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CARTOGRAPHIC VISUALIZATION OF FOUR-DIMENSIONAL DATA

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Richard Groop
Major professor

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CARTOGRAPHIC VISUALIZATION OF FOUR-DIMENSIONAL DATA

By

Lauren Elizabeth Anderson

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ABSTRACT

CARTOGRAPHIC VISUALIZATION OF FOUR-DIMENSIONAL DATA

By

Lauren Elizabeth Anderson

Mapping time has challenged cartographers for centuries, and traditional solutions have forced the map user to mentally interpolate the temporal dimension. The development of cartographic animation techniques will allow time to be included in the visualization of complex geographic data. Since 1959, researchers have examined the power of bringing data on a two-dimensional plane to life. This research examines and evaluates various cartographic representations of three-dimensional data changing over time. Scientific visualization techniques which have been proven successful in numerous other fields were applied to a four-dimensional geographic data set. Animations of three-dimensional ocean temperature data were developed using desktop and workstation technology to show the seasonal fluctuation of the mackerel habitat along the Northeast U.S. Continental Shelf in the Atlantic Ocean. The results achieved show that not only is it possible to effectively display four dimensions of geographic data simultaneously, but also that this new mapping technique is a valuable research tool for exploratory data analysis.

ACKNOWLEDGMENTS

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PREFACE

This work is accompanied by a CD-ROM which contains the animations that were designed for the project. It also contains several examples of other animations, which should enhance an understanding of the history of cartographic animation. Animations can be viewed on the Apple Macintosh or on a PC running Windows using software that is contained on the CD-ROM. These animations were designed on a 16 inch color monitor with 256 colors, and are best viewed in this environment. Several figures in the text depict a single frame from an animation technique, and the corresponding animation is referred to by that figure number. In cases where one figure is representative of several movies, these animations are labeled with the figure number followed by a letter. A list of figures and their corresponding animations, if any, has been included. I hope this will eliminate any confusion.

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CHAPTER 1
INTRODUCTION AND BACKGROUND

> **... not only is a picture worth a thousand words but the interpretation of phenomena geographically depends upon visualization by means of maps.**
>
> **– Allen Philbrick, 1953**

Geographic phenomena are multivariate in nature and change across time as well as space. The ultimate goal of geographic visualization is to represent spatio-temporal data in a way that conforms to human conceptualizations of the world (Peuquet, 1994). This is why maps are crucial to geographic research. By way of a map, the researcher is better able to interact with the geographic data set. Since temporal change is an important aspect of many geographic problems, it is essential to understand not only how the map represents the physical world, but also how time display is incorporated in cartography.

Reducing the complex three-dimensional relationships which occur in nature to the two-dimensional surface of paper or the computer monitor causes distortion and information is lost. When the map user creates a mental picture, reconstructing the three-dimensional world from the two-dimensional map in order to detect patterns and underlying processes, there is much room for misinterpretation of the data. Removing this step of mental visualization allows greater attention to be focused on analysis and synthesis of the data, and this is now possible with the use of computers. Highly sophisticated visualizations of geographic data can be generated which bring the data closer to its natural form by simulating three dimensions. This can provide a level of understanding not always achievable using simpler methods such as static two dimensional maps (Robertson and Abel, 1993).

After the difficulty of spatial visualization has been removed, there is still the question of how to display time. Time and space are inseparable qualities of phenomena, and one cannot be mapped without the other (Wood, 1992). Whether the phenomena being mapped occurs at one instant in time or is a process evolving over time, there is no way to remove time from the map. For dynamic processes, static maps and series of static maps have been used to depict change and movement in geographic data. But it is often difficult to visualize the movement of such complex spatial data sets. Symbology depicting change and movement leave a considerable amount of mental interpretation and interpolation to the map user, especially when the in-between moments not depicted by the maps are of importance. It is clear that there is room for error in this process and there is no way for the cartographer to control for this error, since each map user has the capacity for an infinite number of visualizations of what occurs at in-between moments in slices of time.

As the sheer volume of geographic data continues to increase, it is becoming more important to develop new methods for manipulating and analyzing this data. The complexity of spatio-temporal data demands special tools to visualize multidimensional changes which occur over time. Improved access to temporal maps could lead to an improved understanding of geographic processes (Langran, 1992). While traditional methods fall short of providing researchers with the cartographic output necessary to effectively analyze spatio-temporal data, there is great potential for cartographic animation to fill this void. Animated maps can show how an area has changed over time or how well a process interacts with the area in which it occurs. Because the map user does not have to make leaps through temporal space from one moment to the next, animation allows change over time to be graphically represented in a more powerful manner than static time series maps. The introduction of real and near real-time modeling has numerous implications in examining geographic processes.

Visualization

Real world phenomena occur in three dimensional space and change over time. Given that this is the inherent nature of geographic data sets, the ability to easily and effectively detect patterns and study process when they have been reduced to a two-dimensional surface is diminished. While it is impossible to recreate geographic phenomena without some level of generalization, it is important that the map maintains the integrity of the environment so that the map user is able to visualize the data with the minimum amount of error.

Visualization is the process of creating an image from numerical or graphical data. The image can be strictly mental or it can take a concrete form, an event which can only occur once a mental picture has been formed. Visualization is not a new concept: for centuries, researchers in all fields have sought a better understanding of data by means of graphs, charts and diagrams. By portraying numerical data in a graphic form, researchers have been able to see the functionality of their data sets more clearly. The term *visualization* (or *scientific visualization*), however, has recently been used to describe the phenomena of using computers to generate images from a data set. The best definition comes from Wolff and Yaeger (1993), who maintain that "[s]cientific visualization was invented as the process whereby humans use software to do the work of converting number to image that nature does by physical processes." By using computers to represent numbers as images, the brain is freed from this responsibility, and researchers can direct their attention to comprehending complex data structures. As the quantity and complexity of available data increases, the role of the computer in pattern identification in all areas of research will become increasingly important.

While no one disagrees that scientific visualization is an important research tool, there is some disagreement as to the role the tool should play in research. Larry L. Smarr, Director of the National Center for Supercomputing Applications (University of Illinois at Urbana - Champaign), believes that not only is this a powerful tool for scientists in making discoveries, but that it is also a tool for communicating results to colleagues and to the public. The power of visualization for presenting results is that the human visual system can more easily comprehend an image than it can the underlying mathematics which drive the world (Wolff and Yaeger, 1993).

Weber (1993) sees visualization as a way to alleviate information overload. He points out that patterns in the data can be identified and analyzed more easily using visualization because over half the neurons in the brain are dedicated to visual processing. Weber's discussion focuses on applications of the technology in terms of the researcher, and stresses that visualization is not about graphics but about understanding data.

Like Smarr, others concerned with visualization (DiBiase, 1990; Taylor, 1991) place communication as an important result of the visualization process. Early work by MacEachren et. al. (1992) agreed that presentation of results was part of visualization. Since then his definition has evolved and MacEachren (1994) differentiates between visualization and communication. His work defines visualization as one end of a continuum which cuts through the space of map use, where communication is at the opposite extreme. His view looks at visualization in terms of two broad types of map use - maps used in searching for unknowns and maps presenting knowns. The line between visualization and communication obviously is not hard and fast, because communication is a part of every map, but MacEachren does believe the two are independent pursuits.

Despite these differences, it is agreed that the main objective of scientific visualization is "to develop techniques that make perceptible the most important informational aspects of the data set" (Wolff and Yaeger, 1993). Visualization can be used as a presentation tool as well as a research tool. In the end, how the resulting product is used, be it for scientific inquiry or communicating results, is not the important issue. Rather, what is important is that scientific visualization allows the researcher to recreate reality for the purpose of better understanding a given data set.

There are a variety of components which together comprise a scientific visualization system. The effectiveness of the visualization will depend on how various parameters are manipulated to best suit the data set. Among the elements which can be used to represent data are traditional graphic methods such as color, texture, and three-dimensional graphic rendering; extending these options to a multimedia environment brings the addition of sound, interaction and animation to the data set (Weber, 1993). Animation in scientific visualization allows three dimensions of spatial data to change over time, so the researcher is able to investigate the four dimensions of a complex dynamic data set (four-dimensional data) simultaneously. When all this is happening in an interactive environment where the user is able to rotate the image and view it from another perspective, change the illumination on the image, get a two-dimensional slice of a three-dimensional object, or control the pace of the animation, patterns which may have otherwise gone unnoticed can be identified and analyzed.

With an estimated 50 percent of the brain's neurons associated with vision, it is not difficult to understand why visual mapping is recognized as one of the most powerful analytical tools (Wood, 1994; MacEachren, 1994; Wolff and Yaeger, 1993). As in numerous other fields, the introduction of scientific visualization has given geographers a powerful new tool with which to explore data. Traditionally the fundamental method for visualizing geographic data was through mapping (MacEachren, 1994). Yet mapping extends beyond geographic research and is essential to many sciences. Researchers have successfully used scientific visualization to map three-dimensional models of neuron activity in the brain, DNA particles, chemicals dispersion, wave functions for orbit molecules, airflow dynamics and ozone depletion, and proven that mapping is not limited to the 2-D surface (Hall, 1993).

Cartographic Representation of Time

The study of geographic data through maps has traditionally been restricted to one instance in time. For geographers, the challenge has been the reduction of the "four-dimensional reality of time and three-space into little marks on paper" (Tufte, 1990 p. 119). This generalization of the world results in enormous simplification and the tremendous loss of information. Stripping the world down to a two-dimensional surface, visualization of geographic trends becomes increasingly arduous for the map user.

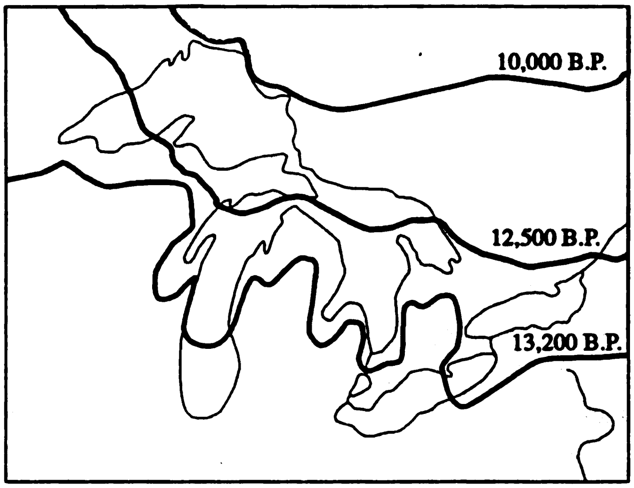


Figure 1. Time map of the Southern Margin of the Laurentide Ice Sheet.

Spatio-temporal data is traditionally displayed using one of two strategies: single static maps or time series "chess maps". A single static map depicts limited aspects of change in or across space by showing change over time in a particular place or place-to-place movement over time (Figure 1). The second type, what Monmonier (1990) refers to as "chess maps", show how a phenomena evolves over time by presenting several snapshots, each for a discrete moment in time, juxtaposed so that the map user can compare spatial positions across time. Figure 2 is am example developed by the National Marine Fisheries Service (NMFS) in Woods Hole, MA. to display ocean temperature data (see also Appendix D). The problem with these types of maps, however, is that they represent states but not the events that change from one state to the next, leaving the burden of dealing with temporal processes to the map user. (Langran and Chrisman, 1988)

It was not until the introduction and widespread use of Geographic Information Systems (GIS) and the subsequent necessity for depicting cartographic time that

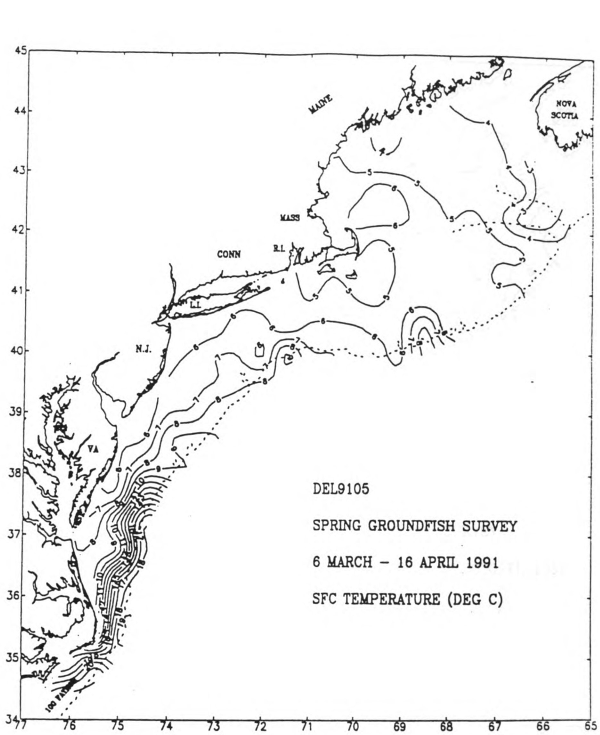


Figure 2a. Ocean surface temperature on Northeast U.S. Continental Shelf (Spring 1991). Reprinted from Holzwarth-Davis and Taylor, 1992.

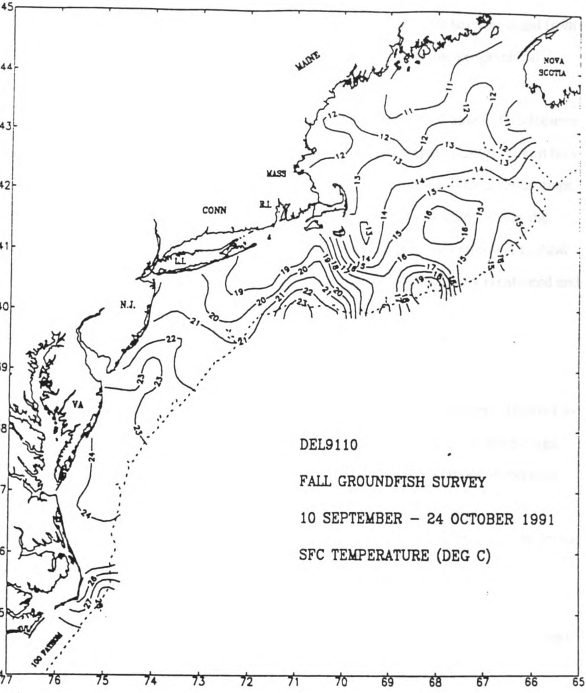


Figure 2b. Ocean surface temperature on Northeast U.S. Continental Shelf (Fall 1991). Reprinted from Holzwarth-Davis and Taylor, 1992.

traditional display methods were challenged. The importance of displaying the resulting maps and statistics from GIS analysis is a natural outgrowth of the technology since the fundamental function of GIS is the analysis of processes which change over time (Koussoulakou and Kraak, 1992). However, as volumes of literature have emerged from the GIS community citing the importance of time as an element of the geographical database, a notable omission has been temporal display methods.

Currently, the most comprehensive work on the dimension of time in GIS focuses on the conceptual and structural problems of representing geographic change, not on how it is displayed (Langran 1992). Langran deemed single static maps and time series maps insufficient for depicting the most important component of time - change. While she does note that in addition to static maps, animation techniques can be employed to show change over *both* time and space, this alternative display method is merely mentioned and is not evaluated.

Animation in Geography

Animation is an effective solution for dealing with temporal data sets. In order to process, investigate, and understand complex data, simple representation is not enough. With the use of computers, the process of mentally visualizing the temporal dimension from a numerical data set is replaced by a graphic rendering of these numbers. As technology has advanced to this point, the map has evolved from a communication device to a powerful visualization tool (MacEachren and Ganter, 1990). Geographic visualization has redefined the map as a research tool whose goal is "to stimulate scientific insight by facilitating the discovery of patterns and relationships in spatial data" (MacEachren and Ganter, 1990). To better understand the merger of scientific visualization with geography, it is important to understand the history of the animated map.

Norman J. W. Thrower (1959, 1961) gave the geographic community its first glimpse of the potential use of animation as an alternative form of cartographic representation. Thrower realized the potential impact animation could have in the field of geography; time could be incorporated and geographic processes could be portrayed as dynamic entities. By using the same techniques as cinematographers, a film could be generated from hand drawn cels which held images in a state of suspended animation. Although animation offered cartographers a new tool for representing the temporal aspects of geographic data sets, the cinematic production skills necessary to create such a map prevented the process from being embraced. From what appeared to be a huge breakthrough in data representation techniques, relatively little research followed. Nine years passed before another article on animation was published in a geographic journal, and had it not been for the availability of computers, the duration may have been longer.

Pioneering work by Cornwell and Robinson (1966) proposed using the computer to generate cartographic animations by using the CRT (cathode ray tube) as the drawing board and exposing the film directly from the monitor. The problem with this method is not the technology, rather the lack of software which will produce the desired images. The authors saw computer generated film as the solution to the problems of animated cartography and provide researchers with a tool which would ease the visualization of data changing over time. Widespread use of computer animation did not emanate from this article.

Tobler's (1970) research on urban growth in Detroit resulted in the first computer generated animated map sequence. This crude isosurface animation was the first attempt at showing a three-dimensional surface changing over time. A simulated statistical surface showing population growth mutated with the passage of time but lacked any spatial or quantitative references, and ultimately was unable to convey more than very general information. The next application was not until Moellering (1973) used computer animation to map traffic accidents on film as a movie. Different sized flashes were displayed on a street network and changed hourly over the course of a week, with larger flashes representing more serious accidents. From this animation it was possible to locate dangerous intersections and identify when the most accidents occurred.

In an article chronicling the 30 year history of animated cartography, Campbell and Egbert (1990) illustrate the advances that have come from these humble beginnings. Even as technology in the 1980's increased the power, speed and efficiency of both personal and super computers, the development of this tool progressed slowly. In the computer environment, the animated map could not only show change over time, but also gave researchers the ability to generate digital terrain models and explore surfaces from different vantage points under various illumination conditions. With the use of the computer, Moellering (1980a, 1980b) showed that a static surface can be modeled and dynamically explored in three-dimensions. By manipulating the image in a highly interactive real-time system, the animation allows the researcher to rotate an image and zoom in to inspect areas of interest. The more complex the surface, the more useful this approach could be. Moellering (1980b) saw the benefit of such a system as the additional capabilities which *could be developed* to incorporate the temporal dimension. However, these developments did not come to pass and the constraints of time and money made animation unaffordable, and interest in research on cartographic animation again faded.

It was not until 1990 that there was a renewed interest in cartographic animation. Computers were now commonplace in geography departments, and software development had reached the point where creating animated maps entirely on the computer was technically and economically feasible. No longer was it necessary for the cartographer to be well versed in computer programming or have to expend tremendous amounts of time and energy to produce an animation. Gersmehl (1990) gave geographers an invaluable research aid with his comprehensive discussion of animation techniques. This framework for determining which type of animation would be most appropriate for displaying a given spatio-temporal data set is based upon "the identification of design issues that are relevant to 'four-dimensional cartography' " (Gersmehl, 1990). This was the first time that the term *four-dimensional* was applied to cartography, and although his work did not specifically address the animation of a three-dimensional cartographic image, Gersmehl sought to establish a common vocabulary to facilitate discussion between cartographers and animators so that animated maps could effectively represent the four-dimensions researchers were investigating.

Since Gersmehl's (1990), a majority of the works being produced in cartographic research programs are focusing on improving dynamic displays on a two-dimensional surface. Adopting the traditional practice of abstracting the three-dimensional physical world to a two-dimensional surface, adding the temporal dimension sets time series maps in motion. This removes the burden of mentally generating the intermediate steps and setting the data in motion, allowing the brain to focus on uncovering patterns or looking for anomalies in the data. Animations of this type have been created to display a wide variety of geographic data. When MacEachren and DiBiase (1991) were asked to produce a series of maps depicting the spread of acquired immune deficiency syndrome (AIDS) in Pennsylvania, they realized that animation would be ideal for the intended application - to convey information about the spatial characteristics of the disease to the public. Recent projects include the use of animation of temperature contours for viewing the spatio-temporal deviations and trends in climatic change across the United States over the past century (Weber and Buttenfield, 1993); in maps depicting historic journeys and events for a CD-ROM encyclopedia (DiBiase, 1994); as part of a multimedia visual supplement to travel writing (Des Roches, 1994); and animated maps which are juxtaposed and linked to statistical graphs and text (Monmonier, 1992). These and other two-dimensional dynamic displays do shed light on many geographic problems, and allow researchers to more clearly and easily distinguish patterns. But by creating a visualization that is limited to a two-dimensional representation, geographers have not realized the full potential of this tool.

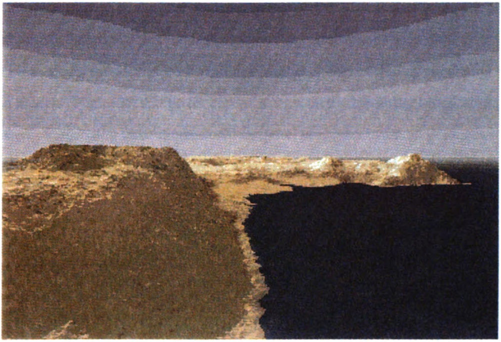


Figure 3. Terrain Model of Sleeping Bear Dunes National Lakeshore.

The use of three-dimensional visualization tools is invaluable when the right problem is being addressed (Dorling, 1992). Unfortunately, little research specific to geographic data sets has been done in this area. Moellering (1980a, 1980b) gave a glimpse of how three-dimensional animation could be used with his terrain model; but until the invention of scientific visualization software, such a product was too costly to produce in terms of time and money when the resulting graphics were so simple. Since then, three-dimensional modeling and animation has found its niche in numerous fields as a powerful visualization tool. Chemists, engineers, astronomers, film makers and medical researchers all have benefited from the increased accessibility of powerful workstations and the development of scientific visualization software (e.g. *AVS*) that now makes three-dimensional animation easy. Previously geographers interested in employing visualization techniques were forced to choose between generalizing a surface to two dimensions and creating a cost effective animation and having a more data intense animation which was costly to create. As workstation technology permeates geographic research, cartographic models will be less abstract and provide researchers with new procedures for examining spatio-temporal data sets. Researchers have used visualization software to model thunderstorms (Wolff and Yaeger, 1993) as well as generating realistic terrain models (Figure 3) that go far beyond the geometric rendering Moellering (1980a) produced. Visualizing three-dimensional temporal processes in an environment which allows the researcher to interact directly with the data should provide new insights into geographic problems.

The purpose of this research is to examine and evaluate various cartographic representations of spatio-temporal change in a complex data set. To do this, three-dimensional ocean temperature data will be animated to show the seasonal fluctuation of the mackerel habitat along the Northeast Continental Shelf in the Atlantic Ocean. Several different animation techniques representing various levels of technical sophistication will be developed and evaluated. The goal is to find difficulties, limitations, advantages, "costs", and other characteristics of the various techniques and to provide recommendations concerning their applications.

CHAPTER 2
METHODS FOR CREATING THE ANIMATIONS

This chapter describes the framework for the development of three-dimensional map animations. Temporal change is an important aspect of many geographic problems, but it is often difficult to visualize the movement of complex spatial data sets. McCormick and others (1987) found that "better visualization of a problem leads to a better understanding of the underlying science, and often an appreciation of something profoundly new and unexpected". With volumes of data collected daily in both the public and private sector, it often is difficult to understand how the pieces fall together. Researchers need a tool which allows data to be mapped in a way which fosters a search for questions rather than merely presenting results (MacEachren and Monmonier, 1992). Using scientific visualization techniques to explore both the spatial and temporal dimensions of a data set gives researchers an alternative to numbers. For geographers, this means reinventing the type of map used for exploratory data analysis of four-dimensional data sets.

Serious work has yet to be undertaken in terms of exploring alternative display methods for four-dimensional data sets. Technology has now reached the point where the researcher is no longer limited to creating "two and one half dimensional" displays where the height (or depth) is a frame upon which different feature can be draped. Volumes can now be rendered, restoring three-dimensionality to the data. Bivins and Palmer (1989) created "smart maps" of ocean resources, three-dimensional sea temperature maps with which the researcher could interact. Their project proposed adding the temporal dimension to study dynamic oceanographic phenomena through three-dimensional animation, but this never came to fruition.

General Design Considerations

Several animations of ocean temperature on the Northeast Continental Shelf in the Atlantic Ocean were developed to assess how well a complex four-dimensional data set can be graphically displayed. It is important to understand how ocean temperatures throughout the volume fluctuate during the year since fish habitats are defined, in part, by temperature zones. For example, the mackerel is a semi-pelagic / pelagic offshore migrant fish, which means that it will move up and down the water column following a temperature gradient. Mackerel are mostly found in water between 8^{o} - 20^{o} C, from the surface to approximately 100 fathoms (182.88 m), and breeding is most productive at 8^{o} C (Bigelow and Schroeder, 1953). Since the goal of this research is to examine geographic visualizations of data in a more 'natural' environment, the mackerel habitat is a good subject to animate because the data is inherently four-dimensional. If the animations are successful, the researcher will gain new insight into the data, and will do so without the burden of creating a series of mental images to recreate the three-dimensional world.

While there are an abundance of scientific visualization packages which run in the workstation environment [Application Visualization System (AVS) (Advanced Visual Systems), Advanced Visualizer, (Wavefront Technologies), IDL (Research Systems, Inc.), IBM Visualization Data Explorer (IBM), Khoros (The Khoros Group)], there are significantly fewer visualization software tools for the personal computer. More visualization software has been designed to run on the Apple Macintosh [IDL, Director (Macromedia), Transform and Dicer, (Spyglass, Inc.)] because it traditionally has been regarded as the superior graphics platform; but as the graphics quality of the PC has improved, many of these products [IDL, Director] are being made to run on either platform. Slocum (1994) gathered reviews from several researchers of various visualization packages and rated them according to documentation, ease of learning and use, and product support. The packages were not compared and contrasted so these results were unable to recommend one visualization package over another. However, the evaluation was helpful in deciding which package use for this research. Purchasing software was not an option since high end workstation visualization software costs thousands of dollars. AVS and Wavefront products were available at Michigan State University, and after examining of both, AVS was selected. Unlike several of the desktop packages, Dicer was specifically designed as a visualization tool and appeared to be the best option for developing animations of three-dimensional data.

Digital ocean temperature data was obtained electronically from the National Marine Fisheries Service (NMFS), Woods Hole MA. Spring and fall bottom trawl surveys from 1991 through 1994 were selected because the survey was consistently done twice a year, over the same area, for 4 years. Each survey contains approximately 300 sampling stations across the Northeast Shelf from Cape Hatteras to the Gulf of Maine. One of the cruise objectives on each of these surveys is to collect hydrographic data of temperature, salinity and density (sigma-t) data measured in the water column from the surface to the ocean floor, averaged into 1 m intervals on an irregular grid of stations (Holzwarth-Davis and Taylor, 1992, 1993, 1994). Because data collection took place over several weeks, the data were compiled into one temporal instance as if all samples were collected at the same time. This allowed the animations to contain information for the study area as a whole rather than as small parts along the shelf. Before this data could be used to create animations, the header record containing country and ship codes, cruise and cast number, time and date had to be removed. A Quickbasic program (Appendix A) was used to extract latitude, longitude, depth (m) and temperature (^{o}C) and convert the files from NODC 80-column ASCII format into ASCII comma delimited format. NMFS also provided the digital ARC/INFO coastline coverage which is used in several of the animations.

After the data were reformatted, they were used as input in several animation packages. Spyglass Dicer was used on a Macintosh Quadra 700 to create several animations of the four-dimensional data set. Dicer is the first program for the Macintosh that displays and animates 3-D volumes of data in color and that allows the researcher to interactively create slices, isosurfaces, blocks and cutouts for viewing those data values (Spyglass, Inc., 1993). The program is excellently documented in the manuals, and Spyglass has a very knowledgeable technical support staff which can be tapped as an additional resource. Since the program is designed to maximize the capabilities of the Macintosh operating system, creating the animations did not require programming experience or prior knowledge of the program and only took. a few hours.

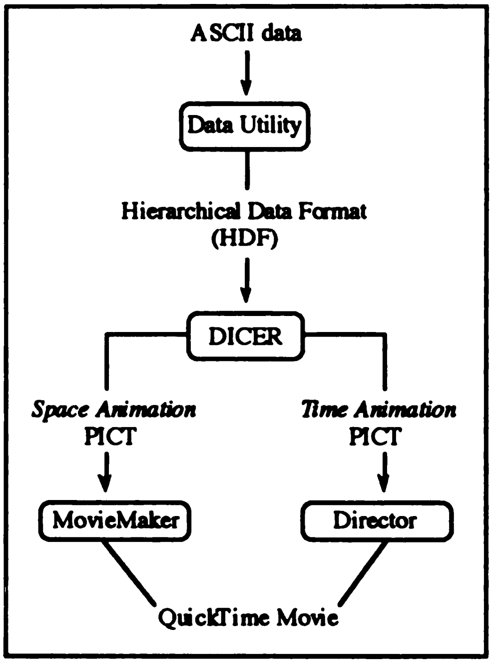


Figure 4. General Diagram of Dicer Animation Process.

Figure 4 shows the general process which is used to create an animation using Dicer. Additional data conversion is often necessary to ensure that the data is readable by the program. Since the ocean temperature data was irregularly sampled, it was necessary to convert it to a regular three-dimensional grid. This gridded volume could then be displayed and manipulated within Dicer. Once the image to be animated had been constructed, the frames were exported from the program using the animation modules.

These frames were then brought into another animation program and linked together to form stand-alone animations.

Six additional animations were created on a IBM RISC System/6000 workstation using AVS. AVS is a scientific visualization program "designed for end-user extendibility and platform independence for high performance computing, graphics and imaging applications" (p.11 AVS, 1992); and based on an extended form of the Data Flow Architecture. The object oriented programming is excellent and easy to use given that the researcher has experience with the program. However, the learning curve for AVS is very steep. AVS has the power to do almost anything imaginable to a data set, but the number of modules and complexity of many processes almost necessitates having an AVS expert available at all times to achieve the desired results. Modules not native to the program can be built in, but this requires strong knowledge of the program and programming skills in either C, C++ or FORTRAN. Animations for this work were done in consultation Mike McPherson, an experienced AVS user at Michigan State University, and required over 40 hours of programming in AVS before they could be generated.

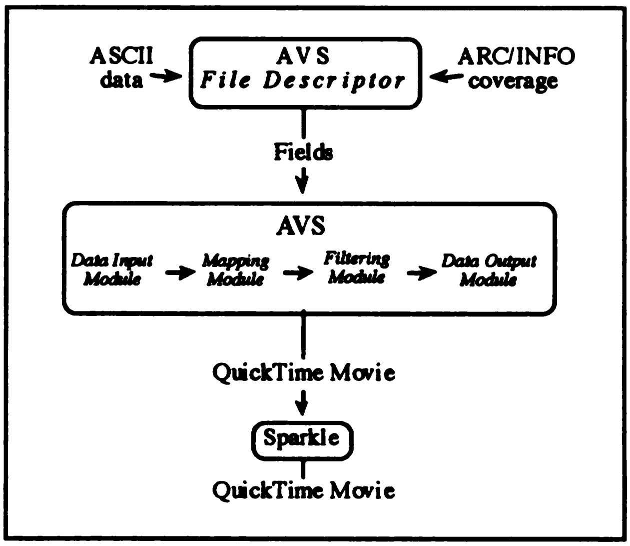


Figure 5. General Diagram of AVS Animation Process.

Figure 5 shows how raw data is converted into an animation using AVS. Again the irregularly spaced data was fit to a regular grid, and was converted into a format AVS could read. This data field was then input into AVS, where it flowed through several different modules. These modules build the raw data into an image, generated the animation and created an output file. The resulting animation was very large (over 15 MB) and needed to be crossed over to the Macintosh platform, so it was transferred through another software package where the animation was converted and compressed into a stand alone movie.

Technical Development Issues

This section gives an in-depth discussion of how the animations were developed. It has been provided for those readers interested in the technical issues behind the animations. In addition to listing the parameters specific to each step, this section will provide some insight into how much time and energy is necessary to create animations using Dicer and AVS.

Dicer Animations

The Data Utility converts a variety of data formats into Dicer compatible three- and four-dimensional data sets. This utility was used to transform the ASCII files into 3D floating-point Hierarchical Data Format (HDF) files. The hydrographic data was converted to a 357x30x30 target matrix, where the z-axis value of 357 was determined by the deepest reading collected from the trawl surveys. The output matrix data locations that were not set by input data values were interpolated using a 3x3 smoothing kernel routine called *simple fill*. A value of -1 was assigned to missing data values. The Data Utility was then used to convert a folder containing a series of 3D HDF matrix files into a single compatible 4D HDF file.

The HDF matrix file opens directly into Dicer. The view size was set to 1/2 times the size of the grid for the z-axis, and 8 times for the x and y-axes. This allowed the volume to be viewed at maximum size within the confines of the desired QuickTime animation size. For all Dicer animations, axes and labels were added to the bounds of the volume to provide some orientation to the viewer. A spectral color scheme was selected to represent the temperature data. Making use of the full range of colors, with the coldest water represented by black and purple and the warmest represented by red, allows for easier pattern identification because the spectrum has logical order as a visual variable.

Two distinct types of animations were generated for the volume representation using two of the options in the *Save Image Sequence...* command. Running *space animation* and *time animation* resulted in a series of PICT files. *Space animation* required a 3D HDF input file and the number of frames to be created to be defined. The output was a series of PICT files which were then brought into the shareware program MovieMaker. MovieMaker converts the PICT files into a QuickTime movie; this application was also used to set the speed of the animation. *Time animation* does not interpolate temporally, so the number of output PICT files is limited to the number of 3D files used to create the 4D HDF file, which in this case was eight. A QuickTime MooV for these eight PICT files was created in MovieMaker, but the resulting animation was unsatisfactory (see animations 15a and 15b). In the absence of temporal interpolation, the images created from the 4D data set were imported as *castmembers* into MacroMedia Director. It was then possible in Director to assemble an animation using pixel dissolves to simulate temporal interpolation. Director was also used to create the clock for the temporal animations. These animations were then exported as QuickTime MooVs, utilizing the animation compressor to reduce the size of the output file.

AVS Animations

All visualizations are created in object oriented execution models called ***networks***, which provides the "data processing pipeline". Each piece in the network, or ***module***, plays a specific role in the creation of the visualization. Modules can be categorized by function: data input, filter, mapper and data output. When wired together, the data flows through the network sending the output from one module to the input of the next. By manipulating module settings, the researcher is able to interact with the data.

Before assembling the network and animating, the data files were converted into a readable AVS format. Several modules not native to AVS were needed for the conversions, which were acquired from the International AVS Center and written specifically for this project (Appendix B). The coastline was converted from an ARC/INFO coverage into an AVS geometry format using *plot_xyz*. Reading the ASCII data files into AVS format required numerous steps. First, the AVS *file descriptor* module was used to read the ASCII files (Appendix C). The *trivar* module, with a radius of 1000 minutes and a weighting factor of $1/d^2$, was used to interpolate each of the eight ASCII files on a 20x20x20 regular grid. A modified version of *trivar* was used to create a mask field, showing which of the elements in the new regular grid covered a physical space which actually contained data in the .csv file.

Figures 6 and 7 show how the AVS network compiles the animation. The networks are identical, except for the mapper module portions, which convert the numerical data into a description of a three-dimensional geometric object. Both simultaneously read the spatially interpolated data and mask fields into the network. The data field then runs through the *timeslice* module, written specifically for this project, which does the temporal interpolation using the routine *POLINT*, which implements Neville's algorithm for polynomial interpolation (Press, 1989). *Clamp* is used to deal with the sub-zero temperature artifacts introduced by the temporal interpolation process. All values less than 0.1 are set to 0.1, since zero has been reserved for undisplayed points

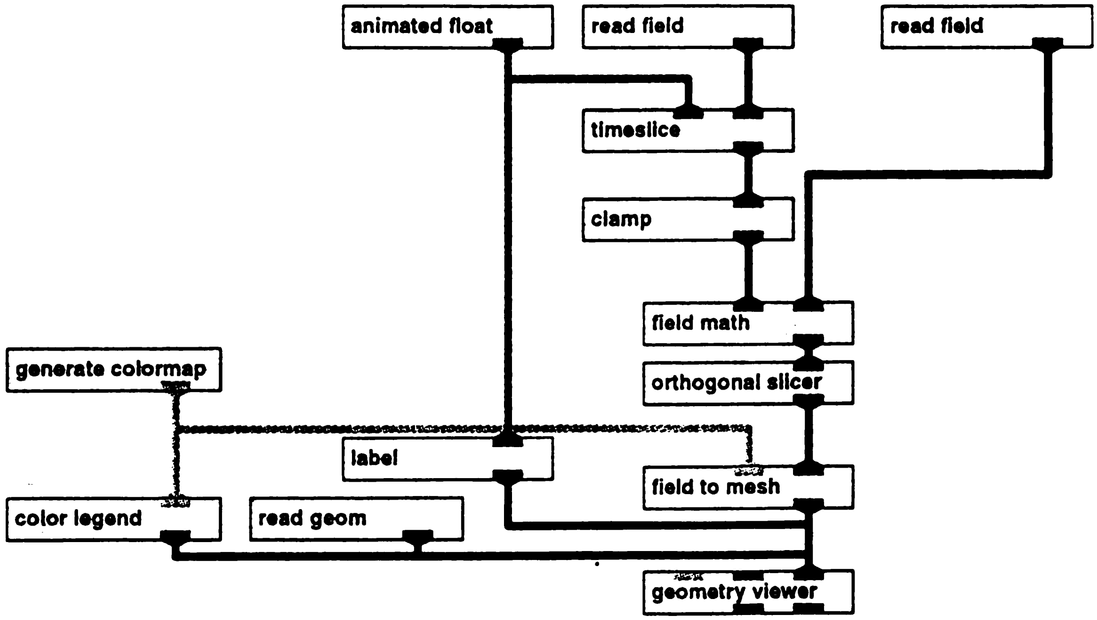


Figure 6. AVS network for slice animations.

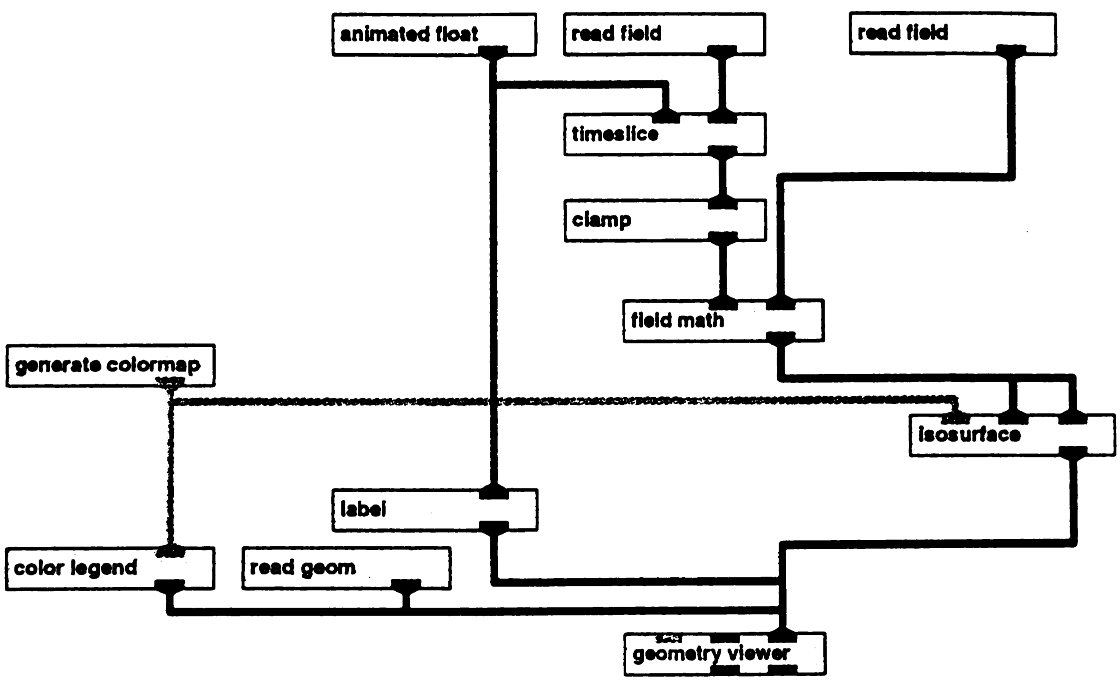


Figure 7. AVS network for isosurface animations.

such as those on the land or beyond the study area. *Fieldmap* then joins the two input fields by multiplying the temporally interpolated field and the mask field. The mask is defined such that locations which are part of the study area are assigned a value of one, others are assigned a zero value. When combined, the data is pared down to only display ocean temperatures along the Shelf. The data then goes through either an *isosurface* (Figure 7) or *orthogonal slice* (Figure 6) where *generate colormap* applies a spectral (high-red, low-purple) color scheme to the graphic image of the temperature data and this, along with labels, legend and the coastline file are displayed in the geometry viewer.

When all viewing parameters are set, the animation was generated by attaching the *write_MooV* module to the output link on the geometry viewer. This writes a (very large) QuickTime MooV file, which was then transferred to the Macintosh in binary mode, with the file type set to "MooV" and the creator type to "TVOD". The files were then compressed using the shareware utility Sparkle 2.3 to reduce the size from 16 MB to less than 1 MB animation. Animations did not suffer any apparent loss in graphic quality due to the transition.

In the next chapter, in depth descriptions will be given of each animation. The animations will be evaluated based on their success as a tool for visualizing a complex 4-D data set. Comparisons will be made between the animations created on the Macintosh personal computer and those made on the IBM RISC/6000 workstation. Some factors which will be considered are data manipulation power, graphic image creation, equipment and time costs incurred to assemble the animations, and output quality. In addition to this discussion, a dozen researchers who are familiar with geographic data viewed the animations and provided their evaluations of the product. Animations were briefly described and shown to individuals or to pairs of researchers, and the reaction of each researcher was recorded for each animation. These researchers represent the various fields of geography, and their subjective evaluations are summarized following the formal discussion of results and evaluations.

CHAPTER 3
EVALUATING THE ANIMATIONS

Visualizing four-dimensions is one of the largest challenges researchers face as they begin to explore their data sets. A general lack of knowledge about scientific visualization software often prevents such techniques as three-dimensional modeling and animation from being employed. This research seeks to remove this barrier and encourage the use of visualization technology to explore complex geographic data set by displaying how effectively a dynamic geographic phenomena can be displayed in an alternative environment.

Table 1. Comparison of Cost for Scientific Visualization Systems

Software	Cost	Hardware	Minimum System Requirements	Average Cost
Spyglasss Dicer	$695	Apple Macintosh	Hard drive, 4 MB RAM, System 6.05/6.07 or 7.0	$2,000
Advanced Visualization Systems AVS	$8,000	Most Unix Platforms	50 MB hard disk, 16 MB RAM	$12,500

The visualizations for this project were created using two software packages. One, Spyglass Dicer, represents a low cost, easy to learn desktop tool for representing volumetric data. The other, AVS, is a much more complicated package representing the high technology end of the spectrum. A comparison of hardware requirements and costs are shown in Table 1. Each package allows the researcher to interact with the data and manipulate the graphic output, but in different ways. Animations will be discussed in terms of how much of the 4-D data set they were able to successfully display, graphic quality, interactivity, output, time cost, and the overall ability to convey information which the researcher previously was forced to mentally interpolate from static representations of the data. Following the descriptions and evaluations is a brief section summarizing some of the comments I received as people reviewed the animations. This section should serve to enhance the success or failures indicated in the previous section, as well as generate additional suggestions for future improvements or changes which would make these visualizations more successful.

When examining a complex data set, it is often desirable to reduce it to smaller parts before examining all the dimensions simultaneously. This is often the case when dealing with four-dimensional data. Without an understanding of the three-dimensional space, it is impossible to understand how that space evolves over time. Creating a mental image of the volume and its attributes from a series of maps results in an inconsistent, inaccurate representation which is difficult to explore. Figures 8, 9 and 10, created with Dicer, show how visualization technology can be used to render three-dimensional space at one instant in time. These animations show the temperature of the ocean along the Northeast Continental Shelf from Cape Hatteras to the Gulf of Maine. Each shows the movement of a slice moving through the volume of water and displays the temperature using a spectral color scheme. The black area in all animations represent space beyond the study area; the black on the left side of the cube is the land, and the area to the right of the temperature display is deep water beyond the shelf. The bottom of the cube which turns black at various depths is the point where readings stopped at the ocean floor.

Figure 8 shows a visualization of the volume by moving a slice along the depth axis from the surface to the bottom which has been set at the deepest location in the study area; thus each slice shows the temperature at a given depth. The pattern illustrated here shows that in late September the water is considerably warmer in the shallower, southernmost part of the Shelf. With the exception of a few canyons offshore of the mid-Atlantic states, the volume of cold, deep water is primarily in the Gulf of Maine. It is perhaps easier to display the ocean depth in Figure 9 as the slice moves through the cube from west to east showing temperature and depth at along a line of longitude, or in Figure 10 where the slice moves from northward from the southern part of cube, where temperature and depth are displayed by latitude. Since Figures 9 and 10 show temperature and depth simultaneously in a graphic environment, the topography of the ocean floor begins to be defined.

Visualizations created using AVS allow for similar representations of the data set. It is possible to create a slice moving through the water on the shelf, this time with a coastline added for reference. To display temperature for late June (Figure 11), the image has been rotated and tilted at an angle so that the coastline and the volume can be shown. Better spatial interpolation and graphics rendering makes it easier to identify ocean floor features as the slice moves from the surface to the bottom.

While these four animations provide an example of ways to investigate the *spatial* component of a four-dimensional data set, they do not touch upon the temporal dimension. Before embarking on this combination, it is often desirable to examine the temporal component in a more conventional animation, one of a two-dimensional surface changing over time. Animating temperature surfaces over is time not new, but doing so in a visualization package as opposed to a graphic animation package allows for temporal interpolation. Figures 12a and 12b depict changes in ocean surface temperature over four trawl surveys, a time period of one and a half years. Again the temperature is displayed with a spectral color scheme, which allows for logical interpretation of order. A coastline, Lake Ontario, Lake Champlain and a portion of the St. Lawrence have been incorporated to provide the necessary orientation and to help to define the extent of the shelf. Time has been indicated by a counter which starts with the spring trawl and progresses through the next three surveys counting by day. The coloring that extends beyond the land boundary is an artifact of the masking process, which in all cases was unable to cleanly clip the coastline to the data set. The line extending from the shore to the St. Lawrence is a line segment which could not be removed without destroying the integrity of the coastline. The fuzzy bound along the outer edge is a result of pixel dithering and is not intended to convey any three-dimensional effect.

To visualize four dimensions the temporal dimension must be combined with the three-dimensional spatial display. There are several ways this can be done. The slice animations can be merged with the two-dimensional temporal animation to create a four-dimensional visualization of temperature change along the shelf at a given depth, as in Figure 13. For the time between the spring survey in May 1991 and the fall trawl in November 1992 the temperature surface at 107 m below the surface has been animated. Again the coastline is in place for reference, and the clock counts the days from the beginning of the first survey through the end of the last survey. The dark "holes" which appear on Georges Bank off the coast of Cape Cod are areas where the topography of the continental shelf is elevated.

If it were possible to effectively animate the entire volume of water to show changed over time, the researcher would be inundated with information, especially if the research focused on a small thermal range. For example, the mackerel habitat is confined to the thermal region between 8-20 ^{o}C. Visualizing the mackerel habitat as it changes over time would benefit from minimizing the output to only temperatures within that range. Dicer allows the researcher to limit the amount of information displayed by blanking colors outside a designated temperature range. Figure 14 shows how layers of information can be peeled off the volume, leaving only the mackerel habitat portion of the data opaque and available for investigation. Making use of this feature allows animations specific to a user defined tolerance to be generated. Once a three-dimensional graphic image has been defined, it should be relatively simple to apply the fourth dimension. Unfortunately, one of the major limitations of the Dicer software is that it is unable perform temporal interpolation. *Time animation* will take a four-dimensional data file and generate images only of the three-dimensional records which comprise the file, limiting the number of output images to the number of time records in the data set. The result is a jumpy visualization that is no more than a slideshow of three-dimensional renderings (Figures 15a and 15b).

However, if these output images are brought into a graphics animation package, it is possible to simulate temporal interpolation by utilizing pixel dissolves as a transition from one image to the next. The full four year period of the data set can be animated (Figure 16a), showing the changing water volume for the mackerel habitat. The layout is similar to other Dicer animations, where the land is located along the left side of the cube, and the water which does not fall in the designated temperature range is not displayed. The legend is divided in half along the horizontal, displaying the full range of temperatures as well as the opaque range. Temperatures displayed, the opaque region, show the mackerel habitat. The volume along the Shelf changes dramatically from spring to fall, and the passing of time is indicated by the timer in the lower right corner. This visualization is dramatically different from Figure 15a because time has been incorporated. Similar visualizations can be developed to examine how stable a seasonal habitat is from one year to the next (Figure 16b). Here the four-dimensional data set was built containing only the four Fall surveys, but the graphic layout is identical to the full year animation. From one Fall to the next, the volume does not change drastically. An irregular sampling and interpolation method account for some of the more dramatic depth changes, but the temperature pattern essentially remains constant.

In the spring and early summer Mackerel breed in the 8 ^{o}C thermal zone. The location of this region has importance to the maintenance of the food chain. Two visualizations (Figure 17a and 17b) show the movement of the 8 ^{o}C isosurface over a one and a half year period. One color, and shading to indicate changes in depth and spatial location, is used for display since only one temperature zone is being animated. The coastline has been tilted to allow the volume to be viewed. The counter at the bottom is used to gauge the passage of time. The ladder effect which appears is a result of the AVS algorithms not knowing how to accurately interpolate across time and space when the isosurface dips into a canyon on the Continental Shelf.

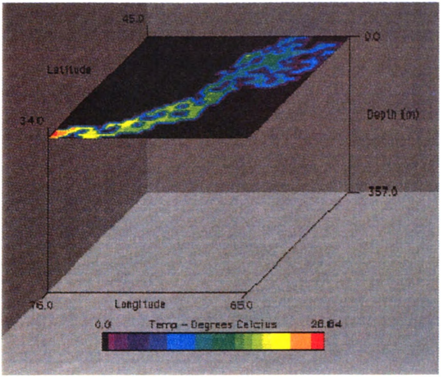


Figure 8. Dicer ocean temperature slice animation (surface to floor).

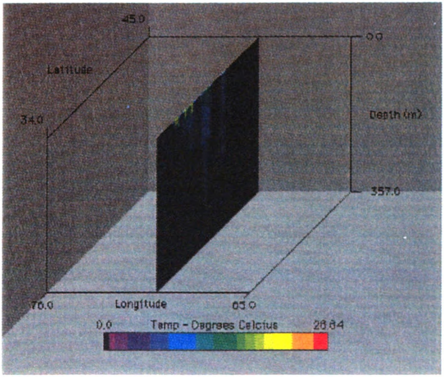


Figure 9. Dicer ocean temperature slice animation (along longitude).

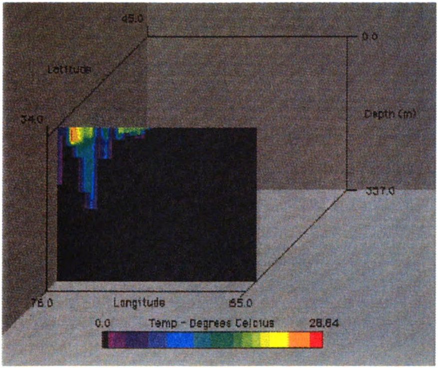


Figure 10. Dicer ocean temperature slice animation (along latitude).

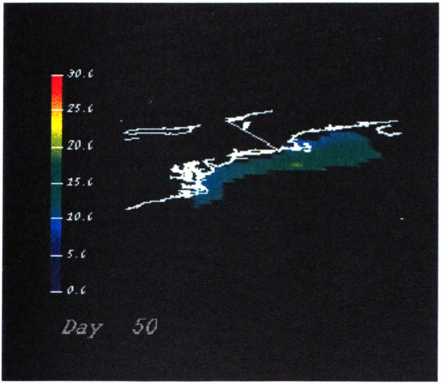


Figure 11. AVS ocean temperature slice animation (surface to floor).

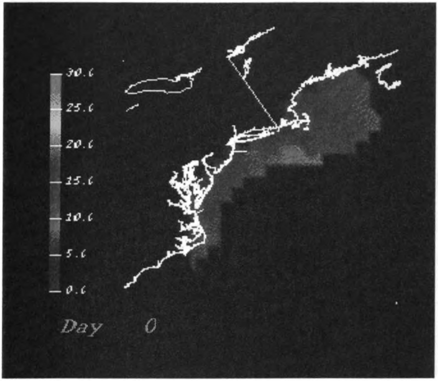


Figure 12. Ocean surface temperature changing over time 1991-1994.

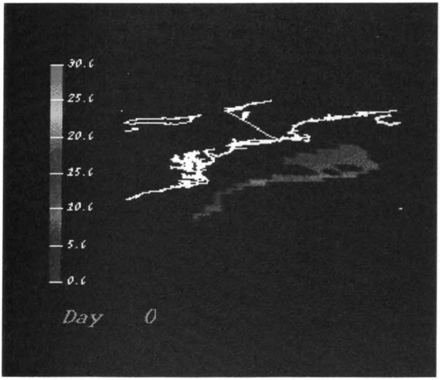


Figure 13. Temperature changes at 107 m (May 1991-November 1992).

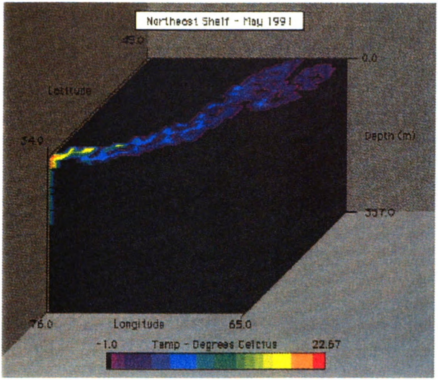


Figure 14. Full volume of ocean temperatures created in Dicer.

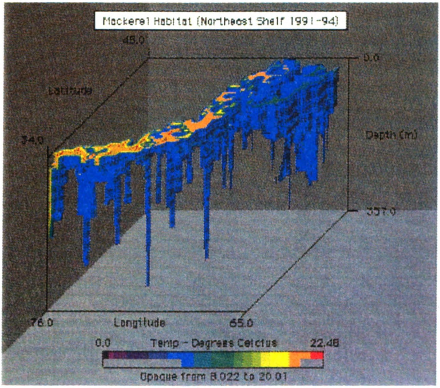


Figure 15. Mackerel habitat in three-dimensions, flipbook animation.

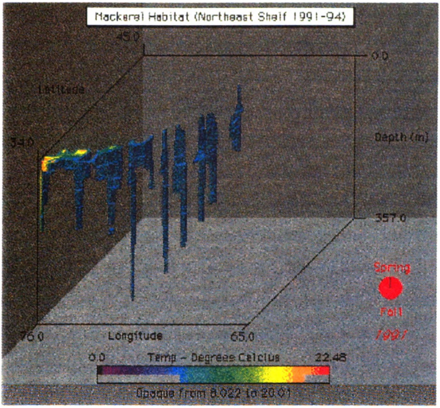


Figure 16. Mackerel habitat in three-dimensions, simulating temporal interpolation.

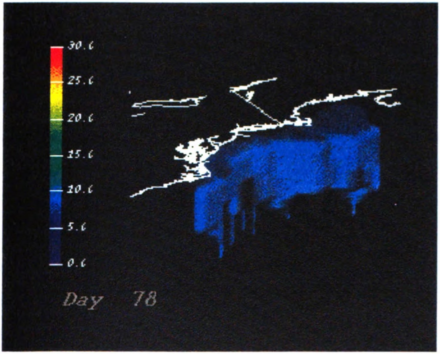


Figure 17. Eight degree Celsius isosurface changing over time 1991-1994.

Discussion

The success of any visualization is largely a function of the data set. For this research, visualization were generated from a real world four-dimensional data set. This means that the unpredictable and uncontrollable anomalies which occur in nature cannot be ignored. It would have been possible to create a theoretical data set and generate relatively flawless visualizations, but that would have defeated the purpose of this research. In order to examine the role of visualization technology in exploratory analysis of four-dimensional geographic data, it is necessary to do so with real data, even if that data does not lend itself to easy, clean visualizations of all four dimensions.

Data is rarely collected in the exact spatial or temporal format the researcher desires. The NMFS hydrographic data is a good example of how the quality and availability of geographic data varies. Numerous surveys are done throughout the year, but the time and location of the sampling varies from year to year. The entire continental shelf is sampled twice a year, while smaller regions are sampled more regularly. Visualizing thermal zone fluctuations from real data presented numerous problems which show up in the animations. These problems are not necessarily a limitation of technology, but rather a reflection of the data under investigation.

Comparing visualizations to static time series maps (Appendix D) is impossible. While they are all depicting the same information, they are two entirely different types of display and research tools. When we make use of time series maps, we are essentially creating our own animation similar to the output from a visualization package and there is no way to compare the two. It is possible, however, to compare animated maps and evaluate their success relative to output from other visualization packages.

Both AVS and Dicer are interactive visualization packages, and when the animations are output from these programs, the visualization which results is one in which all the decisions have already been made. This is beneficial for presentation purposes, but the researcher needs to interact with the data. The animations which were created for this research were designed to demonstrate how visualization software can be used to represent four-dimensional geographic data. It is necessary to understand that each of these packages has numerous powerful features which cannot be adequately demonstrated by these animations. The major feature is the ability in interact in real time with the geometric image which is generated. In both environments, the three spatial dimensions of the data are displayed as part of a cube. In Dicer, the view orientation can be rotated in 90° increments along any of the three planes. The workstation environment allows the AVS user to freely rotate the volume about a center point, so any viewing angle can be achieved.

Orientation is only one of the interactive parameters which is missing from the animations. Both Dicer and AVS allow for the user to define which temperature range is displayed, what color pallet is used and what time frame, if any, is animated. Since the AVS *time slice* module will only interpolate time from four input time periods, which times are used is again decided by the researcher. Each animation has been designed with the intention of demonstrating the power of visualization technology and introducing a new data analysis tool to geographers. Given these limitations, animations are discussed in terms of design and data output quality, ability to extract information, and overall comprehensibility.

It is difficult to discuss the animations in great detail because the purpose of creating a visualization is to substitute graphic representation for figures and words. It is easier to discuss what is missing and detracts from a clear and easy interpretation of the data than to discuss the features which bring the patterns to life. All utilize color graphic renderings of three-dimensional spaces and movement, through time and/or space, to convey information about the four-dimensional data set. How well the data can be explored depends on the options available in each visualization environment. The animations designed for this research all achieved success at some level; thus comparison gives mixed results as to which visualization was 'the best'. Instead, the result is a clearer picture of an ideal to strive for.

Very smooth animations, such as these, require more frames and consequently take longer to assemble and require more memory. On average, Dicer animations are about 1.2 MB, and took about 10 - 15 minutes to create images for each QuickTime movie. AVS animations were significantly larger, about 15 MB, but took less than 5 minutes to create the same number of frames. It took about the same amount of time to convert each file to a self-contained QuickTime movie. The Director movies took an additional 30 minutes to assemble after Dicer generated the images, and exporting as QuickTime movies brought the total assembly time to almost one hour.

The overall color and graphics quality is sharper in the AVS animations, which is to be expected since they were created on a workstation with 24 bit color as opposed to 8 bit color Dicer is designed to maximize. But when Sparkle is used to compress the AVS QuickTime MooV file, they are reduced to 8 bits color, so some of the image sharpness is lost, but the graphic quality is still better than what is achievable in Dicer. The 3-D graphics are blockier in Dicer; when a smooth surface is desired, AVS is a better choice.

The goal of this project was to examine various cartographic representations of a four-dimensional geographic data set, and create animations which allowed the researcher to examine all four dimensions simultaneously. With some of the visualization methods this was impossible. If actual data-based four-dimensional visualization is desired, then AVS must be used. If it is possible to work with simulated temporal interpolation, then Dicer produces very nice results when the images are animated in Director, but that takes a substantial amount of time and often would not be worth the effort. The Dicer *time animation* module images, when animated, were not at all smooth and failed to convey a sense of movement in time. This was due to lack of data. If enough intermediate images could have been input into the four-dimensional matrix, the results achieved in Figures 15a and 15b would be dramatically improved.

Dicer's inability to perform temporal interpolation imposed serious limitations on the success of visualization from the Macintosh. But the fact that the program is easy to learn, data input is straightforward and the cost is reasonable makes this an attractive product. It was possible to generate several animations of 3-D space at one instance in time using Dicer. Slices moving through a cube of 3-D space (Figures 8, 9 and 10) makes more intuitive sense when moving from the surface to the bottom so that changes in temperature can be associated with a change in depth without losing spatial orientation in the x and y plane. Since Dicer does not allow a coastline to be superimposed on the cube, it is difficult to relate temperature information to anything other than depth at points in the same plane is it moves through the cube along the latitude or longitude. The animation is a bit more successful as the slice moves northward from the southern extreme of the study area. Each of these animations suffer from the same problem: it is difficult to identify location within the cube. If it were possible to place additional tics on the axes, the problem might be lessened. These three animations do succeed in bringing the volume to life with sharp colors and conveying a sense of the ocean floor topology. Since each slice is essentially a shaded isoline map, they are easy to understand because they are not unlike maps we are already familiar with. This makes the animations easy to understand because it is not necessary to adjust to a new graphic representation of the data.

It is possible to create similar slice animations in AVS. Figure 11 also shows a temperature slice moving through the volume from the surface to the ocean floor. This animation was not set to record as many frames as the Dicer slice animation (Figure 8), so it doesn't flow quite as well, but the volume is still defined as the slice moves from the surface to the bottom. This animation makes it easier to see where the floor is elevated because the temperature surface has been interpolated more closely. Identification of temperature zone is easier, thanks to smaller classifications along the legend bar. The view angle was selected so that the coastline would provide spatial reference as the slices travels along the z-axis of the data cube. An area where this animation does not achieve the same success as Dicer is that there is no way to gauge depth. As can be seen in all AVS visualizations, this is a glaring downfall.

Reducing the cube area to display only the mackerel habitat allows the researcher to focus on a selected temperature region. This feature shows only the regions of a potential fish habitat at the time of a trawl. While it is easier to locate the habitat with other temperatures removed, Dicer does not allow the bounding color to be made transparent; thus, it is impossible to see how deep temperatures inside the volume extend. However, when brought into Director and animated, these three-dimensional models of the habitat do a very good job of showing how drastically the size of the potential mackerel habitat changes over the course of a year. Since no temporal interpolation is possible, the clock runs based on animation time and arrives at the appropriate season when the full image appears from the dissolve. This "three and a half dimension" animation, which almost shows a time dimension, is a good link between visualizing three and four-dimensional data because it teaches the viewer about a new presentation style. Once comfortable with how to interpret a three-dimensional graphic and assimilate a pseudo-change over time, it is then possible to fully investigate a four-dimensional data set.

The surface temperature animations (Figures 12a and 12b) showing change over one and a half years make it very easy to see temperature patterns. Here, the data cube is being viewed from directly overhead, so only three of the dimensions of the data set are being examined. This view is especially useful if viewing true temporal animations for the first time, since the amount of information which must be processed is minimized. Since the AVS color legend is nicely categorized, it is easy to focus in on specific temperature. Time has been marked with a running count of days to show how drastic changes can occur over short periods of time. This clock could be changed to represent time in any number of ways since each tick of the clock is linked to data which has been temporally interpolated. This is different than the Dicer/Director clock which was limited by the length of time of the dissolve between one image and the next. Pixel dithering around the edge is a result of color compression from 24 to 8 bits, and is not intended to convey any sense of the third dimension. It is unfortunate that generating data for the time between samples was such a difficult problem to overcome. Without a considerable amount of time and an AVS expert on hand, it would have been impossible to display the temporal dimension. Even with this luxury of this technical support, it was unfeasible to interpolate between more than four time periods.

Figure 13 is the simplest display of all four dimensions of the data. Temperatures 107 m below the surface are animated over a one and a half year period. This is an excellent resource for pattern identification at a given depth, and indicates where the ocean floor is elevated in the same way the AVS surface to bottom slice animation . If this slice were viewed from directly overhead, as in Figures 12a and 12b, the graphic would not make as much sense because the areas along the coast where the shelf is shallow would be blacked out, and the temperature data would appear to be floating out to sea. A lack of depth reference is only mildly troublesome here, since the researcher sets the depth at which the temperature surface will be animated.

The isosurface animations (Figures 17a and 17b) provide the most detailed and specific information of the four dimensional data set. By setting the temperature to any desired level, the researcher is able to investigate changes in volume as the thermal zone evolves over time. Shading adds considerable understanding to the volume, defining the shape. There is no way to tell the specific depth or location of a specific point in the volume, but this visualization provides researchers with insights into the patterns and can stimulate thinking about which additional factors should be incorporated into the analysis. Viewing the visualization in AVS gives the researcher the opportunity to examine the volume from any angle, and watch the patterns evolve for different thermal zones.

All the animations are successful in providing a clearer picture of a complex geographic data set. Some convey more information than others, and there is definitely a difference in output quality. The ideal design for a full four-dimensional visualization would be one in which the volume of ocean data was placed within a representation of the ocean floor topology that extended from the shoreline to the edge of the Continental Shelf. Orientation would be less of a problem because the viewer would have multiple vertical and horizontal cues. Unfortunately, this was not possible using any of the visualization techniques. If it were, the AVS isosurface animations would be much more effective, because the researcher could locate the thermal band in relation to the ocean floor. The same would be true for the Dicer/Director animations of the mackerel habitat, and for all of the animations showing three-dimensional space.

Impressions

A dozen geographers with different research interests were asked to view the animations and share their impressions. All are familiar with traditional maps and the role maps play as part of exploratory data analysis. The responses are summarized here to provide additional evaluation of the results achieved.

The overall impression was extremely positive, everyone who viewed the animations was impressed with the data display. Almost everyone commented on how "cool" the visualizations were, almost as if they were surprised that data could be displayed in such a manner. The most common observation was how easily patterns could be detected. Once these patterns were identified, a majority began to question the pattern and hypothesize about the processes driving the patterns. I was surprised at how many people immediately began to explore the data, especially since no one was familiar with the data set. It was also interesting that several people who viewed the visualizations immediately thought of how this could be applied to the type of geographic data sets they work with. I find these responses particularly encouraging since there is strong indication that these visualizations are indeed a part of future geographic research. As more and more people are introduced to the technology and the potential is realized, visualization will play a powerful role in exploratory data analysis.

Comments were also directed at very specific animation issues. People responded positively to the color scheme, and specifically remarked that they liked the colors in the Dicer slice animations. Several mentioned that the animation speed was a bit fast, and that they would really like to have more interactive control over the animations. Since the animations were exported as QuickTime movies, the interaction was limited to looping, looping forward and backward and stepping through the frames. The option to step through the frames one at a time was utilized by the viewers almost every time a new animation was shown. That time was not displayed with a clock counting by month and day or Julian date was troublesome for some, others did not appear to notice the clock at all. The problem of orientation was unanimously commented upon; at least one of the following problems was mentioned by each person: the absence of a coastline in the Dicer animations, the inability to reference depth in the AVS animations and the desire to have the ocean floor topology represented.

Some individuals compared the slice animations to one another, and the consensus was that Figure 9 was not understandable and therefore not very effective, but that Figure 10 worked well and that the slice moving from the surface to the bottom (Figure 8) was one of the best visualizations of the bunch. The animations dealing with all four dimensions of the data set were judged a success, but there were several suggestions as to how to make them more successful. These suggestions include showing the whole volume of water when a temperature isosurface is highlighted to give a sense of surrounding temperatures and the ocean floor, being able to interactively query the image for exact locations or statistics, and linking the image to other data sets such as fish population counts to model the three-dimensional environment over time.

The visualizations were also viewed by two researchers who are familiar with hydrographic data, one of whom had previously worked in NMFS and had experience with ocean dynamics on the Northeast continental shelf. Their comments were more data specific but having a strong background and understanding of the data allowed them to judge how useful the visualizations really are. Both researchers found the animations to be very informative. They specifically mentioned that picturing the data is beneficial and that this methods was better than flipping through a series of maps. They thought that a picture can be easily remembered, and can be remembered more accurately than a long description; and that animation is a good tool for getting an overall impression of data or for describing patterns and processes to others. Since neither researcher was familiar with the data set, their approach was to examine the data as if they would be using it for their own research. After running the animations through once they were more closely examined by stepping through the images, interaction which made it easier for individual pattern identification. The omission of the subsurface and coastline and the fact that the clock was set as a counter instead of displaying calendar time was also mentioned by these viewers as troublesome. However, the comments specific to the animations were quite revealing since they came from people who are familiar with this type of data set.

The two researchers extracted a significant amount of information from the visualizations. Based on knowledge of ocean system functions on the shelf, Figures 12a and 12b were considered to be an accurate representation of thermal dynamics. Cold patterns on the shallow Georges Bank occur because the water here gets very cold very quickly. The warm pocket of water which appears south of Long Island may be the Hudson River plume. Circulation patterns also emerged and for someone familiar with this data, the animation explained why fish assemblages change so much over time. One explained that the east coast pattern from the Gulf of Maine to the New York bight is the most compressed temperature range in the whole Atlantic Ocean and commented that this visualization in particular does a good job of showing the evolution of water masses in that area. Both liked the animation of the 107 m subsurface temperatures as it changed over time, again commenting on the processes that drive the patterns.

The Dicer slice animations were described as interesting and informative to some degree, and overall the researchers' descriptions matched those already expressed. From Figure 9 it was possible to extract temperature zones and get a feel for the ocean floor, but there was a problem understanding how the movement reflects the coastline. The slice moving from the surface to the floor (Figure 8) again showed the pattern nicely and gave a better understanding of the shelf topology. Understanding the location of the coastline was clearer when the slice moved from south to north through the volume, as motion simulated traveling along the coast, a concept which was easier to mentally picture.

While these animations were judged useful, both researchers were more excited about the visualizations which included the temporal dimension. I think this is due to the fact that the data sets they generally work with involve the temporal dimension but they had been unable to visualize it. They found the Dicer/Director animations (Figures 16a and 16b) were a "neat" way to visualize the data but that it was difficult to examine the three-dimensional graphic since it was impossible to see inside the volume. This animation technique, since it did not truly include the element of time, was thought to be useful to look for persistent patterns over successive seasonal observations (Figure 16b).

The isosurface animations (Figures 17a and 17b) were the visualizations these researchers seemed most excited about. Despite the fact that it was a little hard to see specific points on the map and to orient depth without some vertical scale, this visualization successfully defined the thermal habitat. As the volume mutates, knowledge of mackerel migration patterns enhances the amount of information which can be extracted from the visualization. Knowing that the fish migrate along the front edge of the thermal habitat as it moves onshore in the spring after wintering in the warmer offshore waters is an essential piece of information if you are interested in identifying where the fish are likely to be located.

The researchers provided several suggestions which they felt would enhance their exploration of the data. The first was that it would be helpful to look at temperature deviations from the average for an extended time period. This would help to identify anomalies which could provide complications, and they could be investigated before a full analysis is performed. Linking this data set to others and being able to interactively query the visualization was another feature they would like to have when exploring the data.

This additional input provided by two experts confirmed several hypotheses. First, as effective as the visualizations are without knowledge of the data set, they are even more so if the researcher if familiar with the type of geographic data being studied. For organizations such as NMFS or the National Oceanic and Atmospheric Administration (NOAA), where map making is one of the important things they do, animation can be a powerful option for investigating four-dimensional data.

CHAPTER 4
CONCLUSIONS

Visualization is the process of recreating reality for the purpose of better understanding a given data set. In geography, this has traditionally meant extracting many dimensions of information from a two-dimensional surface and mentally assembling a representation of the real world. The inaccuracy of such a method prompted an investigation into alternative methods of representing the 4-dimensions of spatio-temporal data. What this research has shown is that it is possible to display geographic data in a much more realistic manner by utilizing scientific visualization techniques.

Since the map has become so vital to the research process, it is necessary to continue to improve upon the ways geographic data can be displayed. Improving the map means being able to display more information without making the map more complicated. Reducing the amount of generalization brings the map display closer to a model of reality. In this new mapping environment the goal is to maintain the integrity of the 4-dimensional data set so that data exploration does not rely so heavily on mental imagery. With computers it is now possible to render three-dimensional models, and numerous fields have made use of this technology to explore various types of data. Until now geographers have not explored the possibility that visualization can enhance the understanding of geographic processes.

This research has shown that not only is it possible to simultaneously display four-dimensional geographic data, but also that this new mapping technique is a valuable research tool for exploratory data analysis. By looking at the data from a new perspective it is possible to uncover many patterns which would likely go unnoticed if the only resource available was mental interpolation from over generalized maps. It is much easier to extract information about natural phenomena from a visualization which creates a model of the environment in question and sets it in motion.

Sometimes it is impossible to display all four dimensions at once. This does not mean that a better map cannot be created using visualization software. For example, the Dicer slice animations provide more information about ocean thermal zones than can be gleaned from static maps of surface and bottom temperatures, just as the AVS animation of surface temperatures changing over time is more descriptive than static time series maps. Individually these animations allow the researcher to investigate another dimension without the burden of mental image creation. When the brain is freed from this task, more attention can be focused on searching the data for patterns. The resulting analysis will likely be more accurate because visualizations provide graphic output based on mathematical interpolation. Multiple representations of the same data set enhance the understanding of displays when one visualization cannot sufficiently display all dimensions.

People who have had the opportunity to explore complex spatio-temporal data with animation are very excited about the potential of this technology. The initial awe of the technology and novelty of the technique quickly gives way to the realization that patterns may be more easily identified when the data is animated. Once introduced to the technology, it is difficult to stop thinking about other opportunities to explore similarly structured data sets. As other geographers break away from traditional methods of exploratory data analysis and begin to realize the potential of visualization, we will see an increase in the use of animated three-dimensional maps for research and presentation purposes.

Although it is currently time consuming to animate a four-dimensional data set, that will not always be the case. For the moment, the question we must ask ourselves is: do the animations we currently are able to generate add to our geographic knowledge? If so, it is worthwhile to continue researching the effectiveness of four-dimensional cartographic visualizations. For AVS, the quality of the resulting animations is well worth the cost, especially when the results can be viewed in their native environment and the interactivity is maintained. Dicer is a good first step at investigating a four-dimensional data set, but if time is an important dimension to the study, as it often is, then any scientific visualization package that does not allow for temporal interpolation is insufficient. However, technology changes so quickly that this software will be obsolete within a year or two, thus it is not so important as to how to produce animations using this software but rather what we have learned about animating four-dimensional data. Perhaps the most important thing is that it is possible to model real spatio-temporal data and create a visual representation of a three-dimensional geographic object which changes over time. As important is that this technique is useful for research as well as for presentation purposes.

As visualization software is made easier for geographers to use, its power as a data exploration utility will be realized by more people, and its use will become more common and therefore more excepted as part of research process. As the technological age continues, it is not unlikely that these maps will replace traditional maps for presentation and exploration of many types of data. If these animated maps do indeed work better than anything we have ever had before and they become easier to construct, then perhaps they may add to the traditional map as a method of data display

This research is only a first step in the development of a cartographic visualization of four-dimensional data and more work needs to be done. Several animation techniques have been demonstrated but many more are possible and need to be evaluated. It is also possible that some animation techniques will work better for some geographic data sets than others. A set of design standards also needs to be established so that researchers can design animations which will convey information efficiently. Finding these parameters will require testing map users to find the most effective visualization techniques. Further development of this technique will benefit from cognitive testing; once researchers understand how this information is interpreted and remembered, designs can be improved to make the visualizations even more effective.

Until visualization packages are developed which deal specifically with four-dimensional geographic data sets, it is also necessary to conduct more developmental research in order to find ways around the problems that exist in the current software. This may mean writing a program to perform temporal interpolation outside Dicer and then seeing if a satisfactory animation is achieved after more images are generated, or creating new modules for AVS which would allow the ocean floor topology to be modeled. These new features should then be compared to previous methods and their success evaluated.

The success of visualization in other fields highlights how important it is for geographers not to turn away from this technology. A move away from traditional mapping is not bad if new maps can teach us more about the environment we live in.

APPENDICES

Appendix A

Quickbasic Program

```
! Richard Groop
! Department of Geography
! Michigan State University
! converts NODC 80 column format to comma delimited
! January 23, 1995

c$ = ","
count = 0: counter = 0
CLS
OPEN "filename.dat" FOR INPUT AS #1
OPEN "filename.csv" FOR OUTPUT AS #2

' FOR i = 1 TO 200
WHILE NOT EOF (1)
id = VAL(RIGHT$ ( in$, 1) )
ON id GOTO 10, 25, 30
10      count = count + 1: LOCATE 10, 10: PRINT count
        counter = 0
        latdeg = VAL(MID$ (in$, 5, 2) )
        latmin = VAL(MID$ (in$, 7, 3) ) / 10
        londeg = VAL(MID$ (in$, 11, 2) )
        lonmin = VAL(MID$ (in$, 13, 3) ) / 10
        year = VAL(MID$ (in$, 19, 2) )
        mon = VAL(MID$ (in$, 21, 2) )
        day = VAL(MID$ (in$, 23, 2) )
        botdep = VAL(MID$ (in$, 34, 4) )
GOTO 20
30      counter = counter + 1: LOCATE 20, 20: PRINT counter
        FOR i = 2 TO 5
                x$ = MID$(in$, i, 1)
                IF x$ < > " " THEN 35 ELSE
                     1 = i - 1
35      NEXT
        depth = VAL(MID$ (in$, 1, 1) ) : s = 1 + 2
        temp = VAL(MID$ (in$, s, 4) ) : s = s+ 5
        salin = VAL(MID$ (in$, s, 5) ) : s = s + 5
        sigmat = VAL(MID$ (in$, s, 4) )
PRINT #2, count; c$, counter, c$, latdeg, c$, latmin, c$, year, c$, mon, c$, day, c$,
botdep, c$, depth, c$, temp, c$, salin, c$, sigmat, c$

20 WEND
' 20 NEXT
25 LOCATE 1, 1: PRINT "Error"
CLOSE #1, #2
END
```

Appendix B

Formula for Temporal Interpolation

```
C
C POLINT
C From "Numerical Recipes (FORTRAN)"
C Given arrays XA and YA, each of length N, and given a value X, this routing
C returns a value Y, and an error estimate DY.  If P(x) is the polynomial
C of degree N-1 such that P(XAi)=YAi, i=1,...,N, then the returned value Y=P(X).
C
      subroutine polint(xa,ya,n,x,y,dy)
      parameter (nmax=10)
      dimension xa(n), ya(n), c(nmax), d(nmax)
      ns=1
      dif=abs(x-xa(1))
      do 11 i=1,n
        dift=abs(x-xa(i))
        if(dift.lt.dif)then
          ns=i
          dif=dift
        endif
        c(i)=ya(i)
        d(i)=ya(i)
 11   continue
      y=ya(ns)
      ns=ns-1
      do 13 M=1,N-1
        do 12 i=1,n-m
          ho=xa(i)-x
          hp=xa(i+m)-x
          w=c(i+1)-d(i)
          den=ho-hp
          if(den.eq.0.)pause
          den=w/den
          d(i)=hp*den
          c(i)=ho*den
 12     continue
        if(2*ns.lt.n-m)then
          dy=c(ns+1)
        else
          dy=d(ns)
          ns=ns-1
        endif
        y=y+dy
 13   continue
      return
      end
```

Appendix B

AVS Temporal Interpolation Module

```
C mod_gen Version 1
C Module Name: "timeslice" (Mapper) (Subroutine)
C Author: Lauren Anderson
C Date Created: Mon Feb 27 13:46:01 1995
C
C This file is automatically generated by the Module Generator (mod_gen)
C Please do not modify or move the contents of this comment block as
C mod_gen needs it in order to read module sources back in.
C
C input 0 "invector" field 3D 3-space rectilinear float REQUIRED
C input 1 "slicetime" real REQUIRED
C output 0 "outscalar" field 3D 3-space 1-vector rectilinear
C param 1 "time0" typein_real 0.00000 FLOAT_UNBOUND FLOAT_UNBOUND
C param 2 "time1" typein_real 0.00000 FLOAT_UNBOUND FLOAT_UNBOUND
C param 3 "time2" typein_real 0.00000 FLOAT_UNBOUND FLOAT_UNBOUND
C param 4 "time3" typein_real 0.00000 FLOAT_UNBOUND FLOAT_UNBOUND
C param 5 "time4" typein_real 0.00000 FLOAT_UNBOUND FLOAT_UNBOUND
C param 6 "time5" typein_real 0.00000 FLOAT_UNBOUND FLOAT_UNBOUND
C param 7 "time6" typein_real 0.00000 FLOAT_UNBOUND FLOAT_UNBOUND
C param 8 "time7" typein_real 0.00000 FLOAT_UNBOUND FLOAT_UNBOUND
C End of Module Description Comments


C ***************************************
C  Module Description
C ***************************************
      integer function timeslice_desc()
      implicit none
      include 'avs/avs.inc'

      integer in_port, out_port, param, iresult
      external timeslice_compute
      integer timeslice_compute

      call AVSset_module_name('timeslice', 'filter')
      call AVSset_module_flags(single_arg_data)

C        Input Port Specifications
      in_port = AVScreate_input_port('invector',
     $  'field 3D 3-space rectilinear float', REQUIRED)
      in_port = AVScreate_input_port('slicetime', 'real', REQUIRED)

C        Output Port Specifications
      out_port = AVScreate_output_port('outscalar',
     $  'field 3D 3-space 1-vector rectilinear')

C        Parameter Specifications
      param = AVSadd_parameter('time0','real', 0.0, FLOAT_UNBOUND,
     $  FLOAT_UNBOUND)
      call AVSconnect_widget(param, 'typein_real')
      param = AVSadd_parameter('time1','real', 152.08, FLOAT_UNBOUND,
     $  FLOAT_UNBOUND)
      call AVSconnect_widget(param, 'typein_real')
      param = AVSadd_parameter('time2','real', 304.17, FLOAT_UNBOUND,
     $  FLOAT_UNBOUND)
      call AVSconnect_widget(param, 'typein_real')
      param = AVSadd_parameter('time3','real', 547.50, FLOAT_UNBOUND,
     $  FLOAT_UNBOUND)
```

Appendix B

AVS Temporal Interpolation Module (cont.)

```
      call AVSconnect_widget(param, 'typein_real')
      param = AVSadd_parameter('time4','real', 699.58, FLOAT_UNBOUND,
     $ FLOAT_UNBOUND)
      call AVSconnect_widget(param, 'typein_real')
      param = AVSadd_parameter('time5','real', 912.50, FLOAT_UNBOUND,
     $ FLOAT_UNBOUND)
      call AVSconnect_widget(param, 'typein_real')
      param = AVSadd_parameter('time6','real', 1034.17, FLOAT_UNBOUND,
     $ FLOAT_UNBOUND)
      call AVSconnect_widget(param, 'typein_real')
      param = AVSadd_parameter('time7','real', 1216.67, FLOAT_UNBOUND,
     $ FLOAT_UNBOUND)
      call AVSconnect_widget(param, 'typein_real')

      call AVSset_compute_proc(timeslice_compute)
C ----> START OF USER-SUPPLIED CODE SECTION #2 (ADDITIONAL SPECIFICATION INFO)
C <---- END OF USER-SUPPLIED CODE SECTION #2
      timeslice_desc = 1
      return
      end


C ****************************************
C Module Compute Routine
C ****************************************
      integer function timeslice_compute( invector, slicetime,
     $ outscalar, time0, time1, time2, time3, time4, time5, time6,
     $ time7)
      implicit none
      include 'avs/avs.inc'
      integer invector
      integer outscalar
      real slicetime
      real time0
      real time1
      real time2
      real time3
      real time4
      real time5
      real time6
      real time7

C ADD YOUR OWN CODE BETWEEN THE
C FOLLOWING COMMENTS. THE CODE YOU SUPPLY WILL NOT BE OVERWRITTEN.

C ----> START OF USER-SUPPLIED CODE SECTION #3 (COMPUTE ROUTINE BODY)
       integer dims0(3)
       integer n,istat
       real xa(8)
       integer inoffset,outoffset
       real inbase(2),outbase(2)
D      write(0,*)'Here we are in timeslice_compute'
C
C Free old field data
C
      if (outscalar .ne. 0) call AVSfield_free(outscalar)
C
C Allocate space for new field output
C
D      write(0,*)'Calling AVSfield_get_dimensions'
```

Appendix B

AVS Temporal Interpolation Module (cont.)

```
       call AVSfield_get_dimensions(invector,dims0)
D       write(0,*)'Calling AVSdata_alloc'
       outscalar = AVSdata_alloc(
     $  'field 3D 3-space 1-vector rectilinear real',dims0)
       if (outscalar .eq. 0) then
           call AVSerror('Allocation of output field failed.')
           timeslice_compute = 0
           return
       endif
C
C Copy the coordinate information from the input field.
C
D       write(0,*)'Calling AVSfield_copy_points'
        istat = AVSfield_copy_points(invector,outscalar)
        if(istat.eq.0) then
          call AVSerror(
     $      'Unable to copy coordinates from input to output.')
          timeslice_compute = 0
        endif
C
C Now compute the interpolated values.
C
        xa(1)=time0
        xa(2)=time1
        xa(3)=time2
        xa(4)=time3
        xa(5)=time4
        xa(6)=time5
        xa(7)=time6
        xa(8)=time7

D       write(0,*)'Calling AVSfield_get_int for veclen'
        n=AVSfield_get_int(invector,avs_field_veclen)

D       write(0,*)'Calling AVSfield_data_offset for in'
        call AVSfield_data_offset(invector,inbase,inoffset)

D       write(0,*)'Calling AVSfield_data_offset for out'
        call AVSfield_data_offset(outscalar,outbase,outoffset)

D       write(0,*)slicetime

        call timeslice_compute2(inbase(inoffset+1),
     $    outbase(outoffset+1),dims0(1),dims0(2),dims0(3),
     $    xa,n,slicetime)

        call AVSfield_reset_minmax(outscalar)

C <---- END OF USER-SUPPLIED CODE SECTION #3
       timeslice_compute = 1
       return
       end


C **********************************************************************
C Initialization for modules contained in this file.
C **********************************************************************
       subroutine AVSinit_modules
       include 'avs/avs.inc'
```

Appendix B

AVS Temporal Interpolation Module (cont.)

```
        external timeslice_desc
        integer timeslice_desc
        call AVSmodule_from_desc(timeslice_desc)
        end


C ----> START OF USER-SUPPLIED CODE SECTION #4 (SUBROUTINES, FUNCTIONS, UTILITY

        subroutine
     $    timeslice_compute2(indata,outdata,ix,iy,iz,xa,n,slicetime)
        implicit none
        include 'avs/avs.inc'
        real slicetime
         integer ix,iy,iz,i,j,k,l,n,istat,percent
         real xa(8),ya(8),y,dy
         real indata(n,ix,iy,iz)
         real outdata(ix,iy,iz)
         integer nd

D        nd = 0
D        write(0,*)'Here we are in timeslice_compute2'
D        write(0,*)ix,iy,iz,n,xa,slicetime
         do 1003 k=1,iz
           do 1002 j=1,iy
             do 1001 i=1,ix
               do 1004 l=1,n
                 ya(l)=indata(l,i,j,k)
 1004          continue
D              if(nd.le.100)write(0,*)i-1,j-1,k-1,(ya(l),l=1,n)
D              nd = nd + 1
               call polint(xa,ya,n,slicetime,y,dy)
               outdata(i,j,k)=y
D              if(nd.le.100)write(0,*)i-1,j-1,k-1,y,dy
 1001        continue
 1002      continue
           percent = int((float(k)/float(iz))*100.0)
D          write(0,*)percent
           call AVSmodule_status("Timeslice: processing...",percent)
 1003    continue
         return
         end

C <---- END OF USER-SUPPLIED CODE SECTION #4
```

Appendix C

AVS File Descriptor Module

```
#!/usr/local/bin/perl

($minlat, $minlong, $mindepth, $maxlat, $maxlong, $maxdepth) =
   (999999, 999999, 999999, 0, 0, 0);

#
# Get a file name
#

if(!$ARGV[0]) {
   print STDERR "csvtospy requires a filename root as its single argument.\n";
   print STDERR "If you want to process \"nov92.csv.Z\", type:\n\n";
   print STDERR "\tcsvtospy.pl nov92\n\n";
   exit;
}

#
# Now, read the raw CSV file and compute the extrema of latitude, longitude,
# and depth.
#

if(!(@lines = `zcat $ARGV[0].csv.Z`)) {
   print STDERR "Whoops, file \"$ARGV[0].csv.Z\" doesn't exist!\n";
   exit;
}

$currentstation = 0;
$nlines = 0;
foreach $line (@lines) {
   ($station, $reading, $latdeg, $latmin, $longdeg, $longmin, $year, $month,
      $day, $bottom, $depth, $temp, $salinity, $deltat) = split(/\s*,\s*/,$line)
#   print STDERR "$station, $reading, $latdeg, $latmin, $longdeg, $longmin, $yea
   $nlines += 1;
   if($station != $currentstation) {
      print STDERR "Station #$station\n";
      if($currentline) {
         push(@bottomlines,$currentline);
      }
      if($two eq "False") {
         push(@twolines,sprintf("%.2f %.2f %.2f %.2f\n",$long,$lat,-2.0,99.0));
      }
      if($fish eq "justright") {
        push(@eightlines,sprintf("%.2f %.2f %.2f %.2f\n",$long,$lat,0.0,8.0));
      } elsif($fish eq "toohot") {
        push(@eightlines,sprintf("%.2f %.2f %.2f %.2f\n",$long,$lat,0.0,8.0));
        push(@twentylines,sprintf("%.2f %.2f %.2f %.2f\n",$long,$lat,0.0,20.0));
      }
      $currentstation = $station;
      $fish = "toohot";
      $two = "False";
   }
   $lat = ($latdeg * 60.0) + $latmin;
   $long = ($longdeg * 60.0) + $longmin;
   $depth = -$depth;
   $temp = $temp / 100.0;
   if($lat < $minlat) { $minlat = $lat; }
   if($long < $minlong) { $minlong = $long; }
   if($depth < $mindepth) { $mindepth = $depth; }
   if($lat > $maxlat) { $maxlat = $lat; }
   if($long > $maxlong) { $maxlong = $long; }
```

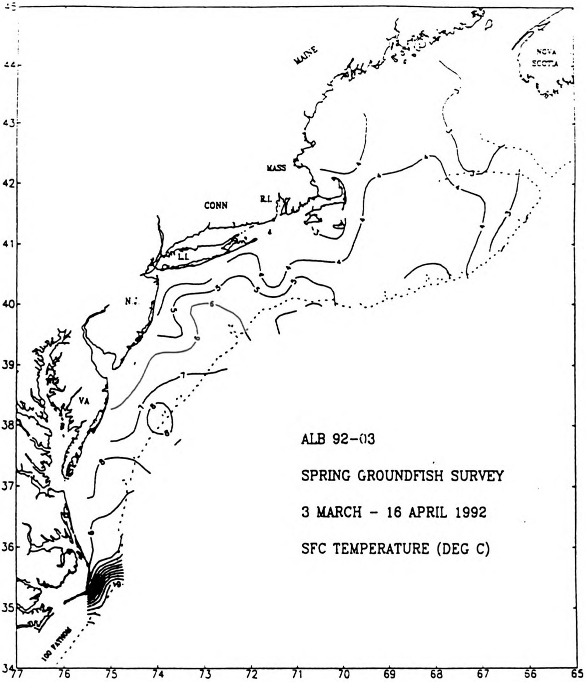
Appendix C

AVS File Descriptor Module

```
    if($depth > $maxdepth) { $maxdepth = $depth; }
    $currentline = sprintf("%.2f %.2f %.2f %.2f\n",$long,$lat,$depth,$temp);
    if($depth == -2.0) {
       push(@twolines,$currentline);
       $two = "True";
    }
    if($temp < 8.0) {
       if($fish eq "justright") {
          push(@eightlines,$currentline);
          $fish = "toocold";
       }
    } elsif($temp < 20.0) {
       if($fish eq "toohot") {
          push(@twentylines,$currentline);
          $fish = "justright";
       }
    }
}

open(TWO,">$ARGV[0].two.spy");
print TWO @twolines;
close(TWO);

open(BOTTOM,">$ARGV[0].bottom.spy");
print BOTTOM @bottomlines;
close(BOTTOM);

open(EIGHT,">$ARGV[0].eight.spy");
print EIGHT @eightlines;
close(EIGHT);

open(TWENTY,">$ARGV[0].twenty.spy");
print TWENTY @twentylines;
close(TWENTY);

exit;


#
# Now, read the raw CSV file and compute the extrema of latitude, longitude,
# and depth.
#

$nlines = 0;
while($line = <>) {
   ($station, $reading, $latdeg, $latmin, $longdeg, $longmin, $year, $month,
      $day, $bottom, $depth, $temp, $salinity, $deltat) = split(/\s*,\s*/,$line)
#   print STDERR "$station, $reading, $latdeg, $latmin, $longdeg, $longmin, $yea
   $nlines += 1;
   $lat = ($latdeg * 60.0) + $latmin;
   $long = -(($longdeg * 60.0) + $longmin);
   $depth = -$depth;
   $temp = $temp / 100.0;
   if($lat < $minlat) { $minlat = $lat; }
   if($long < $minlong) { $minlong = $long; }
   if($depth < $mindepth) { $mindepth = $depth; }
   if($lat > $maxlat) { $maxlat = $lat; }
   if($long > $maxlong) { $maxlong = $long; }
   if($depth > $maxdepth) { $maxdepth = $depth; }
   push(@lines,sprintf("%.2f %.2f %.2f %.2f\n",$long,$lat,$depth,$temp));
}

print "$nlines\n";
print @lines;
# print STDERR "$minlat, $minlong, $mindepth, $maxlat, $maxlong, $maxdepth\n";
exit;
```

Appendix D

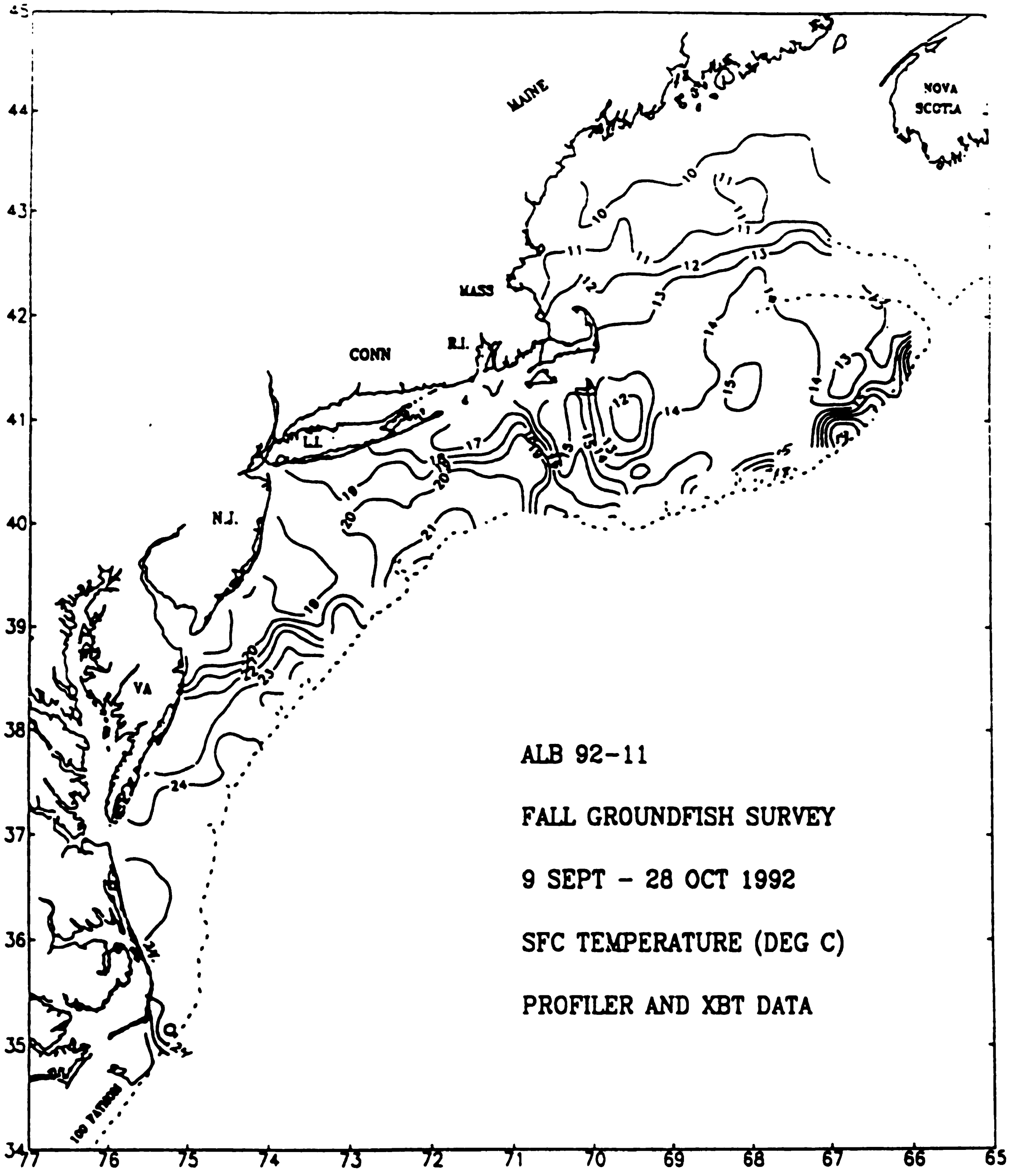
Ocean Surface Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1993.

Appendix D

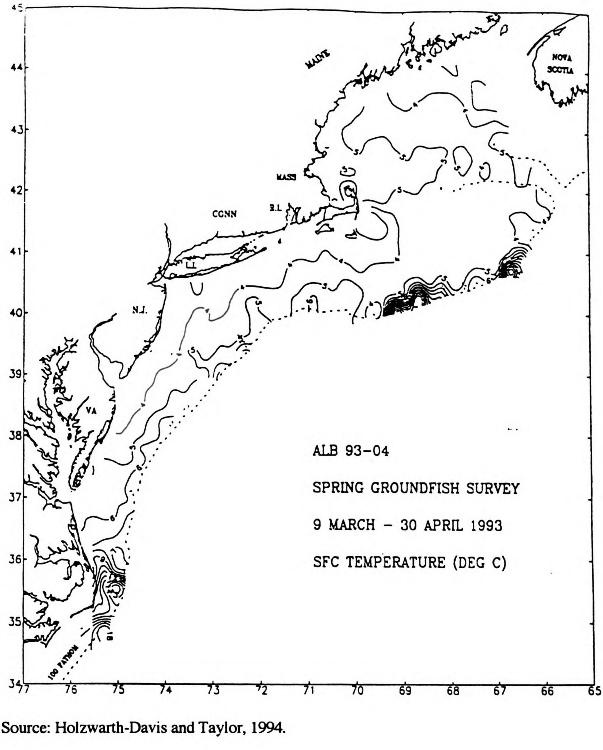
Ocean Surface Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1993.

Appendix D

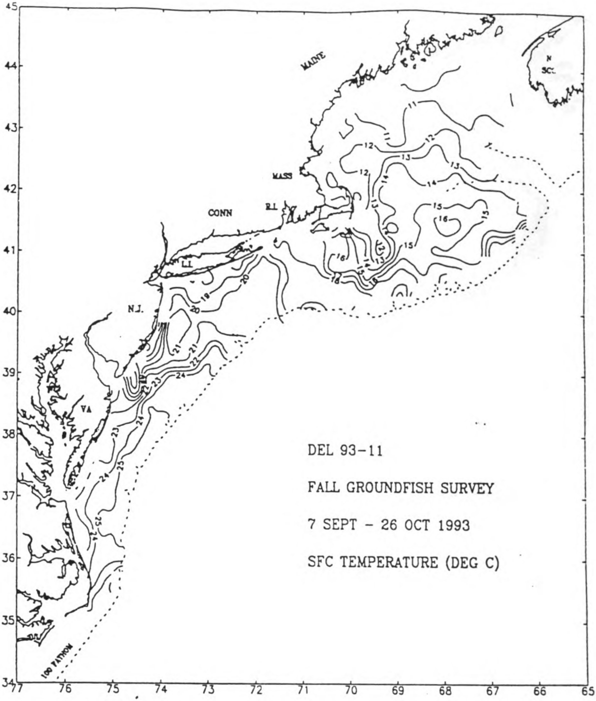
Ocean Surface Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1994.

Appendix D

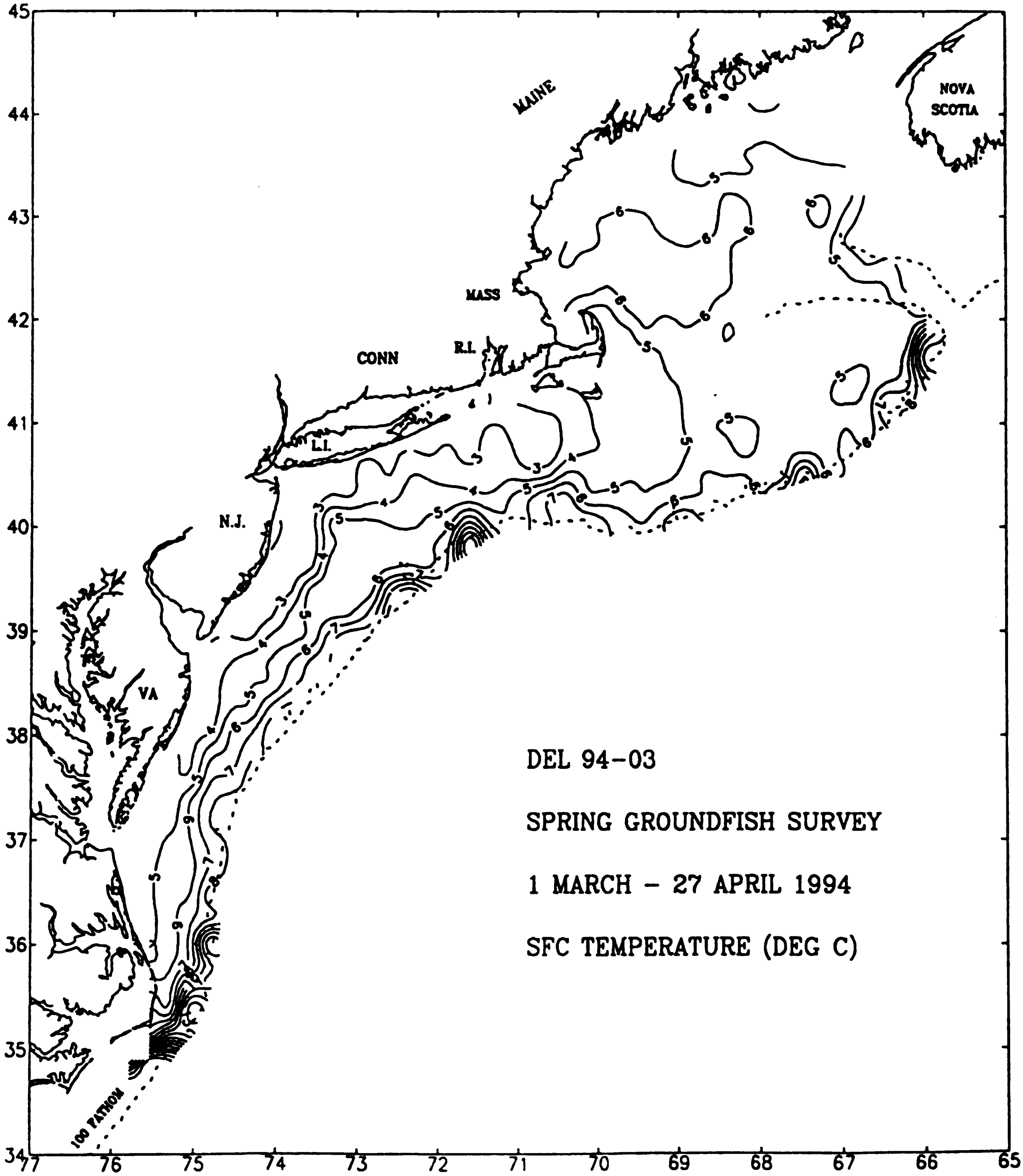
Ocean Surface Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1994.

Appendix D

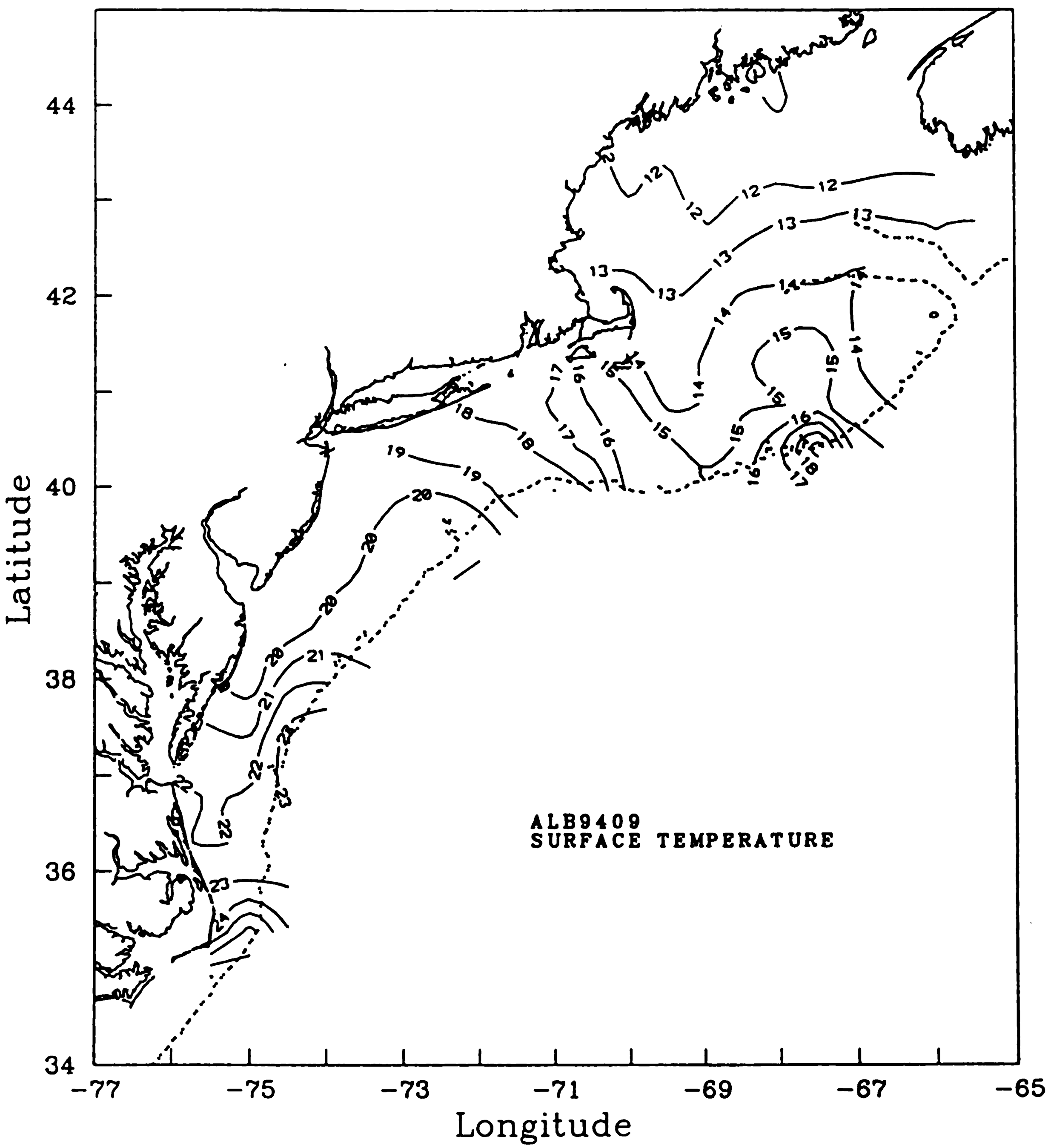
Ocean Surface Temperatures on the Northeast U.S. Continental Shelf



Source: Mountain, 1995.

Appendix D

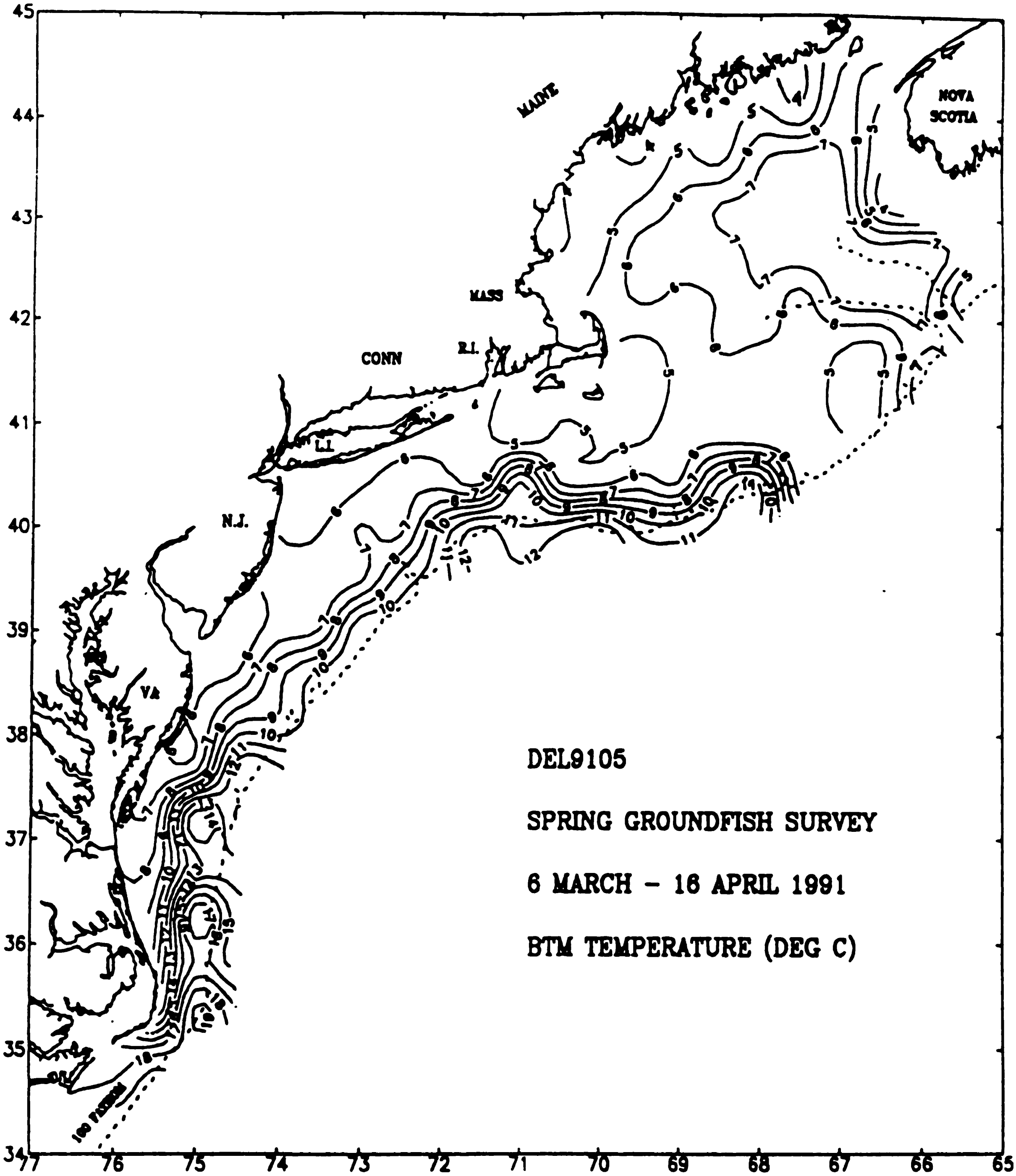
Ocean Surface Temperatures on the Northeast U.S. Continental Shelf



Source: Mountain, 1995.

Appendix D

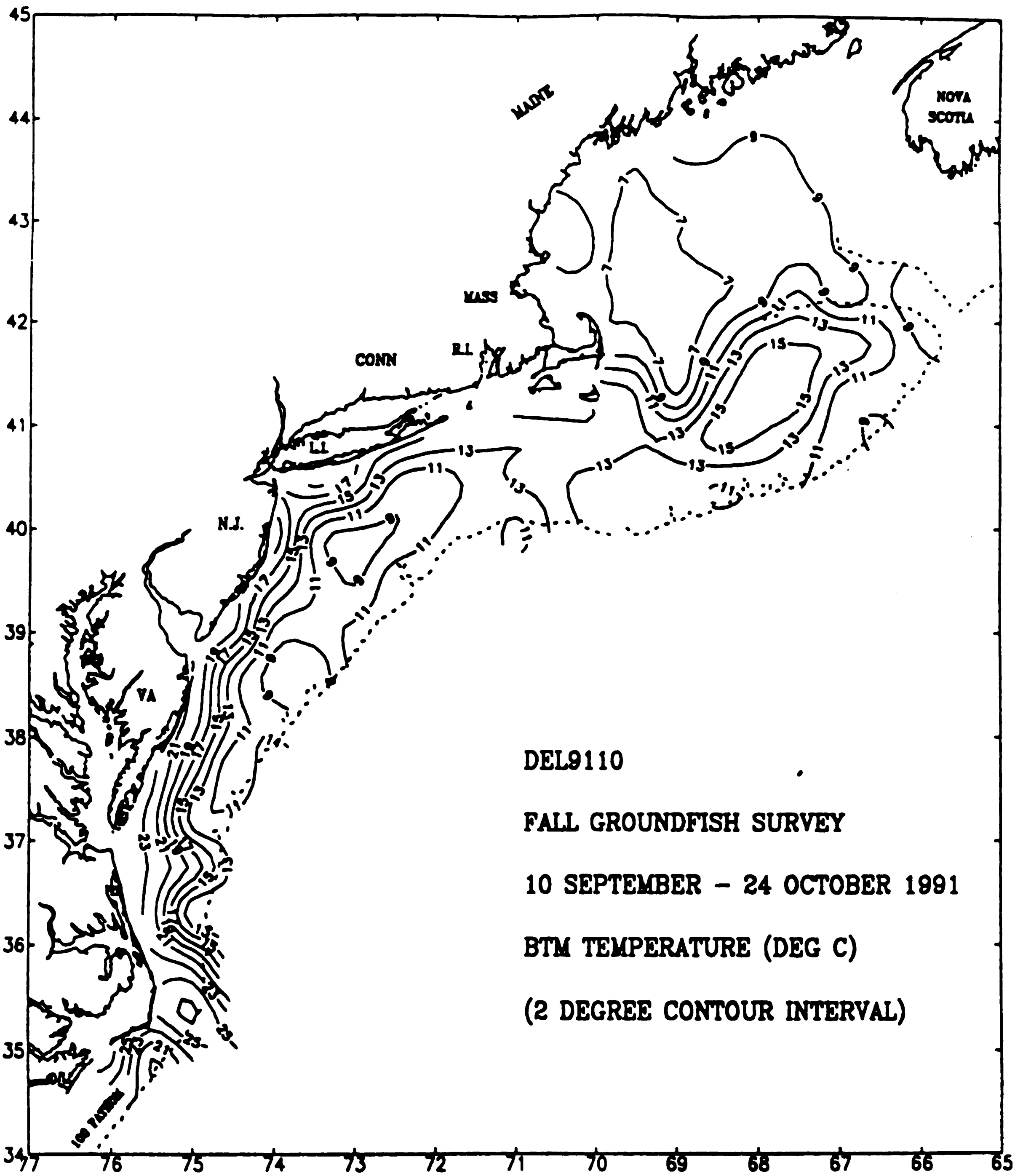
Ocean Bottom Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1992.

Appendix D

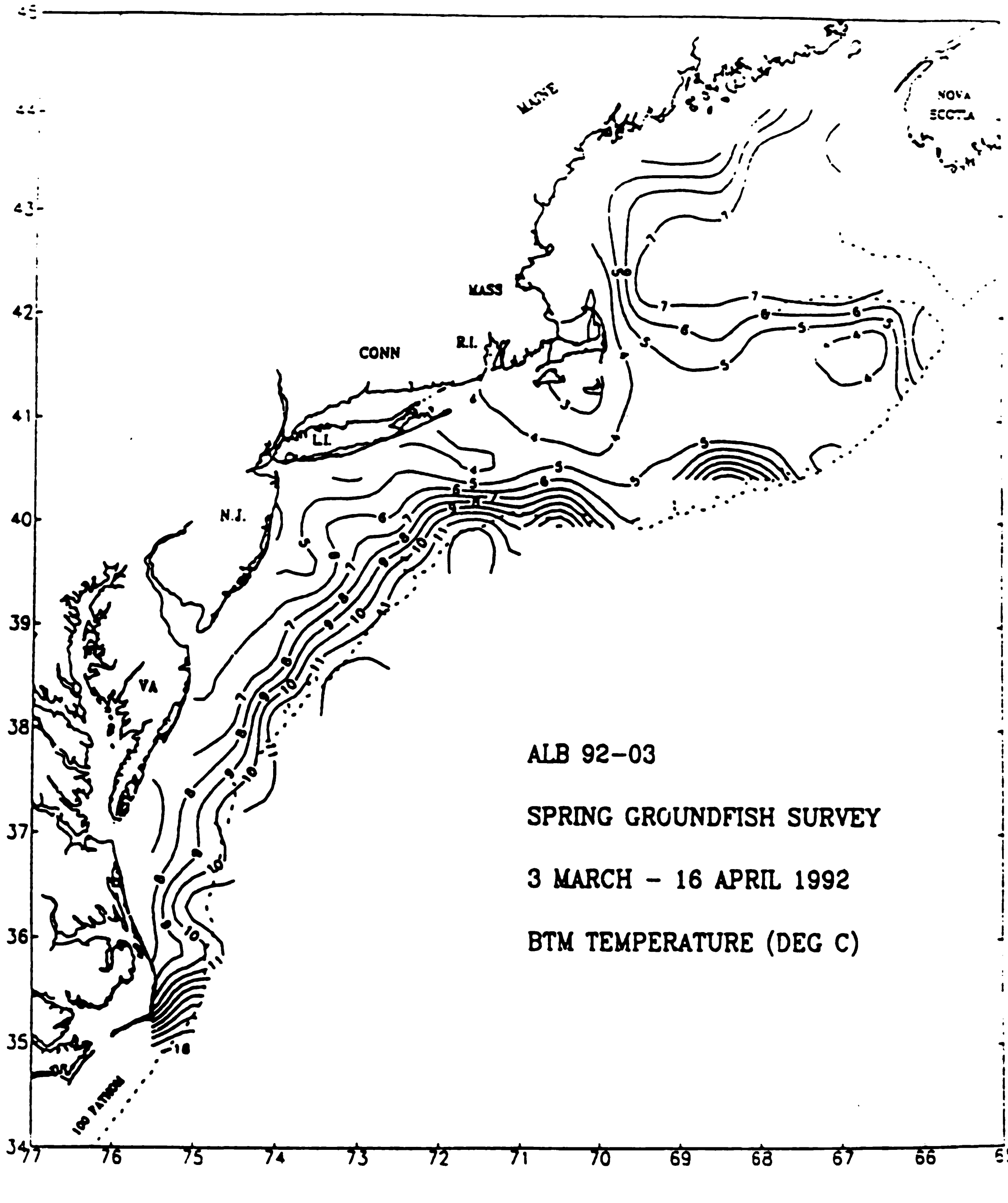
Ocean Bottom Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1992.

Appendix D

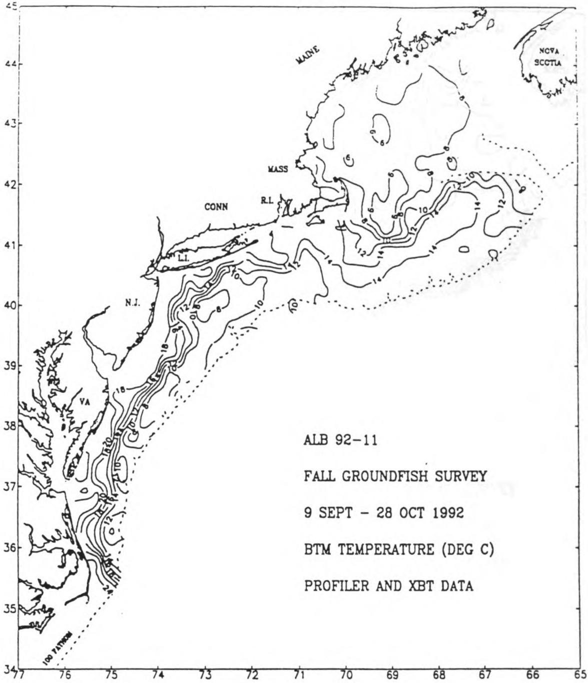
Ocean Bottom Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1993.

Appendix D

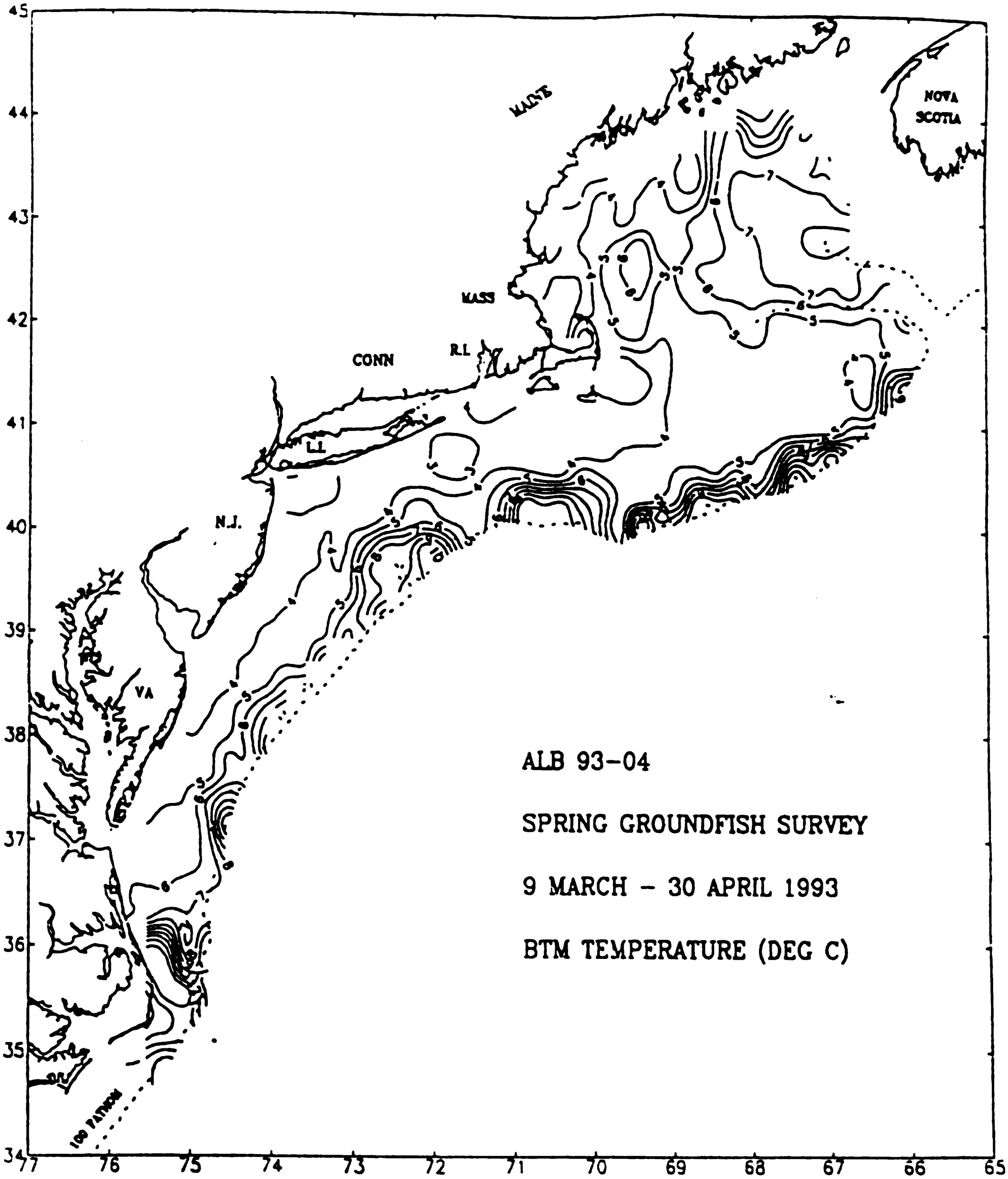
Ocean Bottom Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1993.

Appendix D

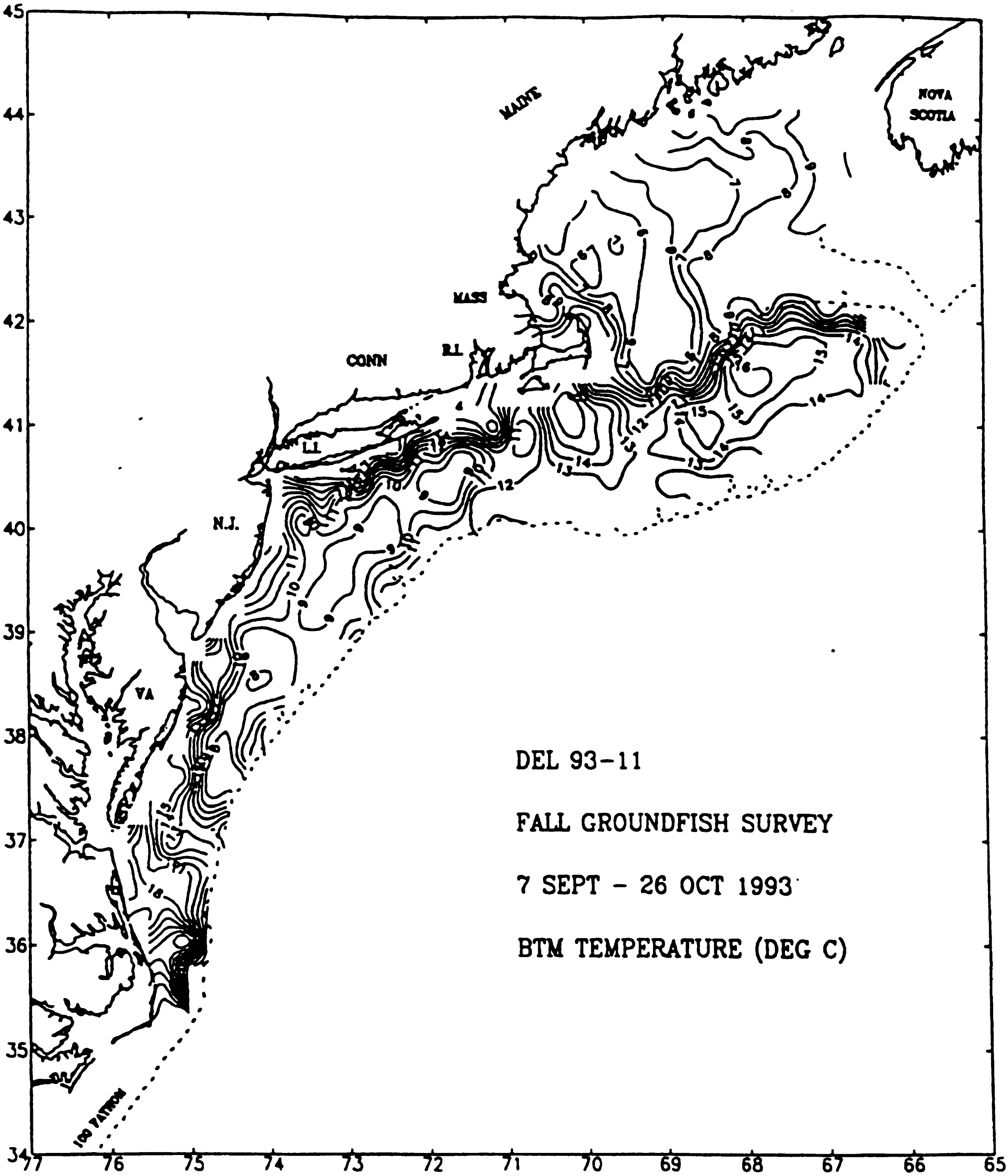
Ocean Bottom Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1994.

Appendix D

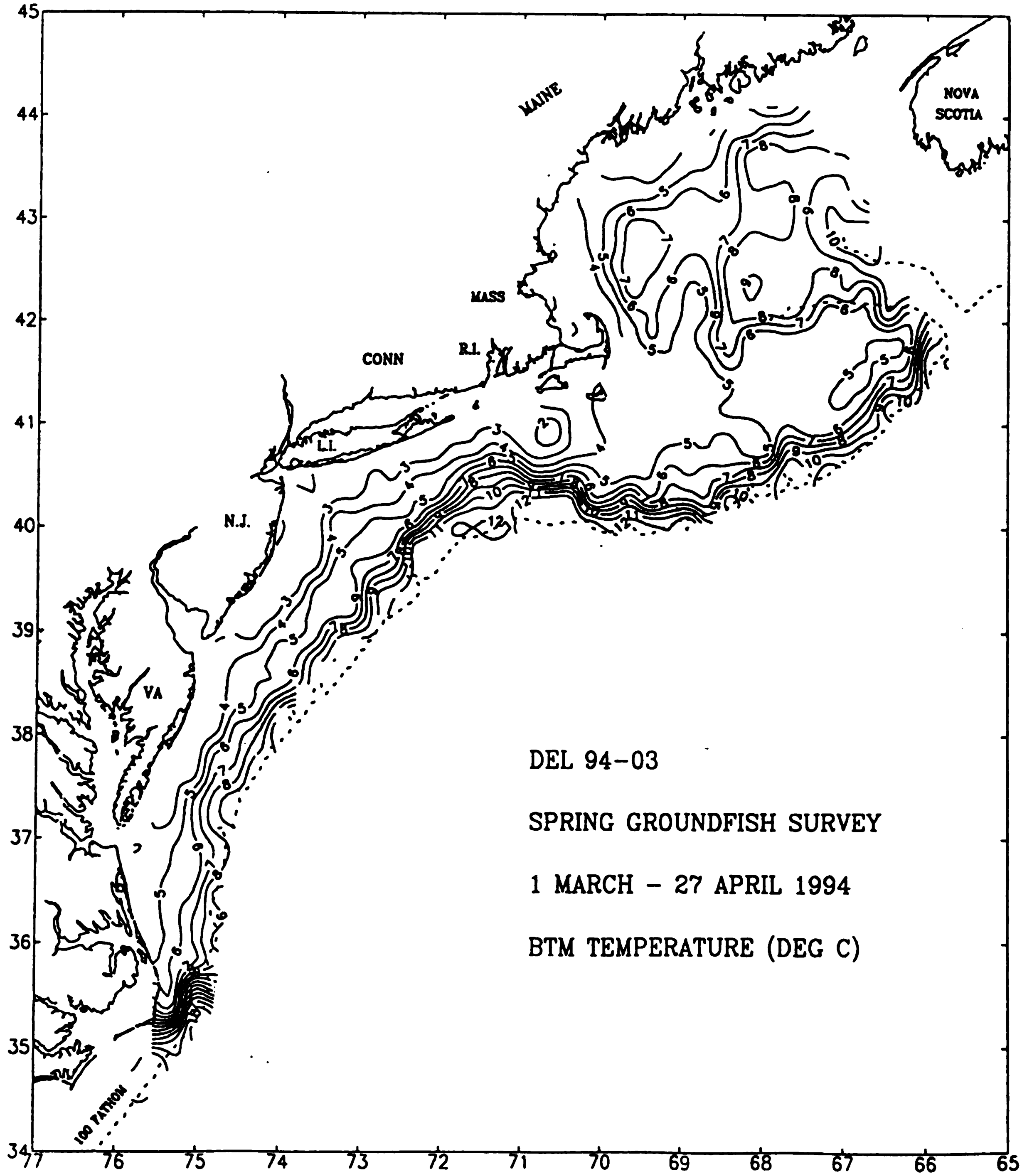
Ocean Bottom Temperatures on the Northeast U.S. Continental Shelf



Source: Holzwarth-Davis and Taylor, 1994.

Appendix D

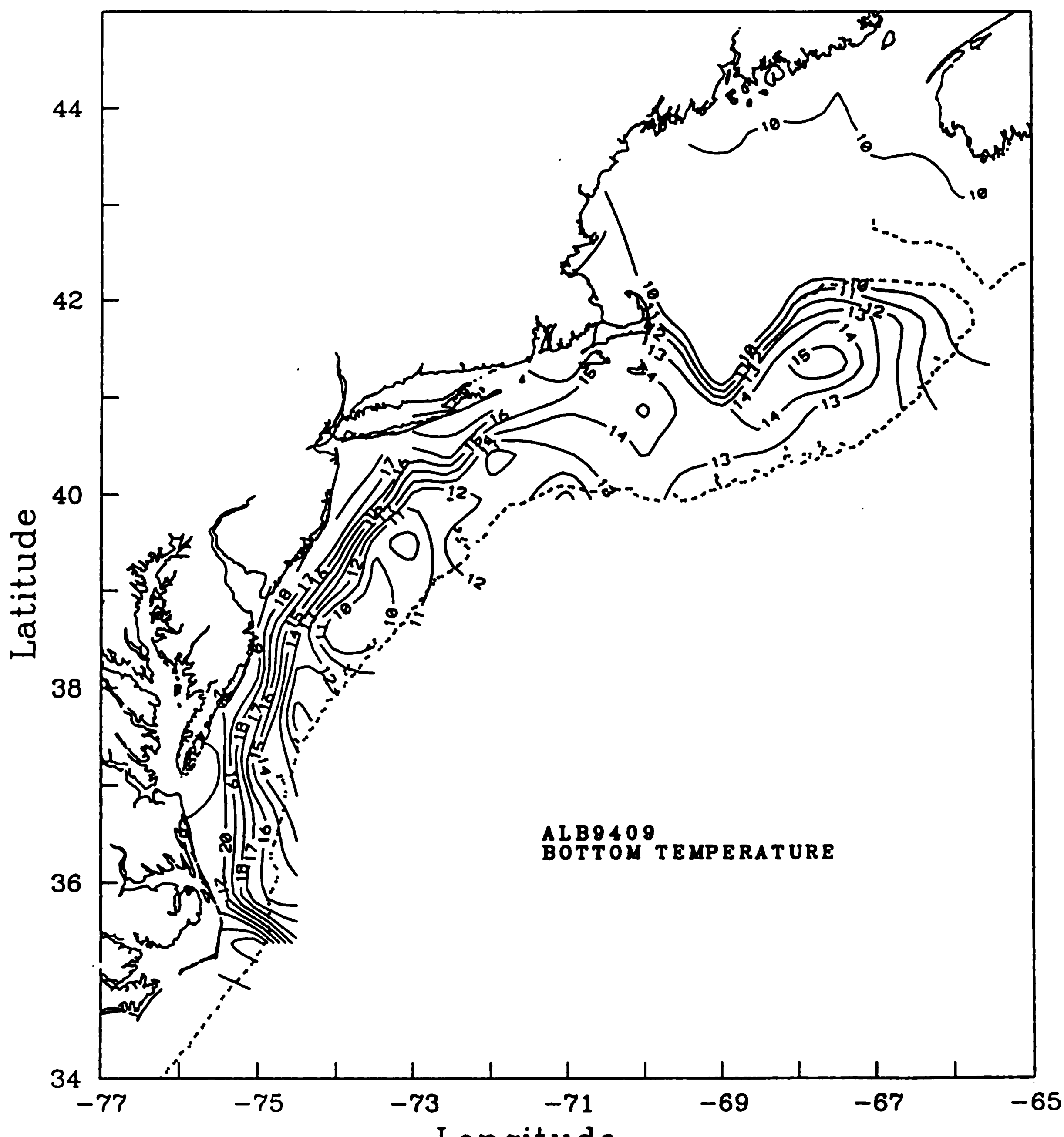
Ocean Bottom Temperatures on the Northeast U.S. Continental Shelf



Source: Mountain, 1995.

Appendix D

Ocean Bottom Temperatures on the Northeast U.S. Continental Shelf



Source: Mountain, 1995.

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List of Hardware and Software used in Thesis

Hardware:

Apple® Macintosh Quadra® 700

IBM RS/6000 POWERstation 560

Software:

AVS™ 5
Advance Visual Systems Inc.
Waltham, Mass.

Macromedia Director® 4.0.3
Macromedia, Inc.
San Francisco, CA.

Spyglass® Dicer® Version 2.0
Spyglass, Inc.,
Champaign, IL.

QuickTime™ 2.0 and QuickTime 2.0.2 for Windows™
Apple Computer, Inc.
Cupertino, CA

SPARKLE2.3 by Maynard Handley 1994.
SPARKLE2.3.sit.hqx
gopher://gopher.archive.umich.edu:7055/11/mac/util/graphicsutil

MovieMaker1.3 by Jesse Jones 1993.

Internet Resources:

AVS Modules (Write MooV, plot_xyz, trivar)

International AVS Center (IAC) at the North Carolina Supercomputer Center

ftp://avs.ncsc.org

Data Acquisition

National Marine Fisheries Service (NMFS), Woods Hole, MA.

ftp site: ftp.wh.whoi.edu directory: /pub/hydro/