for prediction of inundated areas. For example, missing cell values, striping, and other data artifacts may yield inaccurate results when integrated into sea level rise inundation models. LiDAR returns from water surfaces can be unpredictable, leading to flawed elevation data for coastal wetlands where accurate data are needed most acutely. Along with errors related to horizontal and vertical accuracy and precision of the elevation dataset, these errors lead to spatial uncertainty in the geographic extent of predicted inundation areas.

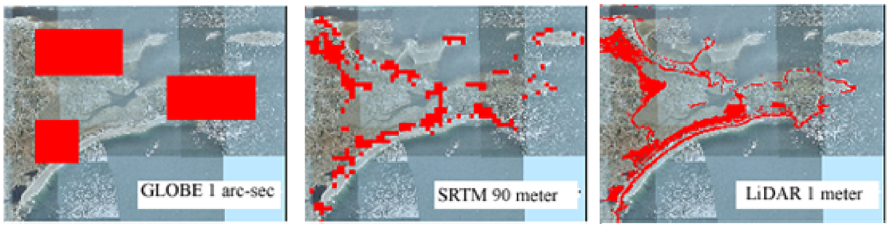

Figure 1. Impacts of varying spatial and vertical resolutions of input DEMs on predicted inundation zones (displayed in red) in Biddeford Pool, Maine using GLOBE, SRTM, and LiDAR DEMs. Area is Biddeford Pool, Maine, United States.

Temporal Uncertainty

Inherently, sea level rise is a temporal event that may be viewed at many temporal scales. Gradual levels of sea level rise may be anticipated for continents over the course of several centuries, whereas more modest levels of sea level rise may be depicted for local areas over the course of a day due to tidal cycles. Regardless of the temporal scale, the difficulties of associating a specific time period to each increment of sea level rise poses challenges for depicting change over time on maps or geovisualizations. The challenge to forecast accurately “X Units” of sea level rise for “Time Period Y” guarantees a certain level of temporal uncertainty displayed on maps and geovisualizations. Temporal uncertainty associated with sea level rise is suggested by the IPCC (2007) report, which according to one scenario predicts a rise of .21 - .48 meters of sea level by the year 2100. Temporal uncertainty is further complicated by the fact that sea level rise fluctuates at varying rates of change and is not linear in manner, which poses limitations for interpolation of sea level rise increments between time periods.

Process Uncertainty

At its most basic level, modeling sea level rise is a conceptually simple exercise of querying an elevation dataset for all areas whose elevation is less than the selected amount of sea level rise. This simplicity, however, can lead to facile research that fails to consider the geographic complexity of the coastline or environmental variables that influence the process of sea level rise, thus introducing uncertainty into the resulting predicted inundation areas. In reality, sea level rise is a complex process that may vary considerably at the local level due to numerous factors such as ocean circulation patterns, tidal regimes, thermal expansion of the ocean, and geologic subsidence and uplift (Szabados 2008). Uncertainty resulting from the complex physical processes of sea level rise may be reduced by utilizing models that incorporate additional input factors such as tides and coastal geomorphology. Such models may consider the characteristics of coastal bedrock and sediment, which will determine whether basins that are not connected to the ocean by surface water will be inundated by means of groundwater passing through porous sediments (Figure 2). More sophisticated models may also consider local tidal variation, which may significantly impact the spatial extent of an inundated area since a change at high tide is a more powerful indicator of potential destruction to coastal infrastructure than inundation at mean sea level. Weather patterns are another variable that may be included in more complex models, and the likelihood of sea level rise coinciding with high tides and storm surges will create inland inundation that may be of short duration but destructive nevertheless. The

Coastal Vulnerability Index from the USGS (Hammer-Close and Theiler 1999) represents one effort to codify the multiple elements of physical geography that contribute to the process of inundation resulting from sea level rise.

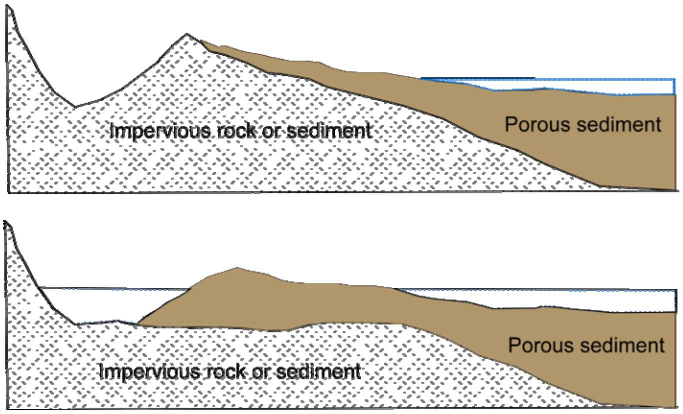

Figure 2. The role of coastal sediment in the inundation process. Note that the basin on the left in the upper figure is not inundated due to the impervious rock or sediment, yet the same basin would be inundated in the lower figure if porous sediment is present instead.

CARTOGRAPHIC STRATEGIES FOR REPRESENTING SEA LEVEL RISE

The various types of uncertainty described previously provide numerous challenges to cartographers who seek to depict inundation from sea level rise, yet some cartographic strategies may be employed to minimize this uncertainty and communicate the uncertainty of such a speculative event to map users.

Spatial Uncertainty

Cartographers have considered graphic strategies for representing spatial uncertainty in a variety of other contexts (e.g., Rossum and Lavin 2000; Pang 2001). Given the various factors influencing spatial and process uncertainty of predicted inundation areas, geographic representations that clearly delineate areas of risk, yet suggest that the degree of risk is uncertain rather than a sharp boundary, are most appropriate for sea level rise maps and geovisualizations. Numerous cartographic methods may be employed to depict this spatial uncertainty, such as jagged or fuzzy edges (Figure 3). Preliminary testing suggests that these methods can suggest uncertainty about the likelihood of inundation to map users. Formal testing with a broader range of users in the future will refine these techniques further.

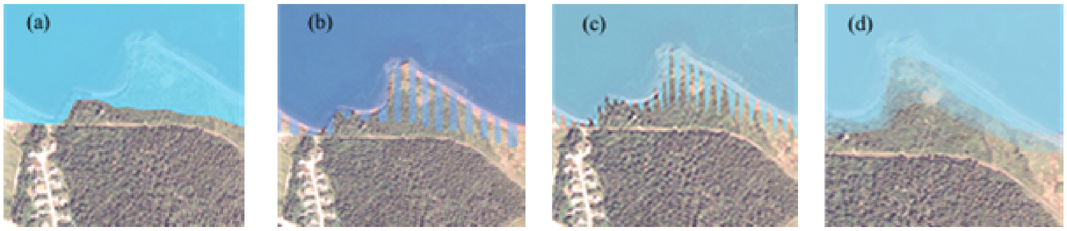

Figure 3. Four possible approaches for representing spatial uncertainty of predicted inundation zones in a coastal area: (a) transparency, (b) piano-key edge; (c) sawtooth edge, (d) edge gradient.

Another simple cartographic technique that may be utilized to minimize spatial uncertainty is to introduce zoom display controls into interactive maps and geovisualizations that prevent users from zooming in beyond the scale of the input data used to derive the predicted inundation zones. A potential hazard of providing unlimited zoom capabilities for map users is the risk that the fitness for use of the data may be violated, where lower precision inputs are utilized to draw conclusions for data that require higher precision. For example, in an informal demonstration of a geovisualization created from a global analysis of sea level rise in one-meter increments with coarse input datasets, one observer attempted to use the zoom in map display controls to estimate the extent of the inundation at a much larger scale, the backyard of a vacation home in a coastal area.

Temporal Uncertainty

Although temporal map animations typically display the time increment that corresponds to the map display as the animation cycles, the challenges of associating a specific increment of sea level rise with a precise time period requires an alternative approach. Rather, the amount of predicted inundation from sea level rise (which increases with the passage of time) may serve as a better focus for the animation or other temporal display such as small multiples. Figure 4, for example, is a screenshot from a sea level rise animation that utilizes a strategy of displaying the temporal progression of the predicted spatial extent of inundation from one to six meters. Such a focus displays the passage of time indirectly to map users, yet avoids the perils of estimating a precise time period for each predicted level of inundation.

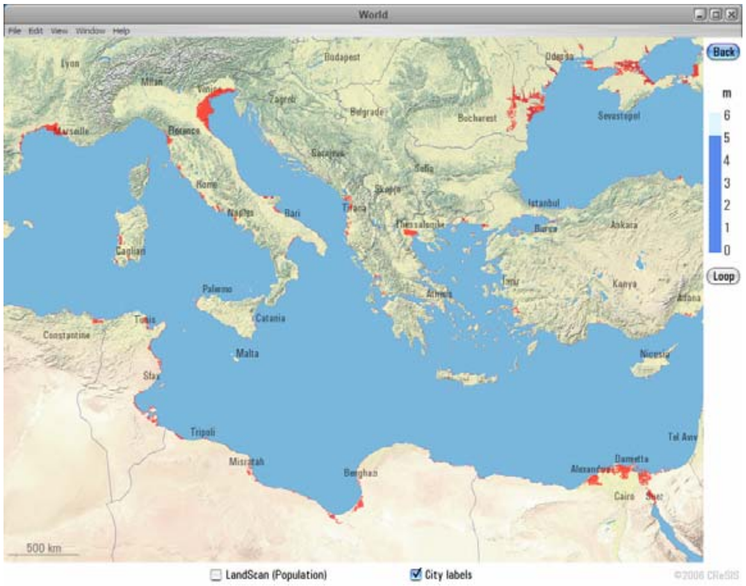

Figure 4. Screenshot from a temporal sea level rise animation focused on increments of sea level rise (in red) rather than specific time periods.

Process Uncertainty

The variables incorporated into GIS models to predict inundation from sea level rise greatly impacts the resulting cartographic displays utilized for visualization purposes. Whenever possible, sea level rise maps and geovisualizations should clearly convey to map users the input variables utilized for predicting inundation. In addition, multiple scenarios, rather than a single display, should be presented to map users to demonstrate the uncertainty associated with the process of sea level rise. The predicted inundation displayed in Figure 5, for example, is a screenshot from an animation that displays predicted sea level rise based on three factors: elevation, coastal geormorphology, and tidal regimes. LIDAR data were utilized to derive geographic areas below the specified elevation value (3 meters in this example). The model assumes that coastal sediments are highly porous, which allows for inundation in low-lying areas that are not connected to the ocean by surface water. While this assumption is appropriate for the sands of southern Maine illustrated here, it would not be appropriate for the clay soils and igneous bedrock of the coast of eastern Maine. To demonstrate the impact of tides on sea level rise, average daily tidal regimes were incorporated into the model to derive three predicted inundation zones (high tide, mean sea level, and low tide) for each increment of inundation. The geovisualization illustrates the importance of tides and storm surges in inundation models, areas in light blue that are landward of the predicted mean sea level extent (medium blue) are still inundated at high tide. By simultaneously depicting the geographic extent of inundation at high tide, mean sea level, and low tide, variation and uncertainty from the process of sea level rise are conveyed to map users.

Figure 5. An animation frame displaying predicted inundation at 3 meters for high tide (pale blue), mean sea level (medium blue) and low tide (dark blue). Area is Old Orchard Beach, Maine, United States.

Additional Considerations

In addition to choosing methods for communicating these various types of uncertainty to map users, cartographers should also strive to depict sea level rise in a "realistic," yet responsible manner. Realistic presentation includes the use of high resolution aerial or satellite imagery and three-dimensional visualization software to represent the impact of sea level rise on the built and natural environments in a less abstract manner. Such geovisualizations may communicate the severe impacts of sea level rise on the natural and built environments in a powerful, evocative manner. However, there is a potential danger that map users may misinterpret three-dimensional geovisualizations as being overly "real." As Figure 6 demonstrates, powerful rendering software can produce images that look like photographs of actual inundation or flooding but which are, in fact, simulations of purely hypothetical events.

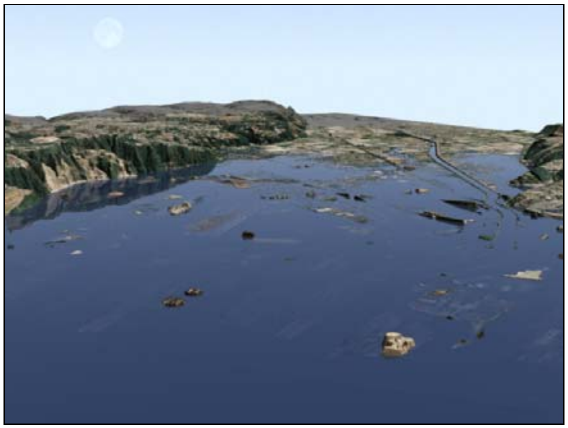

Figure 6. Portion of a 3-D visualization of predicted sea level rise inundation created with Visual Nature Studio (VNS)© for a portion of Puget Sound, Washington.

CONCLUSIONS AND ONGOING WORK

Mapping sea level rise presents a number of challenges that offer a fruitful area for cartographic expertise, innovation, and creativity. Ultimately, maps and geovisualizations that depict sea level rise should carefully consider the map audience and intended purpose in order to be most effective. Given the speculative nature of sea level rise, several types of uncertainty are inherent and cartographers should attempt to convey this uncertainty to map users. Responsible communication includes providing documentation to map users about the potential limitations of such displays to avoid potential misuse. Additional research, in the form of structured user-centered studies, are necessary to further formulate “best practices” for mapping inundation from sea level rise. Sea level rise represents a powerful issue where maps may be used in an evocative manner, which elevates the issue of cartographic ethics to the utmost importance.

ACKNOWLEDGMENTS

The authors wish to thank Nathaniel Haas, Kalonie Hulbutta, Joshua Meisel, David Braaten, and Xingong Li for their contributions to the material presented in this paper. This work was supported in part by the U.S. National Science Foundation under grants ANT-0424589, OPP-0122520, and HRD-0407827.

REFERENCES

Center of Excellence for Geospatial Information Science (CEGIS), U.S. Geological Survey (USGS). 2009. Sea Level Rise. [http://cegis.usgs.gov/sea_level_rise.html (accessed 23 July 2009)].

Couclelis, H. 2003. The certainty of uncertainty: GIS and the limits of geographic knowledge. *Transactions in GIS* 7(2): 165-75.

Dymon, U. J. 2003. An analysis of emergency map symbology. *International Journal of Emergency Management* 1(3): 227-37.

Greene, R. W. 2002. *Confronting catastrophe: A GIS handbook*. Redlands, CA: ESRI Press. pp. 140.

Hammer-Close, E. S., and E. R. Theiler. 1999. National assessment of coastal vulnerability to sea-level rise, U. S. Atlantic coast, Open-File Report 99-593. Washington: U.S. Geological Survey (USGS).

Eliminado:

Hastings, D. A., and P. K. Dunbar. 1998. Development and assessment of the Global Land One-km Base Elevation digital elevation model (GLOBE). *International Archives of Photogrammetry and Remote Sensing* 32(4): 218–21.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate change 2007, the physical science basis; Summary for policymakers*. Geneva: IPCC.

Kostelnick, J. C., J. E. Dobson, S. L. Egbert, and M. D. Dunbar. 2008. Cartographic symbols for humanitarian demining. *The Cartographic Journal* 45(1): 18-31.

Li, X., R. J. Rowley, J. C. Kostelnick, D. Braaten, J. Meisel, and K. Hulbutta. 2009. GIS analysis of global inundation impacts from sea level rise. *Photogrammetric Engineering and Remote Sensing (PERS)* 75(7): 807-18.

MacEachren, A. M., A. Robinson, S. Hopper, S. Gardner, R. Murray, M. Gahegan, and E. Hetzler. 2005. Visualizing geospatial information uncertainty: What we know and what we need to know. *Cartography and Geographic Information Science* 32(3): 139-60.

Monmonier, M. 1997. *Cartographies of danger: Mapping hazards in America.* Chicago: University of Chicago Press. pp. 363.

Pang, A. 2001. Visualizing uncertainty in geo-spatial data. In *Proceedings of the Workshop on the Intersections between Geospatial Information and Information Technology*. Arlington, VA: National Research Council.

Plewe, B. 2003. Representing datum-level uncertainty in historical GIS. *Cartography and Geographic Information Science* 30(4): 319-34.

Rossum, S., and S. Lavin. 2000. Where are the Great Plains: A cartographic analysis. *Professional Geographer* 52(3): 543-52.

Roth, R. 2009. The impact of user expertise on geographic risk assessment under uncertain conditions. *Cartography and Geographic Information Science* 36(1): 29-43.

Rowley, R. J., J. C. Kostelnick, D. Braaten, X. Li, and J. Meisel. Estimating population and land area at risk from sea level rise. 2007. *EOS Transactions* 88(9): 105, 107.

Scott, M. S., and S. L. Cutter. 1997. Using relative risk indicators to disclose toxic hazard information to communities. *Cartography and Geographic Information Science* 24(3): 158-71.

Shortidge, A. 2006. Shuttle Radar Topography Mission elevation data error and its relationship to land cover. *Cartography and Geographic Information Science* 33(1): 65-75.

Slocum, T. A., D. C. Cliburn, J. J. Feddema, and J. R. Miller. 2003. Evaluating the usability of a tool for visualizing the uncertainty of the future global water balance. *Cartography and Geographic Information Science* 30(4): 299-317.

Szabados, M. 2008. Understanding sea level change. *American Congress of Surveying and Mapping (ACSM) Bulletin* (December): 10-14.

U.S. Geological Survey (USGS). 2000. Sea Level and Climate, Fact Sheet No. 2. Washington DC: USGS.

Weiss, J. L., and J. T. Overpeck. 2003. Climate Change and Sea Level.

[http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/sea_level_rise/sea_level_rise.htm (accessed: 9 July 2009)].

Zerge, A. 2002. Examining GIS decision utility for natural hazard risk modeling. *Environmental Modelling and Software* 17(2): 287-94.