Arc Marine

GIS for a Blue Planet

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Multidimensional GIS

GIS has improved its ability in recent years to visualize and analyze three-dimensional (3D) and four-dimensional (4D) spatial relationships and problems. Many of the recent ArcGIS data models in turn have focused on questions related to these multidimensional datasets. This has resulted in different approaches to finding the best way to store, query, and display these data types in a GIS. While the work is oriented toward research and development, the results and findings are extending the limits of using GIS and contributing to choices in software development. While the issues of vertical representation, volumetrics, and temporal query and analysis are important to the marine user community, this interest transcends to other industries and disciplines, including atmospheric, groundwater, geology, archaeology, and petroleum. Collaboration with industry and academia in these areas has provided useful insights regarding new ways to approach the many challenges of implementing GIS using multidimensional datasets. This chapter reviews some of these insights, poses some solutions as they relate to Arc Marine, and discusses similarities and possible linkages to the Climate and Weather, and Groundwater data models.

Introduction

Advances in remote sensing technology during the past 20 years have enabled marine scientists and resource managers to apply high-resolution acoustic and optical imaging techniques spanning the range of mapping scales from kilometers to centimeters. A critical requirement in the success of these efforts is the generation and study of multidimensional datasets. In this chapter, the term "multidimensional" refers to the combined use of the first two dimensions of longitude (x) and latitude (y), with a third dimension of elevation or depth (z, or -z), a fourth dimension of time (t), and a fifth dimension, consisting of measurements from an instrument in the field or the iterative results of models that may go forward or backward in time. Multidimensionality is also discussed at length in chapter 7, which describes Arc Marine's representation of multidimensional data for finite element numerical modeling. Chapter 5 looks at the multidimensionality of a point and the application of multiple variables being recorded at multiple depths for a given location. This is furthered with the additional dimension of values recorded over time. Multidimensionality is a focus in the marine context because it is critical for mapping, monitoring, and understanding currents, tides, shorelines, ice movements, El Niño/La Niña effects, biotic distributions and their associated habitats, navigational obstacles that appear and disappear, and many more. Simulation and continual updating of marine parameters based on location have become important in predicting these changes over time. Space does not permit a full review of the recent progress made in dealing with problems of multidimensionality for the marine environment, but the reader is referred to the suggested reading list at the end of the chapter.

The industry-specific ArcGIS data models have much in common in structuring tabular data, features (points, lines, and polygons), and rasters in ways that intuitively represent multidimensional phenomena in the real world. Common data structures for representing elevation or depth include digital elevation models (DEMs), bathymetric grids, triangulated irregular networks (TINs and terrains), or combinations thereof (figure 8.1). Also common is the use of interpolation methods such as kriging or inverse distance weighting

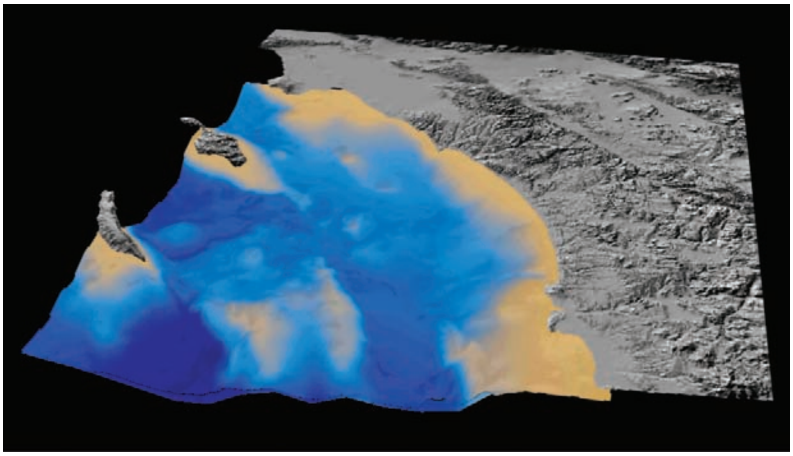

Figure 8.1 A digital elevation model (DEM) represents the land layer and has been integrated with a seafloor layer, which was created from the interpolation of scattered underwater soundings.

Courtesy of National Ocean Service Hydrographic Surveys, U.S. Geological Survey Coastal and Marine Geology Team, and the State of California.

(IDW). These methods provide what has been called a two-and-a-half dimensional surface (figure 8.1), because elevation or depth are treated as an attribute of a 2D point or line rather than as an independent variable that is part of the locational coordinate of the object. This potential limitation is an area of important research in geographic information science (e.g., Buckley et al. 2004; Hobona et al. 2006; Raper 2000) and in related areas of applied oceanography (e.g., Fonseca et al. 2002; Mayer 2006).

Thinking creatively, we can use GIS to implement multidimensional display, query, and analysis as never before. We often start with a set of 3D points and some research questions. For instance, an oceanographer may ask, “Where does the temperature in the water column drop to below 20°C?” A marine geophysicist may consider the question, “Where is the next most likely place to encounter oil within a certain subsurface stratigraphy?” A physical oceanographer may want to trace the extent of a hydrothermal plume near the seafloor or a nutrient layer higher in the water column. A fisheries manager may ask, “What seasonal abiotic conditions in the water column relate most to the density of a target species?” To answer these questions, advanced users may desire the ability to create “cubes” of data, slice through them in any direction, perform volumetric analysis based on any variable, and calculate new variables such as mixed-layer depth, geostrophic velocity, or dynamic height (e.g., Vance et al. 2006). Others may want to work with stacks of rasters while also capturing, querying, and displaying meaningful data between the layers. Users may also need to interpolate in the z-direction between these layers. To accomplish these tasks and analyses, users often need new tools to complement the data model. In turn, a data model design that has already considered aspects of multidimensionality (such as how additional dimension values will be assigned and how they will be used in different applications), allows developers to code proper functions into the complementary tools, or users to take better advantage of existing tools. While some tools build on the additional dimension as it exists in the feature’s attribute table, others use the dimension as it is stored in the value of the shape or geometry of the feature (meaning the features added to the data model will need to be “Z-aware” or “M-aware,” where M is a linear measurement of GIS geometry). Data preparation, including its constructs, naming conventions for storage, and elements for eventual visualization and display, is an important consideration in tool design. As we try to further define space in more dimensions for a more precise representation of natural phenomena, the interpolation of a z (between the layers) of a volume still has limitations similar to those of interpolating planar surfaces, either physical or statistical.

3D interpolator tool

As an example of a tool conceived in tandem with data model development, this section describes the 3D interpolator tool, which was created as a prototype to facilitate analyses with the ArcGIS Groundwater data model and Arc Marine, and may be used with other data models routinely dealing with multidimensional data. The tool is freely available on the companion Web sites for this book. A test case for Arc Marine was created using 3D points generated from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) database. This database is hosted online (http://www.calcofi.org/data/data.html) and represents a longstanding partnership of the California Department of Fish and Game, Scripps Institution of Oceanography, and the NOAA Fisheries Service. The following section presents an example of how the interpolator can be used to solve a problem related to temperature values in the water column.

The CalCOFI database previously mentioned was spatially enabled by creating 3D InstantaneousPoints from the sensor values. Using this point feature class as the primary analysis layer with the 3D interpolator tool, one can begin to make some generalizations about temperature values in the water column where no data exists. The 3D points as shown in figure 8.2 are symbolized based on their temperature properties. Other water column properties measured by the various instruments and stored as attributes include chlorophyll, dissolved oxygen, salinity, depth, and pressure. The case study selected temperature as the variable, or field of values, to interpolate in the 3D environment. The main question to answer is "Where are 8°C temperature values historically found in the water column?"

One of the major problems with using a 3D interpolation engine is searching for the neighboring points before applying the 3D interpolation algorithm. An approach that can help speed up the search of neighboring points is to perform a 3D tessellation and create relationships between neighboring points for interpolation. Voronoï tessellation is an algorithm that divides space based on the influence zone of each point in space and is a good method to work within the interpolation of multidimensional datasets (e.g., Gold 1991, 2000; Pilouk 1996). In 2D, Voronoï neighbors form a triangulation network, while in 3D they form a tetrahedral network. Both networks are the simplest geometric primitives in 2D and 3D, respectively (figure 8.3).

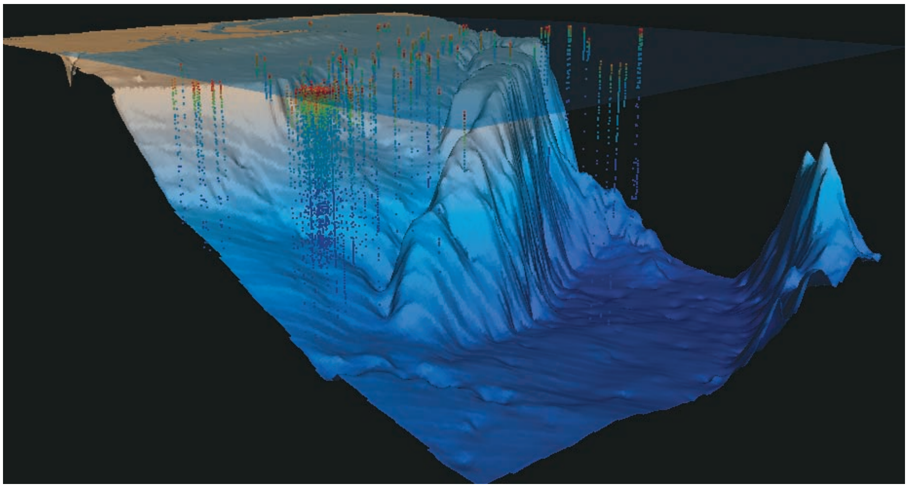

Figure 8.2 The seafloor and sea surface off the coast of San Diego, with CalCOFI water bottle data, where vertical casts are colored in reds, yellows, and greens for warmer near-surface temperatures, and in shades of blue for colder, deep-water temperatures.

Courtesy of NOAA and the California Cooperative Oceanic Fisheries Investigation CalCOFI.

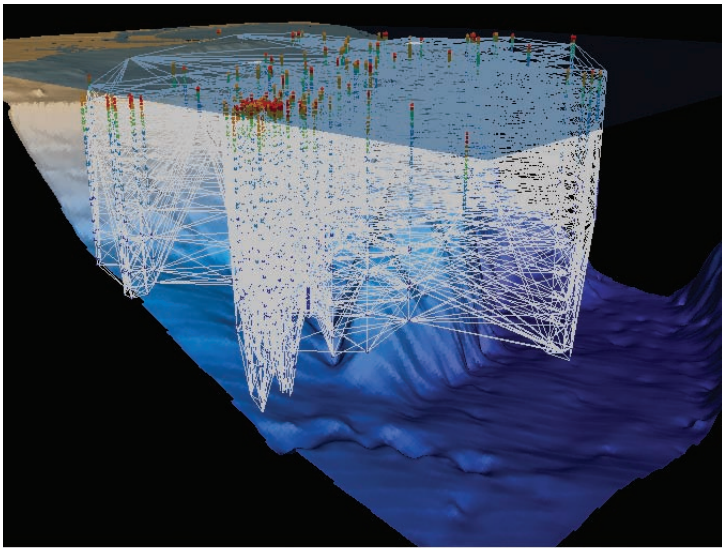

Figure 8.3 To better understand characteristics of the volume of the water column, the interpolation of known discrete point values is spanned in rays that store the interpolation results. The new values created are stored in this network of lines called a tetrahedral network. Similar to the TIN (triangulated irregular network), this model maximizes on the geometric merit of the triangle for interpreting the values of angles, known and unknown. Unlike the TIN, however, the tetrahedral network searches a neighborhood that includes multiple z-values, and so it can be used to generate true 3D objects.

Courtesy of NOAA and the California Cooperative Oceanic Fisheries Investigation CalCOFI.

The 3D interpolation engine performs a fast 3D Voronoï tessellation using a raster approach, as described in Pilouk (1996). A Delauney tetrahedral network (TetNet) is formed to maintain relationships between neighboring points in 3D space to cut down time for searching for neighboring points. The TetNet facilitates quick interpolation into a 3D point set, a volume stack (3D rasters or voxels), and isosurfaces (figure 8.4). The tool currently uses only a linear interpolation algorithm for the sake of simplicity.

Triangles and tetrahedrals can be used as primary geometric structures for interpolation to create a continuous (or prediction) surface from sampled point values. Each vertex of these geometric shapes carries coordinates of the known measurement locations and values. If a point location has no measurement value within the interpolation unit, this tool will allow users to calculate the new attribute value in the same vicinity as the measurements. When users select the attribute values (as in this case with temperature) the tool can calculate the location associated with the given value and create isolines and isosurfaces (figure 8.5). This tool can work with point features stored in many of the data models, including Arc Marine. InstantaneousPoints are an example of a point type in Arc Marine that may store a z or depth value, as well as a biological or chemical parameter to be interpolated using this tool. However, oceanographic data is often sparse in one or two dimensions

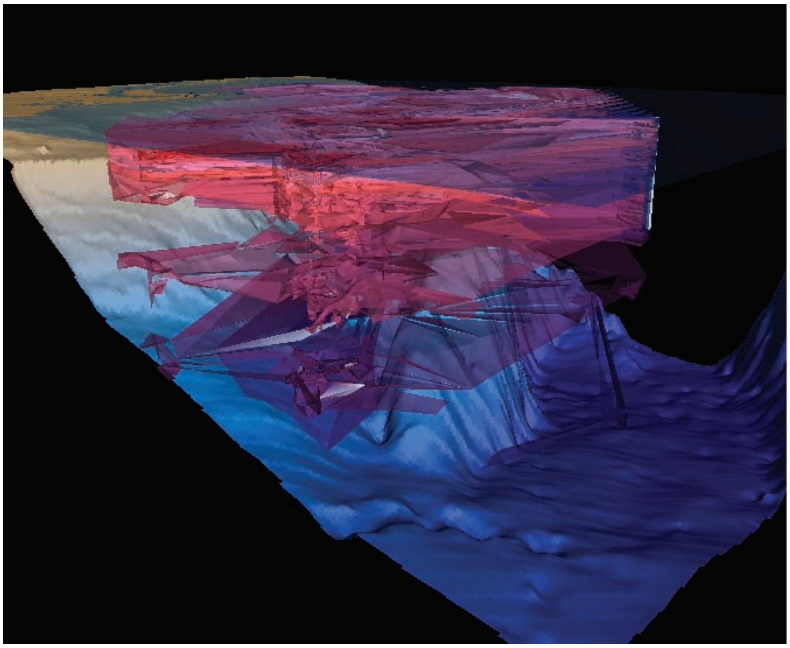

Figure 8.4 These facets of temperature zoning are isosurfaces created with the values stored in the tetrahedral network (TetNet). Each surface represents points of constant value (in this case, temperature in 3 ranges) within the volume space. These facets are stored as a multipatch object in the geodatabase.

Courtesy of NOAA and the California Cooperative Oceanic Fisheries Investigation CalCOFI.

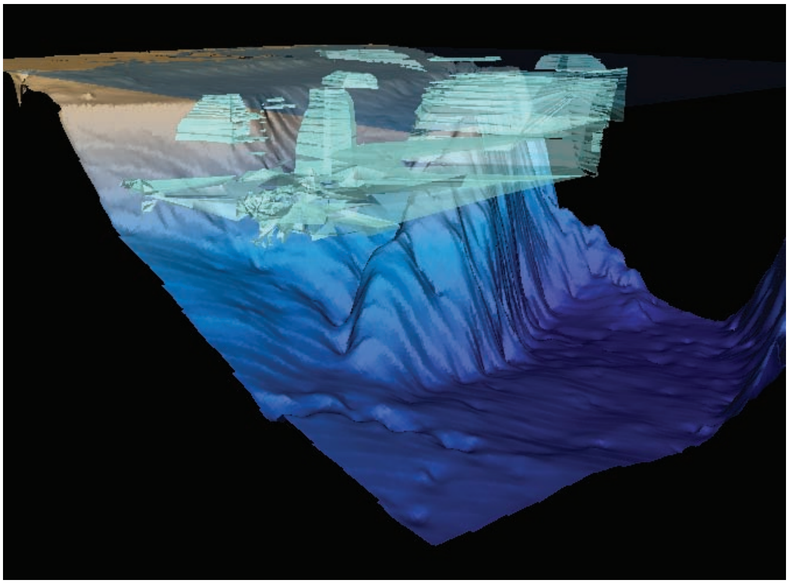

Figure 8.5 The resulting multipatch layer represents the cutoff of 8°C water in the water column. Some shark species like to feed in this range, and it is interesting to see the signature of upwellings that may correspond to underlying bathymetry.

Courtesy of NOAA and the California Cooperative Oceanic Fisheries Investigation CalCOFI.

compared to the third dimension (e.g., seafloor borehole data or vertical casts for salinity/temperature/density, where sampling is frequent in the vertical direction but sparse in the horizontal; Wright and Goodchild 1997). This longstanding issue continues to be a challenge for 3D interpolation algorithms.

NetCDF data

As mentioned earlier, the preparation and formatting of the data and its constructs for storage are important considerations in designing a data model and any accompanying tools. For marine applications, network Common Data Form (netCDF) is an important network developed by the University Corporation for Atmospheric Research (UCAR) as a machine-independent, binary format for exchanging scientific data, particularly for applications in climatology and meteorology. This format often is used to store data as an array, but netCDF is also a series of software libraries and input/output routines that facilitate data storage and documentation. The netCDF format is essentially multidimensional, so the goal is to effectively display and manipulate the variables in the array from within the GIS software itself. Examples of oceanographic data commonly stored in netCDF include sea surface temperature, current speed and direction, wave height, and wind speed. A variation on netCDF is also used as a common format for multibeam bathymetric and backscatter grids that represent the seafloor. Generic Mapping Tools (GMT; http://gmt.soest.hawaii.edu/) and MB-System (http://www.mbari.org/data/mbsystem/) are two of the most commonly used software packages worldwide for the processing, display, and cartographic output of these datasets. Both rely on netCDF libraries and produce output in a netCDF-style format, although the resulting grids do not have the netCDF climate and forecast (CF) metadata convention.

The CF convention is one of many netCDF conventions that provide a description of what each variable in a dataset represents spatially and temporally. The CF convention defines the overall metadata of a grid (e.g., see Unidata's descriptions at http://www.unidata.ucar.edu/software/netcdf/conventions.html). The Cooperative Ocean/Atmosphere Research Data Service (COARDS) convention was introduced in 1995, and CF was introduced in 2003 in order to extend and generalize COARDS. This makes it possible for a wide range of users to recognize and understand the array of numeric values that follow the header in a netCDF file. ArcGIS can display the datasets as a table, a set of points, and a raster, and resulting arrays can be animated based on a user-selected time frame. When the raster view is created from a netCDF file, the dataset remains in its native format and is rendered only for display—new datasets are not created. This is especially useful for physical oceanographic, bio-optical, or air-sea interaction applications, because much of the data derived from satellites or shipboard observations may be stored and shared in this original format. This extends the existing functionality to support time and multidimensional data.

The oceanographic and atmospheric communities have faced the longstanding challenge of using multidimensional array data in a GIS. With the addition of netCDF tools for ArcGIS, it is now much easier to display and analyze multidimensional marine data. The tools enable the direct read and write of netCDF (CF) directly into ArcGIS as input, or within a geoprocessing model to represent oceanographic processes such as tsunami wave propagation or air-sea interactions during a hurricane. In addition, netCDF is one format used for numerical modeling or simulation modeling that can be looped to represent patterns of parameters such as global temperature warming or seasonal rainfall (figure 8.6).

The animation tools can be used together to control the rendered output to display the results over a time span, based on specific user-defined variables. For example, a netCDF file may store sea surface temperature (SST) in an array of numeric values, where each grid cell holds one value of temperature. The same SST grid may look like figure 8.7 when viewed as a raster in ArcGlobe.

The animation of a netCDF layer is a way to capture the multidimensionality of datasets collected by satellites or ships (static or real-time). When bringing netCDF files into ArcGIS, one is essentially viewing a slice of the data, but the capability of viewing data in a 3D volume is most desirable, underscoring the importance of new tools such as the 3D interpolator. Viewing these slices or volumes together with socioeconomic datasets may inspire new ideas for analyses using many different data models. ArcGIS has improved the

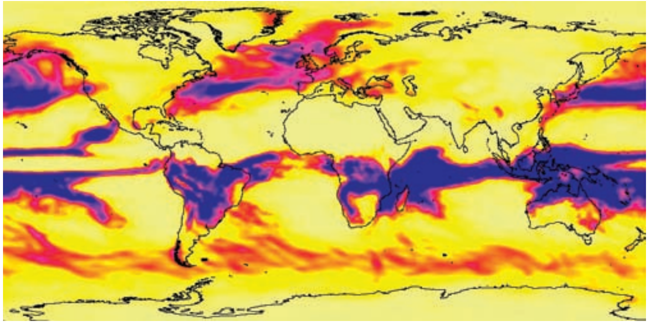

Figure 8.6 Display tools in ArcGIS can animate 10 years worth of rainfall data to show areas of heavy precipitation over a time span. Variables also can be isolated within that time span, such as "months of May rainfall." This type of dataset, similar to the "time duration" feature classes in Arc Marine, can be useful in monitoring change or in predictive models.

Courtesy of CCSM.

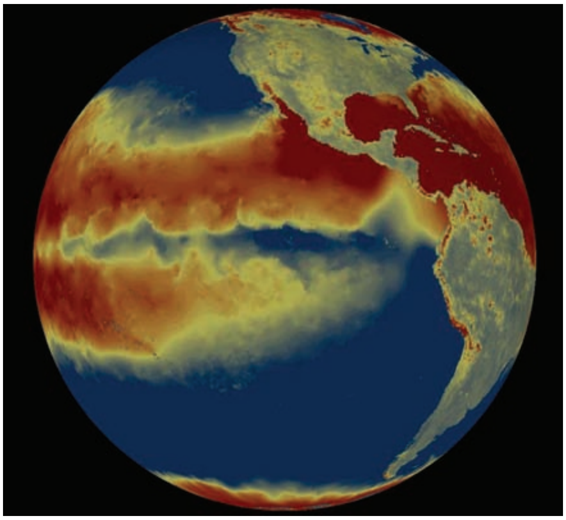

Figure 8.7 A collection of animated raster images represents changes in sea surface temperature (SST) during the 1997-1998, El Niño. During an El Niño-Southern Oscillation, Pacific trade winds and atmospheric pressure cells reverse, resulting in an eastward transport of anomalous warm water across the tropical Pacific (shown by the warm colors).

Courtesy of the NASA Physical Oceonography Distributed Active Archive Center (PO DAAC).

quality and control of animation sequences and the handling and rendering of dynamic content in applications such as ArcGlobe and related server-based viewers. On the horizon are the retrieval, storage, query, and serving of these datasets over the Internet.

Similarities to other ArcGIS data models

Collaboration with other industry and academic leads in ArcGIS model design efforts has provided useful insights regarding new ways to approach the many challenges that we face when implementing GIS using multidimensional datasets (Buckley et al. 2006).

3D objects in the Groundwater data model

The Groundwater data model focuses on multidimensional representation of groundwater in ArcGIS, normally including subsurface stratigraphy of sediment and rock layers, aquifers, geologic cross sections, and volumes. The model builds on the existing functionality of Arc Hydro for surface water (Maidment 2002), future development initiatives, and collaborations with other organizations. It enables the integration of surface water and groundwater data, while supporting the representation of site-specific groundwater data, regional groundwater systems, and the integration of groundwater simulation models with GIS (Strassberg 2005). Four of the primary features of the model are 3D points, 3D lines, vertical cross sections, and volumes (figure 8.8).

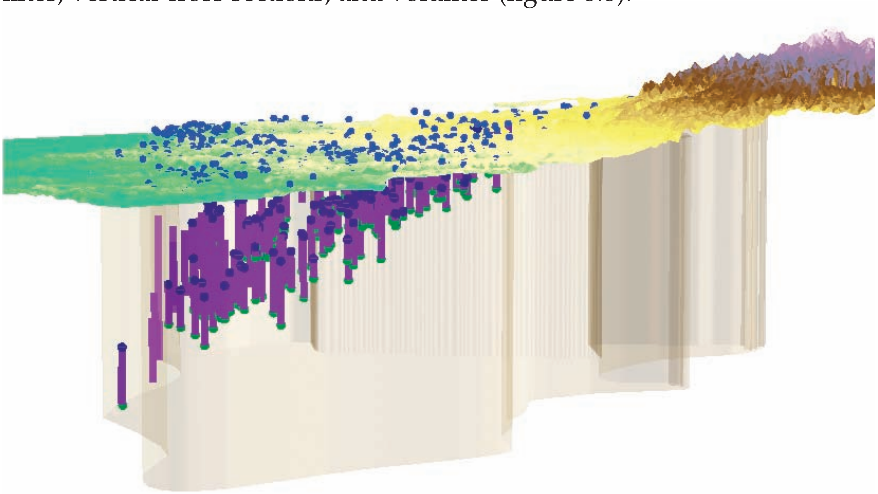

Figure 8.8 Some of the features in the Groundwater data model show the relationship between wells (blue points), bore points (purple and green points), and bore lines (vertical lines) representing rock stratigraphy or hydrostratigraphy.

Figure used by permission, G. Strassberg, University of Texas.

As with Arc Marine, the source dataset is most often a set of 3D points that store measurement values. In the case of the Groundwater data model, these are collected from boreholes and wells. Other features for Groundwater, such as stream depths or riverbeds, can be represented by soundings similar to the single or multibeam echosoundings used to capture depth information for the seafloor. The GIS stores these values as Z-aware points, also called PointZ. The use of 3D lines (PolylineZ) also represents the vertical classifications for the lithology of the well and can define subsurface units such as aquifers. Three-dimensional polygons make cross sections that connect the top and bottom of the 3D points, while the database can store the values of more complex geometry as a multipatch feature class. In ArcGIS, a multipatch is a type of geometry composed of 3D rings and triangles and may be used to represent geometric objects that occupy a 3D area or volume (such as spheres and cubes), or real-world objects such as buildings and trees (http://support.esri.com/knowledgebase/). The multipatch describes and stores volume objects in the Groundwater data model. The volume of this shape can be calculated and assigned as an attribute or label to the object. The aforementioned 3D interpolator tool can also be used to fill regions between horizontal stacks of points or lines. This brief overview is meant to show some of the touch points between the Groundwater data model and Arc Marine. For more information related specifically to Groundwater, please see Maidment (2002), Strassberg (2005) and the Groundwater link at http://support.esri.com/datamodels.

The Climate and Weather data model: Another approach to multidimensionality

The input of weather and climate data, using varying methods for measuring and storing time, has been a common interest between many data models, including Climate and Weather, Hydro, Groundwater, Agriculture, Transportation, and Biodiversity/Conservation. Remotely sensed data often includes land and sea surface parameters, biological distributions, atmospheric conditions at the earth's surface, and layers of information representing the air-sea or land-sea interface (figure 8.9). Satellite sensor readings that are collected in

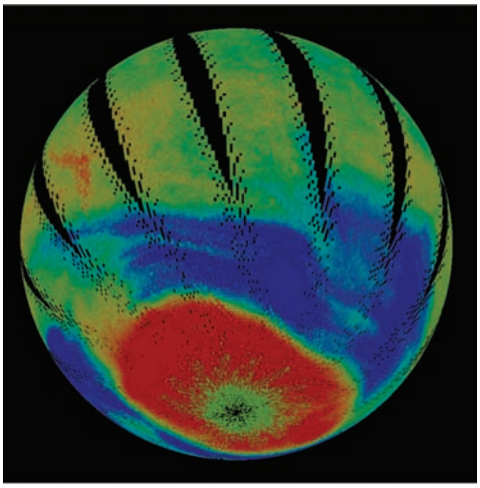

Figure 8.9 Global satellite ozone data with time attributes can be viewed and analyzed, such as this example from ArcGlobe, showing a significant hole in the ozone layer over Antarctica. The challenge is combining this data to effectively represent change over time.

Courtesy of the NASA Physical Oceanography Distributed Active Archive Center (PO DAAC).

swaths, or belts, of data can also be used to derive parameters just beneath the surface of the ocean. The way these variables are represented in the source dataset and stored in the data model can influence how the application tools work with them.

The application of GIS in climate change research aims to work with the integration of global climate model outputs, with many types of socioeconomic data from various sources (e.g., see the National Center for Atmospheric Research's GIS climate change scenarios at http://www.gis.ucar.edu). For the Climate and Weather data model, the values associated with time are an essential consideration in data analysis, query, display, and visualization. One way to accommodate this is to use the personal or enterprise geodatabase to store a time-stamp or time-series table that can associate point, line, or polygon features to a relationship class. The relationship connects the feature to the table storing the time attributes. Ultimately, new tools provided direct read of netCDF data to support spatiotemporal queries and analyses of the dynamic characteristics of satellite data formats. For more information on the Climate and Weather data model, please see the Atmospheric link at http://support.esri.com/datamodels and the Web site of the Atmospheric Special Interest Group at http:/www.gis.ucar.edu/sig/.

Conclusion

This chapter has touched on practical issues of multidimensional representation.

Marine geographical data and patterns will almost always be complex, constantly changing with time, spatial resolution, and even sampling strategy. The emphasis has been on the computational and mechanical aspects of inputting, organizing, manipulating, and rendering this multidimensional data. This requires faster processing hardware, more sophisticated computer graphics, and oftentimes computer animation. These essentially fall in the realm of data visualization (geovisualization), primarily as a method of computing. However, MacEachren (1995) regards visualization primarily as an act of cognition, allowing scientists to "develop mental representations to identify patterns and to create or impose order." Thomas and Cook (2005) echo the emphasis on cognition. They recognize that, aside from being a set of tools, visualization can assist in human information processing, which aims to generate new insights and potential solutions to the problems being addressed. As mentioned earlier, esoteric research and development in the computing and cognitive aspects of multidimensional data handling and visualization will be ongoing in the academic, government, and private sectors. These issues are deemed important enough to warrant the attention and support of several federal agencies and of large research cooperatives such as the University Consortium for Geographic Information Science (UCGIS), the International Cartographic Association Commission on Geovisualization and Virtual Environments, and the San Diego Supercomputer Center's Geosciences Network (GEON). However, the most immediate impact likely will be felt in the data models and associated tools placed in the hands of average users. These approaches and tools need not be limited to one data model in a single application area. Readers are encouraged to leverage the ideas, tools, and Web sites described in this chapter as they use Arc Marine and to stay abreast of related developments as the integration of multidimensional data into GIS continues to challenge related data models.

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