GeoModeler - linking scientific models with a GIS for scenario testing and geovisualization

T. C. Vance [ad*,], S. Mesick[b], C. Moore [c] and D. Wright[d]

[a] NOAA/NMFS/AFSC, 7600 Sand Point Way NE, Seattle, Wa. 98115
tiffany.c.vance@noaa.gov
[b] NOAA/NESDIS/NCDDC, 1100 Balch Blvd., Stennis Space Center, Mississippi, 39529
sharon.mesick@noaa.gov
[c] JISAO, University of Washington, Seattle, Washington, 98195
[d] Department of Geosciences, Oregon State University, Corvallis, Oregon, 97331

* Corresponding author.

Abstract:

Models provide a way to understand and predict the behavior of natural and human systems. Ideally models would be easily linked to a geographic information system (GIS). In the past, these two have not been well integrated for scientific uses. This lack of true integration hinders the ability of managers and scientists to create interactive, GIS-based models for management and research. However, GIS packages are starting to expose code and objects to allow closer coupling of core GIS functionality and analytical/modeling tools.

In creating GeoModeler, we have provided a prototype of how one might integrate a GIS with a number of oceanographic and decision-support models. Through the use of Java-based application programming interfaces and connectors, a GIS is directly linked with the Regional Ocean Modeling System (ROMS) model and with the Method of Splitting Tsunami (MOST) model. Scientists and managers are able to use a graphical interface to display datasets, select the data to be used in a scenario, set the weights for factors in the model and run the model. The results are returned to the GIS for display and spatial analysis. The project creates a framework for linking to other types of back-end models written in a variety of programming languages.

Ocean-atmosphere models such as ROMS are intended to provide a multi-purpose, multi-disciplinary oceanic modeling tool. A basin-scale ROMS has been developed over the Pacific Ocean with a spatial resolution of 12.5 km (http://ourocean.jpl.nasa.gov/). ROMS and MOST implementations in GeoModeler are used to introduce oceanographic modelers to GIS techniques.

For smaller areas, decision-support models provide ways to create and test scenarios during natural or manmade crises. A model might allow emergency managers to specify the location, magnitude and time of day for an earthquake and the model would return the number of people who might be in areas affected. Similarly, a model might look at the effects of climate-change on a fishery and return results based upon a number of different change scenarios.

1. Introduction

1.1 Background

Models provide a way to understand and predict the behavior of natural and human systems. In simplifying natural and human systems, they provide a window to greater understanding. Chorley and Haggett (1967) argue that models can take a number of forms - they can be a theory, a hypothesis, a role, a relation or a synthesis; they can include translations in space to create a spatial model, and translations in time to create a temporal model (Chorley and Haggett, 1967, citing Skilling, 1964). More recent models attempt to deal with both types of translations in order to create spatio-temporal models. As such, models, while simplifying reality, can still involve complex mathematical and analytical exercises. While some of these calculations are possible within a geographic information system (GIS), others require greater computational abilities than are currently available in a GIS. This requirement for greater computational capabilities produces the need to integrate the graphical analytical abilities of a GIS with the computational abilities of various programming languages. Models can be created within a GIS, created entirely using scripting or advanced programming languages, or ideally they might be created using combined techniques yielding the best of both worlds.

Examples of GIS-centered models include modeling of seafloor habitat (Monaco et al., 2005; Greene et al. 2005), models of the spread of diseases (Cromley, 2003) and models of the aesthetics of landscapes (ESRI, 2005). Examples of hydrological models created within a GIS, taking advantage of the native analytical functions of the GIS, include those built for vector data using the Arc Hydro Toolset (Arctur and Zeiler, 2004), or for raster data, such as TauDEM (Tarboton, 2005) and the Groundwater Modeling Tool for GRASS (Carrera-Hernandez and Gaskin, 2006).

Examples of standalone models that could then be visualized in a GIS include weather models such as the Community Climate System Model (CCSM), Rapid Update Cycle (RUC) and ECMWF Re-Analysis models (Unidata, 2006). Tools such as RAMAS GIS use a GIS to organize data for input into a standalone habitat model (Akçakaya et al., 2004). The MODFLOW groundwater flow model can be visualized with the GRASS GIS (Brodie, 1999 and http://grass.gdf-hannover.de/twiki/bin/view/GRASS/JaimeCarrera). Use of a GIS for model parameter setup and the display of results is seen in the watershed management modeling of the ArcView Non-Point Source pollution Modeling (AVNPSM) system (He, 2003).

GIS-model linkages are a part of the national research agenda of the University Consortium for Geographic Information Science (Albrecht, 2002; Usery, 2005). In this research, these linkages are seen as a way to introduce dynamic modeling to the GIS community and to integrate computationally intensive applications within a GIS.

1.2 Motivation and aims

A GIS has great abilities to organize, analyze and display geospatial information. It can provide powerful tools for the integration of data and for the creation of new data products. Its application to oceanography has been limited by a number of factors, including the lack of truly three-dimensional analytical capabilities, an inability to easily handle datasets such as three-dimensional model output, the inability to handle common data formats such as netCDF, and a perception that there is a steep learning curve for their use (e.g., Valavanis, 2002; Vance et al., 2005; Wright and Goodchild, 1997; Wright and Halpin, 2005). However, there has been a wide acceptance of GIS by emergency managers and others who use scenario modeling capabilities and spatial analyses to provide for rapid input to decision support and crisis response systems.

Models can be implemented within a GIS in a number of ways. They can be loosely coupled, with the GIS basically used to prepare data for use in a separate computational model; the model can be implemented using the functionality of the GIS, for example in calculating hillslopes and drainage patterns for hydrological model; or the model and the GIS are tightly computationally coupled, with the GIS used both for the input and for visualization of the output,

Ideally, data could be exchanged directly and seamlessly between and model and a GIS. In this instance, the user would choose datasets, define model structures and select parameters for a scenario or model run within the GIS user interface. The model itself would combine spatial analytical tools from the GIS world with scientific modeling capabilities from the theoretical realm. Use of high end processors for the models would create an almost real-time interaction between the model back-end and the GIS front-end. Users would be able to describe a scenario, generate results and rerun the scenario with altered parameters in a timely and efficient manner. The results would be enhanced by the automatic generation of maps and geospatial displays.

2. Methods and Results

2.1 Methods

The GeoModeler interface and display use graphical objects to provide functionality related to the type of data being displayed. The tools are intended to be familiar both to GIS users and to users of scientific graphics packages. GeoModeler builds upon an earlier tool called OceanGIS (Vance et al., 2005). OceanGIS was initially designed to allow 3D oceanographic calculations on *in-situ* data, and to overlay the results. As such, tools were developed to calculate some basic properties of conductivity-temperature-depth measurements, such as mixed-layer depth, geostrophic velocity, and dynamic height. As a data layer is added, the relevant tools for analyses are exposed for use. In the example shown in Figure 1, the addition of a layer of conductivity-temperature-depth (CTD) data causes tools for calculating mixed layer depth and other appropriate oceanographic parameters to become available. Data can be read directly from an OPeNDAP (Open-source Project for a Network Data Access Protocol) server by the Java code in GeoModeler.

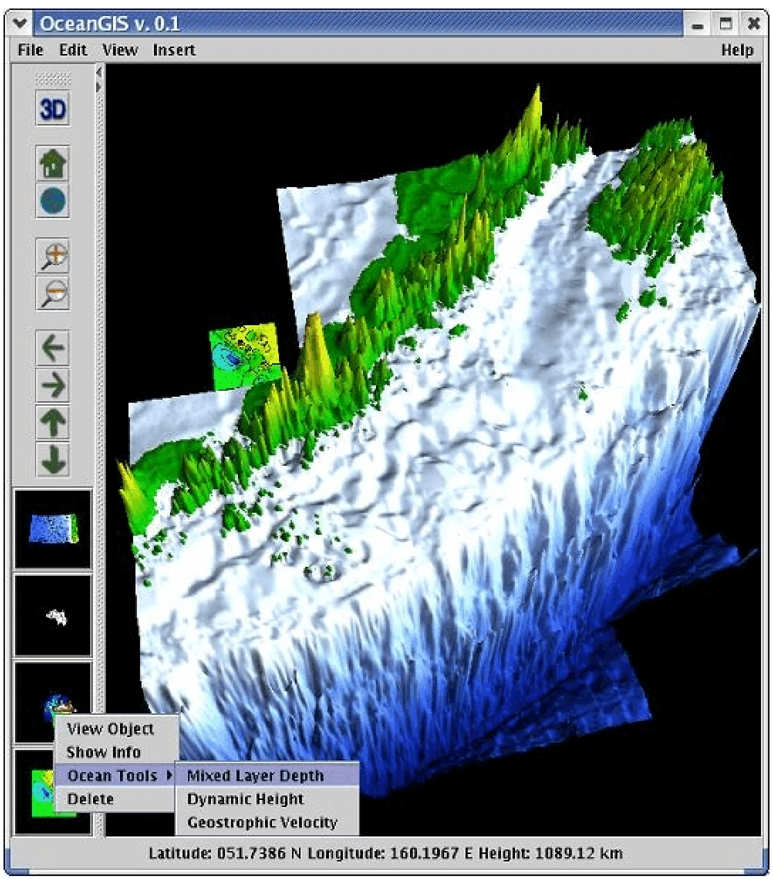

Figure 1 - CTD specific tools in OceanGIS

The initial implementation of GeoModeler was done using a VTK interface to the Regional Ocean Modeling System (ROMS). The test application, OceanGIS (written in java) used an interface that allowed the user to modify any of the C-preprocessor directives that ROMS uses in its build-script to enable various physical and numerical options. The initialization file can also be modified to reflect changes in timestep, tiling, and initial conditions.

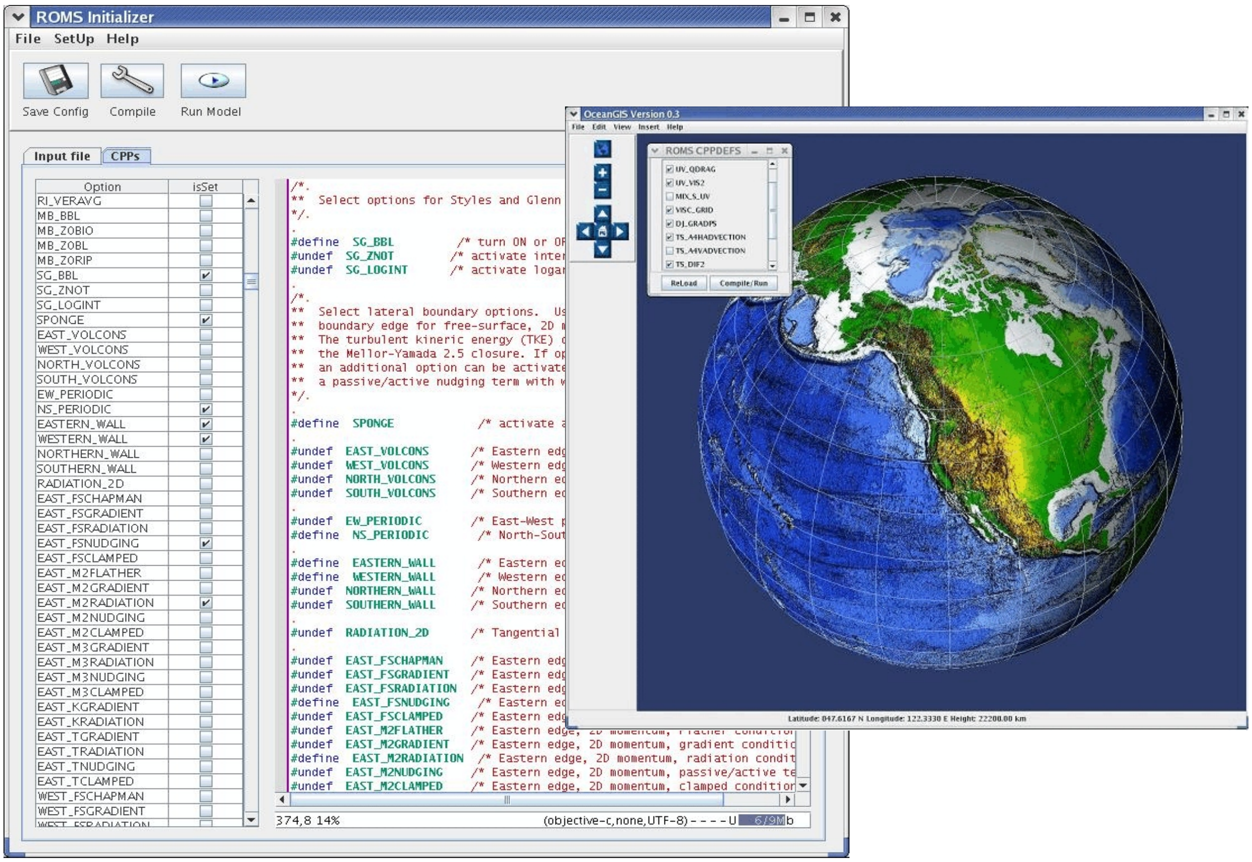

Figure 2 - Setting up the parameters for the ROMS model

The model is configured, compiled and launched through the GeoModeler interface, and model results are output to an OPeNDAP (www.opendap.org) server directory, allowing either viewing in OceanGIS or sharing results with remote colleagues.

The OceanGIS ROMS Data Reader is a GUI class that reads netCDF output of ROMS model data, and allows 3-D renderings to be created and animated in a geo-referenced framework. Since OceanGIS utilizes the Geotools (www.geotools.org) library, shapefiles of data using standard projections can be rendered simultaneously (as opposed to simply overlaying). The user loads a shapefile of seismic fault data, shown as yellow rectangles along the coastal trenches. Then ROMS model output is loaded through the ROMS Data Reader, and the user selects the variable of interest, contour levels, color maps, etc., and animates the

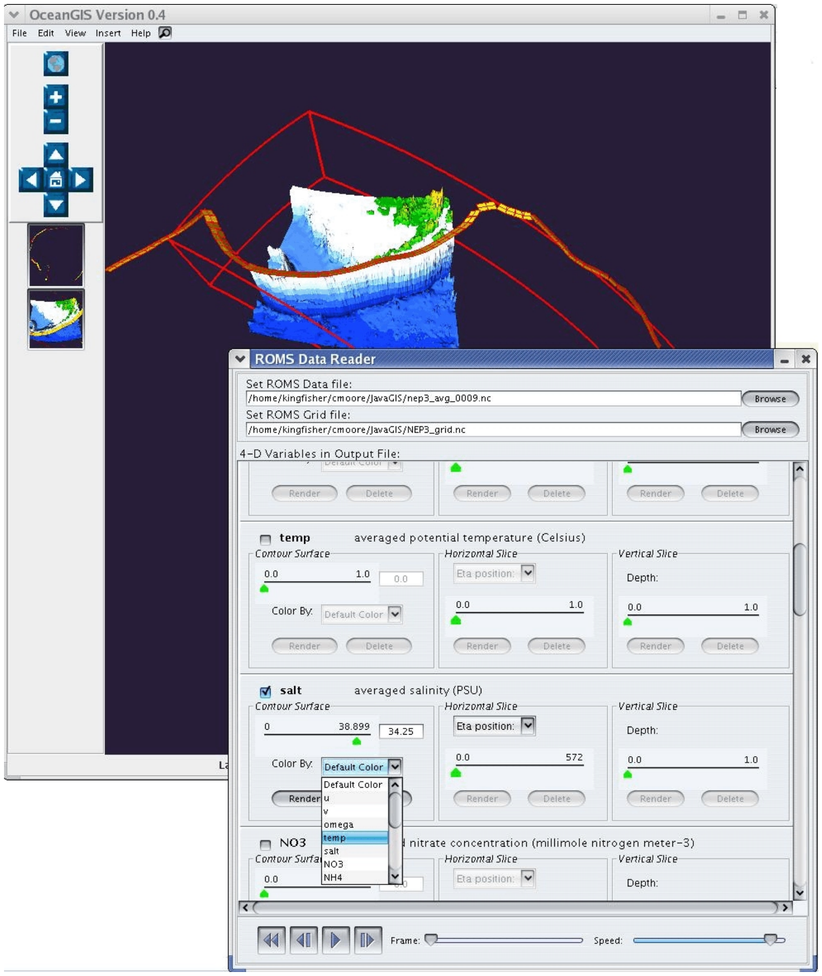

Figure 3 - Setting the display parameters

resulting rendering along with the seismic rendering (Figure 3).

2.2 Software components

GIS packages are starting to expose software code and objects to allow closer coupling of core GIS functionality and analytical/modeling tools. GeoModeler prototypes the direct integration of GIS and modeling capabilities in support of management and decision making. Through the use of Java-based application programming interfaces (APIs) and connectors, a GIS front-end is directly linked with models. Scientists and managers are provided with a GIS-based graphical interface to display datasets, select the data to be used in a scenario, set the weights for factors in the model and run the model. The results are returned to the GIS-based application for display and spatial analysis.

The project creates a Java-based framework for back-end models that incorporate a variety of programming language-based models. The Java3D API extension is designed as a high-level, platform independent 3D graphics programming API, and is amenable to very high performance implementations across a range of platforms. To optimize rendering, Java3D implementations are layered to take advantage of the native, low-level graphics API available on a given system. In particular, Java3D API implementations are available that utilize OpenGL, Direct3D, and QuickDraw3D. This means that Java3D rendering will be accelerated across the same wide range of systems that are supported by these low-level APIs.

We also make use of a second 3D API called the Visualization Toolkit (VTK) (www.kitware.com). VTK is a cross-platform 3D application programming interface built upon, and independent of, the native rendering library (OpenGL, etc). It exposes Java bindings (as well as Tcl and Python). It is written in C++ and includes similar scene-graph, lighting models, and graphic primitives as Java3D. VTK performs boolean operations on 3D volumes (intersection, union), volume rendering, filtering, including convolution, FFT, Gaussian, Sobel filters, permutation, high- and low-pass Butterworth filters, and divergence and gradient calculation. The VTK data model allows for fast topology traversal, making these filters very fast, and allows for rapid mesh decimation. VTK also offers powerful 3D probe "widgets" that allow easy interaction with the data, and has methods to utilize parallel architecture through the Message Passing Interface (MPI).

In a future development, we plan to use ArcGIS Engine and implementations of ArcObjects to communicate with an ArcGIS based front end. As with the current framework, the front end would provide both setup - allowing the user to specify the datasets to be used, the weights for elements of the model and the outputs desired, and for display - showing the results of the model run in a map or other spatial output. With the use of the Java connector to ArcIMS, the results may also be displayed in an ArcIMS or other map server.

ArcEngine is an ESRI developer product for creating and deploying ArcGIS solutions. It is a simple API-neutral cross-platform development environment for ArcObjects - the C++ component technology framework used to build ArcGIS. ArcObjects are the core of the ArcGIS functionality and include tools such as overlay - union, intersect; proximity - buffer, point distance; surface analysis - aspect, hillshade, slope; and data conversion - shapefile, coverage and DEM to geodatabase. ArcEngine's object library makes full GIS functionality available though fine and coarse-grained components that can be implemented in Java and other environments. Using ArcEngine, solutions can be built and deployed to users without requiring the ArcGIS Desktop applications (ArcMap, ArcCatalog) to be present on the same machine. It supports all the standard development environments, including Java, and C++, and all the major operating systems. In addition, some of the functionality available in the ArcGIS extensions can be embedded. This product is a developer kit as well a deployment package for ArcObjects technology.

2.3 Results

GeoModeler has enhanced OceanGIS so that is can be used as a front end for the Regional Ocean Modeling System (ROMS) circulation model. In this application, the user selects which parameters are to be used and assigns values to the parameters. The initial conditions (parameters) are then sent to the model, and the model results are returned for display in the GeoModeler/OceanGIS viewer. This type of integration, where parameters are passed to a model and the results are returned for display, could be applied to many types of models. We are currently extending this technique to prototype decision support models used by the NOAA National Marine Sanctuaries off of the US West Coast.

A second test model for GeoModeler was the implementation of an interface to launch tsunami models and allow the integration of results into a GIS framework. The initial results for this implementation are shown in Figure 4. The model output renderer/animator reads results of the Method of Splitting Tsunami (MOST) model, and surface height is rendered at each of 1440 timesteps. This model run includes "runup", or the adjusting of the model boundary condition to simulate inundation (Titov and Gonzalez, 1997). Rendering this surface over high-resolution

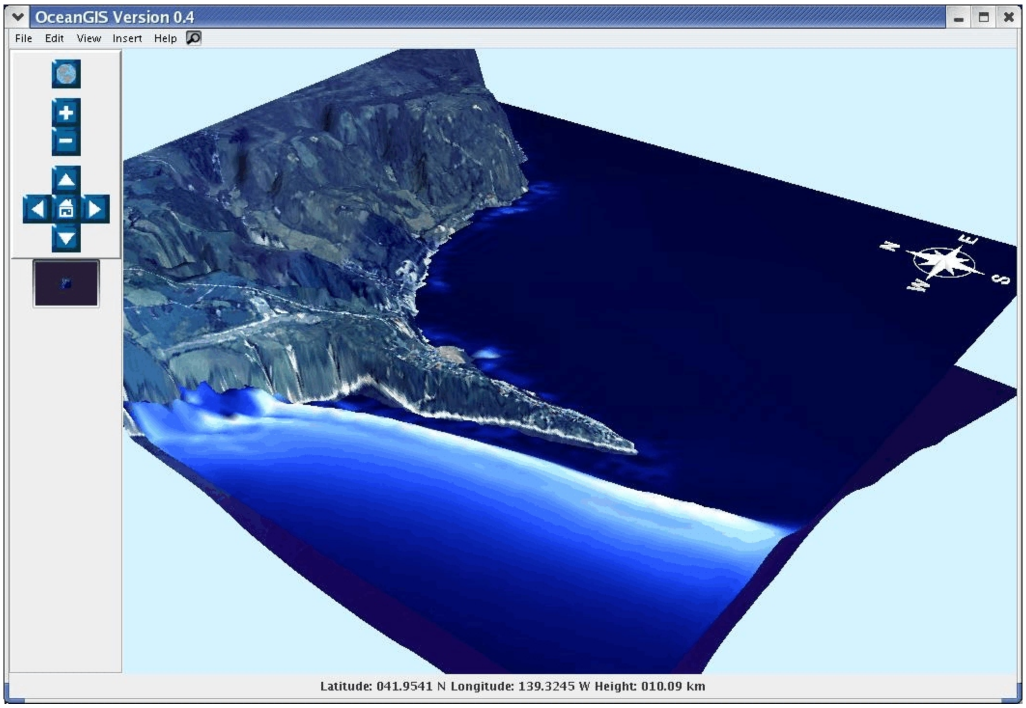

Figure 4 - MOST model output animation of tsunami runup

topography, overlaid with an areal photograph produces a fairly realistic view of the event. A complete description of this event can be found in Titov and Synolakis (1997).

The MOST model parameters include a series of uniform-sized seismic faults, called "unit sources", shown in Figure 5. These sources are initially set using an interface that allows the user to set the magnitude for each source, as well as the vertical distance the fault moves (the slip). An initial condition for running the inundation model is built up of a linear combination of model runs for each unit source. This initial condition is passed to the inundation model, with default parameters pre-set to give a rapid estimate of inundation in time for emergency managers to view results well before the approaching wave strikes populated areas. Future work includes getting all the parameters for MOST model runs into the interface so the GeoModeler tool can be used for research.

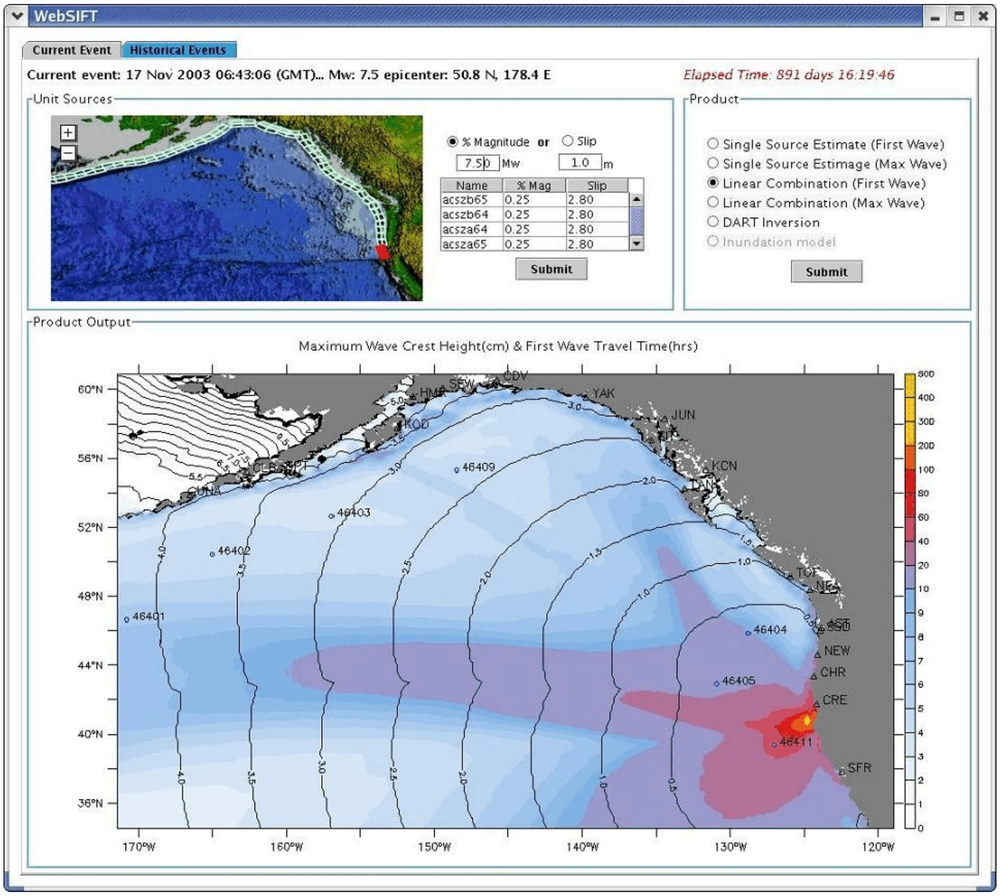

Figure 5 - Model parameters for the MOST model

3. Conclusions

3.1 Future Developments

We plan to expand the capabilities of the current GeoModeler and to prototype its application to two new projects. The expansion will include capabilities of the tool for handling three-dimensional analyses, such as the intersection of two volumes or the intersection of a three-dimensional path with a volume. This will require implementation of complex algorithms for volume on volume calculations. We are also going to take advantage of new developments in ArcGIS to include netCDF as a native GIS data format for GeoModeler. In addition, we plan to generalize the existing interface for the ROMS model so that a variety of oceanographic and atmospheric models might be used. GeoModeler's capabilities for scenario testing and decision support will be expanded. We also hope to provide a simple method for allowing new analytical modules, especially those utilizing parts of the ArcObjects library, to be inserted into the tool. This would allow us to implement enhanced geostatistical and other capabilities.

These new capabilities will be demonstrated by using GeoModeler to prototype three applications. The first would involve making the tsunami models outputs shown above available for scenario testing. Users would be able to choose a source region, the intensity of triggering event, the time of day and area of study. The tool would take these parameters, choose model output from a compendium of model results and return the inundation model results. The results would be combined with social data, such as population, to calculate populations at risk. The user could create any number of scenarios by changing the input parameters for the test. As the model results are pre-calculated, the response time is quick and the tsunami modelers are able to ensure that correct tsunami model parameters are chosen.

The second demonstration would be an application to visualize and analyze the results of two models; a model for mammal-prey interactions and a model to look at the effects of climate change on the recruitment of economically important fish species. The first model is an Individual-Based Model (IBM) that models the fate of individuals using characteristics such as age, size and prey consumption. As such, it is a typical example of the models used for ecosystem interactions and studying the consequences of changing environmental conditions. The second model is a Nutrient-Phytoplankton-Zooplankton (NPZ) model looking at the effects of climate change on young fish. The adults of these species studied are the target of major fisheries. This part of the project would take advantage of the new direct reading of netCDF data and the multi-dimensional analysis techniques described above.

For testing the decision support implementation, two NOAA activities that have identified a need for such decision support tools are the joint NMFS-states Southeast Area Monitoring and Assessment Program (SEAMAP)[http://www.gsmfc.org/seamap.html], and the NOS National Marine Sanctuaries (NMS) West Coast Observing System (WCOS) [http://www.mbnms-simon.org/sections/obs/nms_wco.php]. Modeling of NMS Monitoring Program data with the display capabilities developed through this project will enable Sanctuary scientists to integrate observed physical and biological data into predictions of the effects of environmental and anthropogenic variables on marine sanctuaries. For the prototype of linking a decision support model with a GIS, we will use ArcGIS Engine to create a front end linked to back end ArcObjects based modeling tools. The front end provides both setup, allowing the user to specify the datasets to be used, the weights for elements of the model, and the output desired; and for display by showing the results of the model run in a map or other spatial output.

3.2 Conclusions

GoeModeler provides a fully functional prototype of closely linking scientific models and a GIS. The results have been applied to two types of models - ROMS ocean models and the MOST tsunami model. The ease with which these models have been implemented suggest that the implementation of further models should be straightforward. The ease with which modelers have been able to integrate new GIS-based functionality has made them more open to implementing GeoModeler. The enhanced visualization capabilities and the ability to easily include GIS-based socioeconomic data will enhance the results of the existing scientific models.

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