AN ABSTRACT OF THE DISSERTATION OF

Tiffany C. Vance for the degree of Doctor of Philosophy in Geography presented on December 7, 2007.
Title: If You Build It, Will They Come? Evolution Towards the Application of Multi-Dimensional GIS to Fisheries-Oceanography.

Abstract approved:

Dawn J. Wright

The development of new technologies in science is a balance between existence and use. There are three versions of this duality – something is built and users come, something is built and users don't come, and, finally, potential users show up but the ballpark has not yet been built. In each instance there is a combination of three factors at work. The first is a scientific *need* for a type of data or analysis. The second is a *technology or technique* developed to meet the need; and the third is a *perception* that using the technology is somehow "better" that the existing tools and that the tool is easy to use.

This work examines closely the development of a tool within oceanography – the Stommel diagram for displaying the time and space spectra of oceanographic phenomena – and the spread of the use of the diagram to other disciplines. The diagram was the product of a number of elements - the mind of a truly original oceanographer, the development of equipment able to collect the detailed temporal and spatial data used to create the plot, and the rise of "big oceanography", which led Stommel to argue

graphically for taking care in the design of expeditions.

Understanding the spread of the Stommel plot provides a viewpoint for examining the unexpectedly slow development of multi-dimensional geographic information systems (GIS). The development of GIS's began in the 1970's. Data structures to hold multi-dimensional data have been developed, tools for multi-dimensional map algebra have been created, and test applications have been developed. The current non-development of multi-dimensional GIS is examined as a background for creating and disseminating GeoModeler, a prototype of scientific GIS able to ingest and display multi-dimensional data. Taking advantage of recent technical developments, we have created a scientific GIS that can display three-dimensional oceanographic data. GeoModeler is used to visually explore and analyze the relationship between water temperature and larval walleye pollock (*Theragra chalcogramma*) growth in Shelikof Strait, Alaska.

If You Build It, Will They Come? Evolution Towards the Application of Multi-Dimensional GIS to Fisheries-Oceanography

by
Tiffany C. Vance

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented December 7, 2007
Commencement June 2008

Doctor of Philosophy dissertation of Tiffany C. Vance
presented on December 7, 2007 .

APPROVED:

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Major Professor, representing Geography

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Chair of the Department of Geosciences

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Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Tiffany C. Vance, Author

ACKNOWLEDGEMENTS

This dissertation is the product of the guidance and assistance of many people. Deep thanks to my committee members: Dawn Wright, Ron Doel, Gordon Matzke, A. Jon Kimerling, Bruce D'Ambrosio and Nick Pisias. Dawn Wright provided invaluable encouragement. Special thanks to Ron Doel and Gordon Matzke for extended conversations and exchanges at those crucial points when this effort might have run aground. Professor Nick Chrisman, now of Université Laval, provided wise counsel early in the process. Joanne van Geest, Melinda Peterson, and Katherine Hoffman of the Department of Geosciences and the Ecosystem Informatics IGERT program provided flawless advice and assistance in dealing with the bureaucratic underpinnings of the graduate student life while Mark Meyers provided invaluable technical support.

Financial support was provided by the National Science Foundation via an IGERT graduate fellowship in Ecosystem Informatics (NSF award 0333257) at Oregon State University, NOAA's Advanced Studies Program, NOAA's High Performance Computing and Communications program, and the NOAA/NMFS/AFSC Recruitment Processes Program.

I especially appreciate assistance of a number of librarians and archivists who have helped me to find the materials that I needed to tell this story. With thanks, I acknowledge the assistance of Deborah Day of the Scripps Institution of Oceanography Archives; Marissa Hudspeth, Lisa Raymond, and Rosemary Davis of the Data Library and Archives, Woods Hole Oceanographic Institution; Sonja Kromann of the NMML

Library in Seattle; and the librarians of the Architecture and Urban Planning branch library of the University of Washington.

Many people have been generous with their time and memories. Carl Wunsch, David Schneider, Peter Wiebe, John McGowan, Bob Reid, and Andrew Vastano provided the third dimension to my thoughts about Henry Stommel and his work.

The editorial comments and suggestions of Nazila Merati, Kristine Harper, Jeff Napp, Sharon Mesick and May Yuan are gratefully acknowledged. Gary Stauffer provided encouragement and the time and place to do much of this work.

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Encouragement and moral support have come from a number of quarters. Lynn and Ed Long provided a wondrous home away from home in Salem, without which this would have been a very much harder task. The men and women of the Amtrak *Cascades*, Amtrak personnel at both Seattle's King Street Station and Portland Union Station, and the ground and air crews of the Horizon Airlines *Portland Shuttle* provided much more than transportation. Their kindnesses made the early mornings, long days, and late nights not only bearable but also enjoyable. My colleagues in the Geography, Ecosystems Informatics IGERT, and History of Science programs challenged my assumptions and taught me by example. Capt. Terry Christensen and Dutton did me a great service by pointing me to David Kaiser's work on Feynman diagrams.

Friends around the world provided encouragement by asking "How is it going?" at the right times, and not asking "It is done yet?" at the wrong moment. JCDM and RPMM provided continual lessons on the importance of close investigation of one's three-dimensional environment at the beginning of the process – if only they could have seen the end. E-dd is providing endless diversions at the end of the process. LB and Boswell were steadfast companions for the whole journey.

CONTRIBUTION OF AUTHORS

Ronald E. Doel is the co-author of Chapter 3. Nazila Merati, Sharon Mesick, Christopher Moore, and Dawn J. Wright are co-authors of Chapter 5. Annette Dougherty is a co-author of Chapter 7. Christopher Moore provided the programming wizardry that made GeoModeler possible.

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DEDICATION

In memory of Professors Jean and Jay Vance, who always believed it *could* happen.

To Professor Paul Groth, who persuaded me it *should* happen.

To Nazila Merati, whose patience and support ensured it *would* happen.

If You Build It, Will They Come? Evolution Towards the Application of Multi-Dimensional GIS to Fisheries-Oceanography

Chapter 1: Introduction

"If you build it, he will come."
Field of Dreams, W. P. Kinsella, 1989

While this spare phrase proved sufficient to evoke the ghost of Shoeless Joe Jackson and the other members of the 1919 Chicago Black Sox, the same cannot always be said for the development of new technologies in science. There are three possible versions of this duality – something is built and users come, something is built and users don't come, and, finally, potential users show up but the ballpark has not yet been built. Whether the development is a new tool for gathering data, or a new graphical technique for analyzing the data, if these do not meet a perceived need users may not congregate. Even if a new technique is accepted and used, the need it meets may not be that which the developer originally intended. In turn, a need may be widely described while a technology to mitigate it remains either undeveloped or unused. In this case, a theoretical need may not translate into a practical need.

This work will examine two examples of the build/come duality. The first is a case where a technology was built and it was used, but the audience who most used it was not the one originally anticipated. In the second case, the technology has not yet been fully built, though many argue users would come if it were to be built. In each instance there is a combination of three factors at work. The first is a scientific *need* for a type of data or analysis. The second is a *technology or technique* developed to meet the need; and the third is a *perception* that using the technology is somehow "better" that the existing tools and that the tool is easy to use. The technology can be both cause and effect; in some cases the result of a new technology can drive the need for a second technological development. In the examples studied in this work, the relative importance of the three factors is not equal, and this leads to some intriguing differences among the situations.

The impetus for this investigation was a comment made at the 2002 University Consortium for Geographic Information Science (UCGIS) Summer Assembly in Athens, Georgia that questioned the need for truly three-dimensional representations.[1] The comment was part of a discussion during a breakout session entitled “Multimedia and Visualization” where researchers were proposing and defining long- and short-term research priorities for geographic information science (http://www.ucgis.org/priorities/research/2002researchagenda.htm).

This led me to wonder: what might underlie such a comment? One argument in geography is that the computational and perceptual costs of adding another dimension outweigh the benefits (DiBiase et al., 1994). While these doubts are valid, they still beg the question: why do some geographers still debate the necessity of three and higher

[1] Dawn Wright, pers. comm., 5 September 2007.

dimensional representations of data, while oceanographers and meteorologists take four dimensions for granted, and often seek to use five or more dimensions?

At its most simplistic, the difference may be related to the dimensionality of the phenomena that each research community studies. The surface of the earth is really 2.5 dimensional - that is, it is a surface warped in space, but the volumes that cause the warping are not the primary concern. For geographers, the surface of the earth is probably the primary area of interest - at least if one is not a geomorphologist. For an urban geographer, the patterns of human use and change on the surface (2.5D) are studied through time (1D) for a total "world" of 3.5D. How the vertical dimension (the traditional third dimension) is used is of only relatively minor interest unless one is an architectural historian. For geologists three spatial dimensions are important - but data collection is frequently via the means of two-dimensional outcroppings.

In contrast, the ocean and the atmosphere are inherently three-dimensional. Air masses and ocean currents are volumes. The basic unit used to express the characteristics of an oceanic current is not usually current speeds but rather is the Sverdrup (Sv), which is a measure of volumetric mass transport. If the world being studied is inherently 3D (x, y and z) then the addition of time makes 4D the *lingua franca* and modeling efforts can easily add further dimensions - at least in the mind of the researcher.

Another contrast between geography and oceanography/meteorology might be called the “level of technology” factor. Both oceanography and meteorology are very technical disciplines. Collection of multidimensional meteorological data started in the 1930's. The 1930’s also saw the start of frequent collection of three-dimensional data in the oceans. In both disciplines, soundings had been used for considerably longer to gather quasi-3D data. With the availability of large volumes of data it became possible to initialize multidimensional models - leading to the need to understand and display these data. This made the use of three-dimensional analysis and visualization tools fairly self-evident.

It seems considerably harder to gather multidimensional data for geographic questions - especially to collect temporal data (Owens, 2007). While newer remotely sensed data are making this process easier for physical geographers, for human and cultural geographers the collection of data for the past may well mean time-consuming surveys of archives, census records, historical accounts, and old maps. Few of these techniques lead to the gathering of the massive datasets that demand some sort of automated analysis and visualization.

A third and final consideration comes into play. For want of a better term, I will call it the philosophical difference. In geography, cartography is a separate research area. Research into perception, techniques and the use of symbols is commonplace. Introspection leads to questions such as, “is a 3D visualization really a map?” For oceanography and meteorology visualizations are simply another tool. The data are multidimensional, so the views of the data need to be multidimensional. There is considerably less angst about the straightforward use of a tool. From the scientific side there is no field of "oceanographic visualization studies" - except maybe in computer science, psychology, or the newer disciplines of informatics, e.g. ecosystem informatics.

Interestingly, given all the arguments against the need for multi-dimensional geographic information systems (GIS), some geographers strongly perceive that it is needed. The arguments for a multi-dimensional GIS are as strong, or stronger, than those against. In practice, techniques for storing multi-dimensional data have been created, technologies for displaying visualizations have been developed, and software for creating both analyses and visualizations have been created -- in theory at least. What has not yet been built is a commercially available volumetric multi-dimensional GIS. Tools that simply visualize volumes do not provide spatial and analytical capabilities such as storing the data in a relational database, the ability to query the data, or tools for calculating buffers and spatial intersections, and thus are not a true GIS. The capability to read in and write GIS formatted data without being able to perform spatial analyses is insufficient. While a commercial product is not the only definition of the creation of something, it does provide a very concrete example of a technology. To understand the acceptance of new technologies, this work explores the development of a new graphical technique in oceanography, its widespread acceptance outside oceanography and the reasons for this mis-match. This balance of need, technology and the perception of usefulness is contrasted with the balance of the same factors in the (non)development of multi-dimensional GIS. The goal is to apply the lessons of the former to the future of the latter.

The first example studied in this work is the development of a graphical technique to meet the need to plan for the collection of large oceanographic data sets. This need was the direct result of the great expansion in oceanographic data collection techniques after WWII. With the development in the 1950's and 1960's of technologies such as conductivity-temperature-depth (CTD) sensors for water properties, moored current meters, and a variety of continuous plankton samplers, oceanographers were able to gather large amount of spatial and temporal data about the oceans. These technologies created a need for simple graphical summaries of large datasets. For some scientists this need was pedagogical: they saw danger in the prospect that these new developments would overwhelm scientific reason, and lead to collecting data for the sake of collecting data. To counter this, they sought a visual way to represent the targets of data collection. Others had collected these datasets to test hypotheses, and simply needed a way to present the results clearly. At the same time, computers were being developed to handle the analysis of large data sets and output devices to display these visualizations, such as CRT monitors, were being used for graphical display.

In 1963, the oceanographer Henry Stommel created a new graphical tool in response to these new data collection technologies. It was the Stommel diagram, a plot of the time and space spectra of oceanic phenomena (Figure 1). The diagram was the

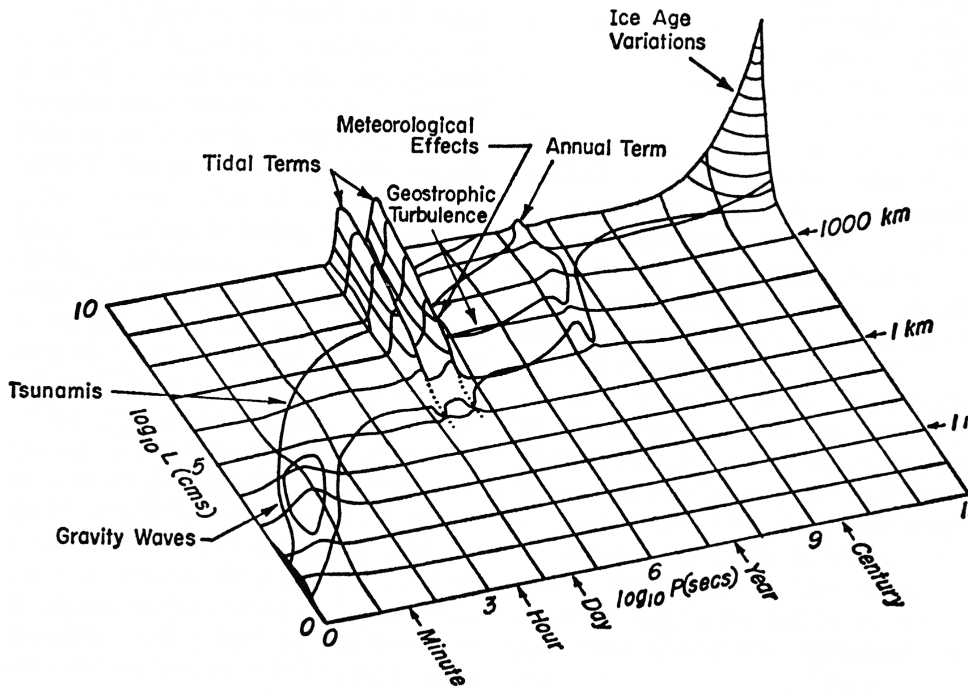

Figure 1 The original Stommel diagram. “Schematic diagram of the spectral distribution of sea level”. Reproduced from Henry Stommel. “Varieties of Oceanographic Experience”, Science 139 (1963): 373. Used with permission from AAAS.

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product of a number of elements - the mind of a truly original oceanographer, the development of equipment able to collect the detailed temporal and spatial data used to create the plot, and the rise of "big oceanography", which led Stommel to argue graphically for taking care in the design of new expeditions (Figure 2). In this case the

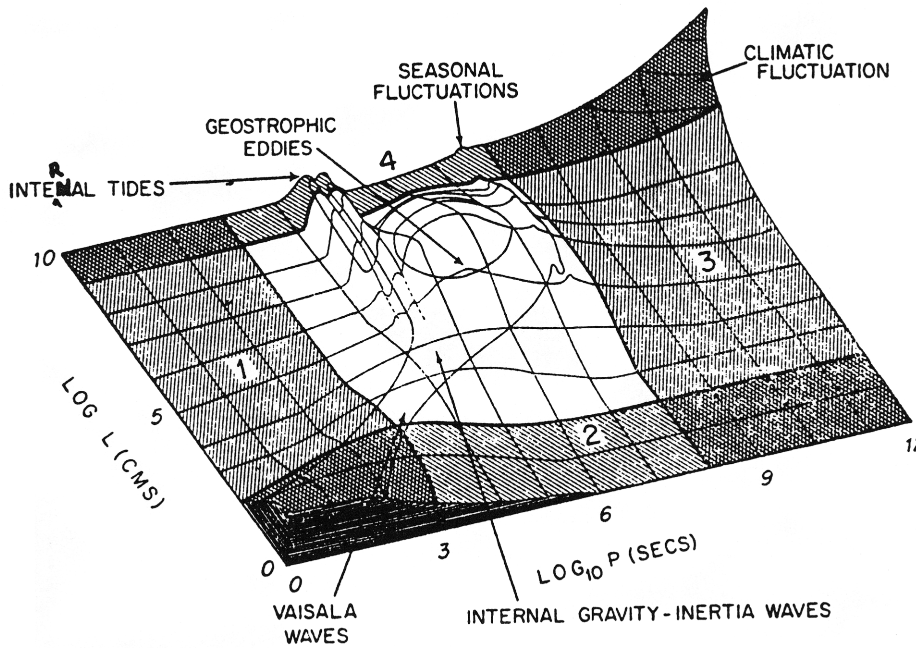

Figure 2 Diagram from Stommel (1965) showing the phenomena that can be sampled during a research expedition to study the Kuroshio Current. "In a program where reversing bottles and thermometers are the only measuring instruments, regions 1 and 2 cannot be measured because of the time constant of the thermometer-bottle system, and the uncertainty of depth determination respectively. Region 3 is inaccessible because the measurements are confined to a two-year program; Region 4 is excluded because of the limited size of the survey area." Diagram reprinted in Hogg and Huang (1995) and used with permission of the American Meteorological Society.

new technologies of oceanographic data gathering led to a need for a new graphical tool. But, the perceived benefits of this new graphic were not universal. While biological oceanographers saw it as a simple straightforward way to summarize spatio-temporal patterns, physical oceanographers did not share the need for a graphical summary. They continued to use earlier mathematical descriptions and two-dimensional plots. The plot was used extensively by a number of terrestrial and atmospheric disciplines. In these disciplines, the diagram was used more as a research tool than as the planning tool Stommel first envisaged. The tools leapt into other disciplines in unexpected ways. Understanding this process provides clues to ways in which new methods can be developed and introduced to potential users.

In contrast, the need for a multi-dimensional GIS has been stated for decades. The development of GIS's began in the 1970's. Data structures to hold multi-dimensional data have been developed, tools for multi-dimensional map algebra have been created, and test applications have been developed. Conferences have been held; books have been written. Examples include Raper's (2000) classic book *Multidimensional geographic information science*, Breunig's (2001) book entitled *On the way to component-based 3D/4D geoinformation systems,* and Caluwe et al. (2004) Spatio-*temporal databases: flexible querying and reasoning*. But, there is still not a widely available implementation of multi-dimensional GIS. Current efforts such as ESRI's ArcGlobe and 3DAnalyst products display 2.5-dimensional data and drape data over a spherical globe. They do not support the storage and display of convex hulls or volumes and cannot perform analyses such as intersecting a three-dimensional line with a volume. In this case there is the research need to display multi-dimensional data. There is the technology available in both data structures to store the data and visualization techniques to display them.

This work explores the development and adoption of new multi-dimensional display tools within oceanography and fisheries. It examines closely the development of a tool within oceanography – the Stommel diagram for displaying the time and space spectra of oceanographic phenomena – and the spread of the use of the diagram to other disciplines. This example provides insights into the processes of creating a new tool, and the path that a tool may take after its development. Understanding the spread of the Stommel plot provides a viewpoint for examining the unexpectedly slow development of multi-dimensional GIS. The current non-development of multi-dimensional GIS is examined as a background for creating and disseminating a prototype of scientific GIS able to ingest and display multi-dimensional data. Taking advantage of recent technical developments, we have created a scientific GIS that can display three-dimensional oceanographic data. This prototype is then used to visually explore and analyze the relationship between water temperature and larval pollock (*Theragra chalcogramma*) growth in Shelikof Strait, Alaska.

Chapter 2 describes the semantics that I will be using - as there seem to be a number of terms that get used in multiple ways depending upon the discipline. As time is so much a part of multidimensional views of the world, I will then provide a short introduction to space and time in geography. Following this I will provide brief summaries of the history of multidimensional cartography - including perspective maps, topographic maps and truly multidimensional maps; block and profile plotting in geology; multidimensional modeling in meteorology - including earlier two-dimensional maps, data collection and mapping and modern animated weather maps and scientific visualizations; and multidimensional data collection and display in oceanography and fisheries ecology- again considering both the technology for data collection and the computation of scientific plots, maps and visualizations.

Chapters 3 and 4 are a consideration of a particular example of a multi-dimensional plot, the Stommel diagram, and the ways in which it diffused, and didn't diffuse, into other disciplines. The history of the Stommel diagram is described in chapter 3 and the associated technological and political factors that provided the backdrop for the creation of the diagram are detailed. The diagram is placed in the larger structure of Stommel's works and its relationship to his thoughts on the planning of expeditions is detailed. At the same time, Stommel's intentions in creating the diagram are explored and contrasted with the ways in which others used the diagram. This chapter will be submitted to *Historical Studies in the Physical Sciences* as a manuscript entitled "Henry Stommel and the emergence of multi-dimensional plotting: transferring techniques across scientific disciplines" with Ronald Doel as co-author. In chapter 4, techniques for analyzing the diffusion of scientific ideas are detailed and are used to track the spread of the diagram into other disciplines. Finally, the Stommel diagram is deconstructed and the elements are applied to the creation of a new Stommel diagram. Current and possible future efforts to create new Stommel diagrams are described.

Chapter 5 provides a brief history of the development of multi-dimensional GIS’s from the mid-1960’s – when the Stommel plot came into common use – to the present. This was a time of rapid developments in the technologies for data collection and processing. It became possible to collect spatially and temporally detailed datasets to study phenomena and it became possible to process and view these datasets via the tools of computer cartography, GIS and finally visualization and virtual reality. These parallel developments in technologies for data gathering and technologies for analyzing data built upon each other rapidly.

Chapter 6 details the development of a prototype of a scientific GIS that provides some tools for analyzing and displaying multidimensional data. New applications programming interfaces (API's) have made it possible gain access to the analytical tools embedded in a GIS. The use of Java as a tool to link analytical tools and traditional geographic information systems provides a way to test techniques for a multi-dimensional GIS. The prototype of a scientific GIS, called OceanGIS/GeoModeler, is able to ingest and manipulate three-dimensional data. The prototype can be used to explore both the technical aspects of creating such a tool and the factors that might ease the acceptance of the application. The technical aspects of the tool, and the development of the tool are detailed. A number of specific analytical needs are described, and the elements of the tool that meet these needs are illustrated. This paper has been published as a peer-reviewed article entitled “GeoModeler: Tightly linking spatially-explicit models and data with a GIS for analysis and geovisualization" [Vance, T.C., N. Merati, S. Mesick, C.W. Moore, and D. Wright. *15th ACM International Symposium on Advances in Geographic Information Systems* (ACM GIS 2007)].

Chapter 7 describes an application of the tools in OceanGIS/GeoModeler to a problem in fisheries oceanography. Multi-dimensional temperature and salinity data are combined with data on the size and development of otoliths in pollock larvae to explore the relationship of environmental factors to daily increment development. While previous works have considered the temperature at the sea surface or at a single depth, this work considers the water column as a fully three-dimensional entity. Ancillary data, including satellite data and modeled current data, are added to the visualization and analyzed using GIS based tools. These results will be submitted as a paper co-authored with Annette Dougherty.

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Chapter 2: History of multidimensionality in mapping and plotting in the earth sciences – to 3-D or not to 3-D?

Introduction

One of the basic tenets of cartography is that reducing the dimensionality of a phenomenon can be the key to its display, and ultimately to understanding. The spherical world with three dimensions is reduced to two dimensions in the paper of a map; the four dimensions of oceanographic and atmospheric phenomena are reduced to three dimensions in a scientific visualization. Geographers have traditionally created two-dimensional maps but, many geographic topics, for example the locations of the transcontinental railroads, human settlement patterns or the diffusion of organisms, are inherently four-dimensional. Intuition would suggest that a three-dimensional analysis and display of these phenomena is warranted. In most cases though, their display and representation are two-dimensional. This seeming over-reduction of dimensions extends even to new technologies. Researchers have spoken of a multi-dimensional geographic information system (GIS) for years, and there is still not one commercially available. There are GIS and visualization tools that can display multidimensional data but they cannot perform analyses in three dimensions on features such as volumes.

In oceanography and meteorology, the use of three-dimensional plots (Figure 3) and various types of scientific visualizations is much more widely accepted. Scientific

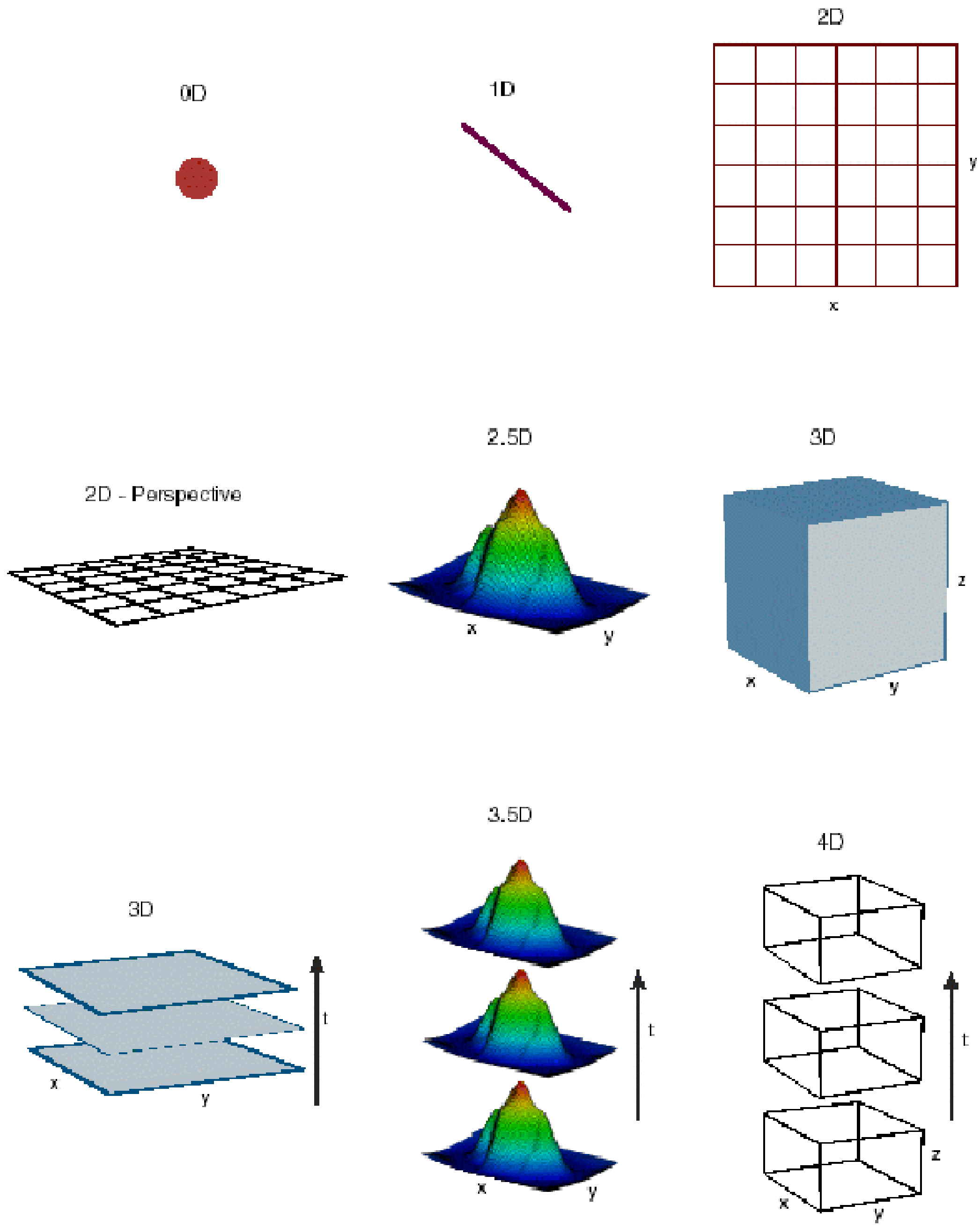

Figure 3. Examples of the various terms for dimensionality used in the text

publications use a variety of standard multi-dimensional plots, virtual reality is starting to be a commonly used tool, and the nightly weather report shows animations and multi-dimensional plots. While some of these differences may simply be due to the types of data collected in the three disciplines, the amount of computer processing time available to researchers, and the funding available to create advanced visualizations, there also seems to be an historical and cultural difference evident. Understanding the historical development of plots in these three disciplines provides insight into the needs in each of the disciplines, the technologies available to all, and the benefits of these new technologies to researchers in geography, oceanography and meteorology.

In seeking to understand the roots of these differences, I will consider a number of aspects. First of all, I will simply describe the semantics that I will be using - as there seem to be a number of terms that get used in multiple ways depending upon the discipline. As time is so much a part of multidimensional views of the world I will then provide a short introduction to space and time in geography. Following this I will provide brief summaries of the history of multidimensional graphics and mapping - including perspective maps, topographic maps, and truly multidimensional maps. Next to be considered are block and profile plotting in geology; multidimensional modeling in meteorology - including earlier two-dimensional maps, data collection and mapping and modern animated weather maps and scientific visualizations. The final discipline covered is multidimensional data collection and display in oceanography - again considering both the technology for data collection and the computation of scientific plots, maps and visualizations. In conclusion, I will describe how these historical developments set the stage for the creation of new multi-dimensional diagrams in oceanography and for research on the creation of a multi-dimensional GIS. This historical material will be broken into two chapters – this one describing developments prior to 1960 (and the development of the Stommel diagram) and Chapter 5 detailing developments associated with the widespread adoption of computers in the 1960's. These later developments aided our creation of a prototype of a multi-dimensional GIS application for oceanography and fisheries.

Terminology/Semantics

One of the challenges in following discussions of multidimensional cartography and GIS is simply the terminology used. I will use the following definitions:

multi-dimensional	data and plots and maps representing more than two dimensions
two-dimensions or 2-D	either the representation of an attribute located in x and y (a surface) or the representation of an attribute at a location x through time.
2.5 dimensions or 2.5-D	a surface that has been crumpled in space, so that it has a thickness or roughness but does not truly represent a volume. Raper defines these as "three-dimensional visualizations of single-valued surfaces (with) depth cues to show the z attribute variation using perspective views" (Raper citing McCullagh, 1998, p145). From a data storage standpoint, the z-measure is in the attribute table of the GIS, not a part of the object or field data structure.
three-dimensions or 3-D	either representation of a volume in x, y and z or the representation of a surface in time. In either case, the

	third dimension is stored as a part of the spatial object, not merely as an attribute. This allows data selection and analyses to be performed on the object.
3.5-dimensions or 3.5D	representation of an attribute in a volume
four-dimensions or 4-D	representation of a volume changing in time, e.g. a cloud or a plume of warm water in the ocean
cartography	" . . . is the art, science and technology of making maps, together with their study as scientific documents and as works of art" (Kraak, citing ICA, 1973, p9)
GIS	"The organized activity by which people • measure aspects of geographic phenomena and processes; • represent these measurements, usually in the form of a computer database, to emphasize spatial themes, entities, and relationships; • operate upon these representations to produce more measurements and to discover new relationships by integrating disparate sources; and • transform these representations to conform to other frameworks of entities and relationships. These activities reflect the larger context (institutions and cultures) in which these people carry out their work. In turn, the GIS may influence these structures." (Chrisman, 2002, p. 5) This implies the storage of attributes linked to locations in space, the ability to perform analyses on these data and the ability to tie these locations to places on the surface of the Earth or another planet.
map	a map is "a representation, normally to scale and a flat medium, of a selection of material . . . on . . . the surface of the earth or a celestial body" (Kraak, citing ICA, 1973, p11) Maps can be permanent (printed), virtual (mental) or temporary (a computer display). Artimo defines a 3-D map as one which "contains stimuli which make the map user perceive its contents as three-dimensional." (Artimo, 1994, p52)
plot	a plot is a representation of scientific data. In this use it tends not to have a spatial component except possibly as a single distance axis.
scientific visualization	"primarily concerned with the visualization of 3-D+ phenomena . . . where the emphasis is on realistic

	renderings of volumes, surfaces ... perhaps with a dynamic (time) component" (Friendly and Denis, 2003, p2). Term coined by a panel of the Association for Computing Machinery in 1987 (McCormick, DeFanit and Brown, 1987, cited in Yu thesis, ch1)
data visualization	"the science of visual representation of data" (Friendly and Denis, 2003, p2)
animation	a series of visualizations, maps or plots that are replayed to provide the suggestion or illusion of motion in space and/or time.
naive geographic space	term coined by Mark and Egenhofer (1995, cited in Raper, 2000, p137) to describe a two-dimensional space where the horizontal and vertical dimensions are decoupled and "the third dimension can be reduced to an attribute of position"
timeless space	term coined by Raper (2000, p58) and others to describe traditional cartography where dynamic and temporal processes are not explicitly displayed.

The fourth dimension - space, time and Time Geography

While time series analyses and temporal GIS are not the focus of this work, time and space are intellectually linked. Prior to Einstein's Special Theory of Relativity, space and time were treated as separate domains. Space had three dimensions and time was a separate matter. Classical mechanics supported this separation of the temporal from the spatial. If there was a fourth dimension it was presumed to be another spatial dimension. In his 1884 work *Flatland: a romance of many dimensions*, Edwin Abbot introduced the fourth spatial dimension while writing of a two-dimensional world. The world consisted of a plane populated by females - who were lines with sharp points on the ends, and males - who were triangles, squares and other geometric features, with increasing numbers of sides denoting a higher social class. This world was visited by entities from higher dimensional worlds - three and four-dimensional spatial worlds. This idea of a spatial fourth dimension persisted for 40 years and was promulgated by events such as the *Scientific American* contest in 1910 for essays about non-Euclidian geometries (Langran, 1993, p27). The idea of the spatial fourth dimension faded after Einstein and the idea of special relativity argued for a temporal fourth dimension. With these new theories came the ideas of linear time versus time as multiple parallel lines, tree structures and circular time (Langran, 1993, p27). All of these would now be thought to exist in conjunction with a spatial world that is limited to three dimensions.

Time has always been an integral part of geographical thought. William Morris Davis argues for "time as an element of geographical terminology" in his 1899 work looking at erosion as a part of a "geographical cycle" (Davis, 1909, p241). Whittlesey (1945) looks at the sequent occupancy of human societies and Hagerstrand (1952) looks at the diffusion of ideas about farming techniques. Thrift (1977) provides an overview of Time Geography as it has evolved from Hagerstrand's ideas. Interestingly, the plots he uses are primarily 2-D plots of space with time as a third (vertical) dimension. As with so many cartographic and geographic studies, understanding is achieved by reducing the dimensionality of the problem - time geography frees space and time but fixes the attribute by expressing it as an identity or other fixed attribute (Langran, 1993, p12-14). Interestingly, some researchers see four dimensions as containing three spatial dimensions (x, y and z) with time (t) while Langran and others see it as two spatial dimensions (x and y) with a third dimension for the attribute and the fourth temporal dimension (Langran, 1993, p28).

Representations of time can include the space-time cube of Hagerstrand (1952) which displays worm plots in time, sequent snapshots which capture the state of a variable as a single time, base states with amendments to show change, space time composites where topology exists, and uncomposited space-time representations where topology is not included (Langran, 1993, p37-43). The third dimension can be shown as a perspective plot (for a spatial third dimension) or by symbols and tones (for an attribute third dimension). The addition of time means that maps can have a tense - they can represent what was, what is or what will be. They can also be somewhere on a continuum between space dominant and time dominant representations. Topographic maps would be an example of a space dominant representation where the height of the surface being represented is paramount, nautical charts are seen as being in the middle as both depth and the date at which the depth was measured are important (Langran, 1993, p74) and a map of rainfall data might be an example of a map where time is paramount, especially for flood forecasting. Langran argues that mapped data fixes time and a time series fixes location; the true challenge is to not fix time, location or attribute. Fleming and Schneider (cited in Langran, 1993, p22) have critiqued the portrayal of time in two-dimensional maps arguing that it does not work for moving objects such as traffic. Given Webb's work that suggests that traffic is actually a sort of compressible fluid flow[2], what they may in fact be critiquing is the inability of two-dimensional maps to portray true spatial three-dimensionality (volumes) that vary in time.

Geography and cartography

Though the widespread use of multidimensional maps is a very recent development, there is a progression of graphical representations that led to today's maps.[3] One of the most rudimentary maps that might be thought of as three-dimensional is the shell and palm ribs maps used by the Marshall Islanders to represent wave patterns and the position of atolls (Monmonier, 1985, p19). Shells and palm ribs are woven together to provide a basically two-dimensional, tactile, representation of three-dimensional wave patterns. Panoramic maps probably served as the first perspective views of features on the surface of the earth - with plans of buildings and their grounds in 2nd millennium Egypt showing elevations on a ground plan (Wallis and Robinson, 1987, p41). Representations of towns in oblique views in the 2nd and 3rd century BC are probably the earliest true perspective maps. Eighth century maps of

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[2] Martyn Webb, pers. comm.
[3] For general histories of cartography see The History of Cartography project at http://www.geography.wisc.edu/histcart/; J. B. Harley, and Paul Laxton, *The new nature of maps: essays in the history of cartography*. (Baltimore, Md: Johns Hopkins University Press, 2001).; Walter Ristow, *Guide to the history of cartography; an annotated list of references on the history of maps and mapmaking*. (Washington: Geography and Map Division, Library of Congress, 1973).

Japanese estates provide the earliest topographic maps. Oblique views of cities in Italy were drawn as early as the 10th century. Panoramic maps were also used for regional maps in parts of Europe as early as 1291, with their use becoming widespread by the 15th century. Pictorial maps - where the map is really a realistic drawing - date from 1500BC in northern Italy and have also been seen in Babylonian tablets. Other 2.5-D maps include the 1538 aspect relief map of Tschudi, a perspective drawing of Amsterdam from 1544 by Anthonisz, the 1889 hachure map of relief in the Swiss Alps, the 1975 analytical map of Peucker et al. and USGS topographic maps (shown in Kraak, 1988). A variety of techniques were used to produce a feeling of multidimensionality, including shading, hachuring and the creation of false perspective.

Wallis and Robinson (1987) argue that the development of the true hypsometric map, with elevation as a continuous surface rather than spot elevations, required the improvements in the measurement of elevation made in the mid-18th century (Wallis and Robinson, 1987, p145). They suggest that the 1791 map of “La France ...” produced by Dupain-Triel was the first true hypsometric map. An 1813 map of the Tatra Mountains is given as another example. France led the way in the production of hypsometric maps in the 19th century and the use of contours was adopted by the 1830’s and 1840's (Wallis and Robinson, 1987, p151).

Friendly and Denis have produced a time line of “Milestones in the history of thematic cartography, statistical graphics, and data visualization".[4] Though this document looks at the topic from a statistics viewpoint, they do describe a number of the technical innovations that contributed to multidimensional cartography. One of the threads of the Friendly and Denis time line is the rise of topographic mapping and techniques for gathering the data for topographic maps. Topographic mapping provides a 2.5-dimensional representation of the three-dimensional world. As such, it is not totally germane to this discussion, but it does provide an interesting exploration of how technological developments can contribute to the development of advanced graphical techniques. It can also be seen as a precursor to true three-dimensional mapping and plotting. A progression of technical developments - including aerial photography, improved surveying techniques and ultimately techniques such as radar mapping and LIDAR - have provided needed technologies. Advances in computation have allowed these increasingly massive and detailed datasets to be processed and displayed. Physical terrain models, such as those created during WWII, contributed to thinking about three-dimensional worlds - the tactile representation of 2.5 dimensions leading to consideration of three-dimensional volumes. As with meteorology, the relationship of military and civilian science has produced a more scientific cartography - concerned more with techniques than with the more philosophical realms of what and what isn't a map.

[4] Michael Friendly and Daniel Denis. "Milestones in the history of thematic cartography, statistical graphics, and data visualization," http://www.math.yorku.ca/SCS/Gallery/milestone/. (Viewed 8/16/2007).

The start of the 20th century saw the emergence of photographic techniques for surveying. These pictures, taken from balloons or high points on the landscape, provided enough data for the creation of topographic maps (Collier, 2002, p157). Prior to this time maps had been created by ground based surveying and the laborious collection of elevation data precluded widespread surveys and tight meshes of elevation data. The process of triangulation had been improved by the use of invar (a nickel steel alloy with a low coefficient of thermal expansion used for reference measures) and 19th century improvements in theodolites (Collier, 2002, p157). Transmission of time signals via telegraph had also increased the accuracy of surveys by allowing better longitude calculations. By 1900 this process had produced maps of much of Europe at scales of between 1:10,000 (Great Britain and Belgium) and 1:50,000 (France and Spain). The United States had been mapped at either 1:25,000 or 1:250,000 and, through the efforts of the East India Company, India had been mapped at varying scales (Collier, 2002, p155-156).

In the decades prior to WWI there were experiments in surveying, but few practical applications of the new methods. WWI produced a need for the rapid production of maps for military purposes. The need to locate and aim artillery led to early sound-based methods of triangulation and ranging. Grids were also added to maps (Collier, 2002, p159). The 1920's saw technical developments in instrumentation and the first use of aerial photogrammetry for civilian maps. Radio time signals replaced telegraphic ones and improvements in cameras enhanced aerial photographs. The 1930's produced large scale civil mapping, the use of slotted templets and multiplex (Collier, 2002, p155) and the final shift from ground based surveys to photogrammetric methods (Collier, 2002, p167). As with WWI, WWII produced a need for rapid creation of maps and other graphics for the planning of battles. Terrain models created of wood and plaster were used extensively in planning (Pearson, 2002, p.227). The models were created by a combination of survey data, air photos and any pre-war maps that might be available. The physical models, unlike the virtual models produced later by computers, provided a tactile feel for the terrain. Though they were strictly 2.5 dimensional, their tangible presence might be said to have been a precursor to virtual representations of terrain. These types of terrain models were mass produced using vacuum forming methods during the Korean War (Pearson, 2002, p.239).

The 1950's were the time of the Cold War, which had a major influence on both the technology for data collection for mapping and on the implementation of these new techniques. Cloud has written of the changes in American cartography during the Cold War. He specifically looks at the technologies that produced the World Geodetic System (WGS) as a terrestrial reference frame, the development of remote sensing, and the mapping programs that ultimately became the Military Geographic Intelligence Systems (MGIS) (Cloud, 2002, p261). One of his arguments is that cartography had fragmented into geodesy, cartography and geography in the late 18th century as national level mapping programs had become widespread in western Europe (Cloud, 2002, p262). He then posits that the disciplines experienced a "re-convergence" during the Cold War and that this convergence was to prove to be very productive. At the end of WWII map datums were a major challenge as each country worked off of a different reference. Unification of these datums would be necessary for the aiming of long range weapons. The result of this unification was the WGS datum, which is still in use. The post-War era was also a time when the United States military could gather much of the advanced technology developed in Germany and other European countries (Cloud, 2002, p264) which was, in many cases, superior to the American equipment. The captured materiel also included geodetic data for now inaccessible areas of the Soviet Union and the Communist Bloc. The rise of the quantitative revolution in geography was in part a function of the need to develop techniques for the analysis of data gathered by the military (Cloud, 2002, p268). Developments in cameras continued and ultimately led to the equipment used in spy flights and finally in satellites. The need for digital terrain representations led to the development by a joint Army-Air Force project of a Military Geographic Intelligence System (MGIS), the precursor to modern day GIS (Cloud, 2002, p279). The need to manage, consolidate and analyze the vast amounts of data being gathered for these intelligence tasks ultimately led to the creation of the Defense Mapping Agency and the distribution of declassified versions of much of the heretofore secret data collected by these projects.

Geology

Rudwick (1976) describes how geological maps use the pattern of outcrops combined with topography to give clues to three-dimensional structure and how the three-dimensional pattern and the topography can be used to gain clues about the causal and temporal aspects of features. Block diagrams, where the features are shown as if a block had been cut from the earth, appeared as early as 1500. Hutton's *Theory of the earth* used block diagrams in 1795 to show geological features. Block drawings in conjunction with perspective drawings were also used in John Wesley Powell's *Exploration of the Colorado River of the West* (1875) and William Morris Davis used them in his *Physical geography* (1898) (Wallis and Robinson, 1987, p139). Wallis and Robinson posit that the first geological map was the map produced by Christopher Packe in 1738 in his "...Philosophico-Chorographical Chart of East Kent...". Another early geological map was a set of maps produced by Buache for a geological paper in 1746. Geological maps were increasingly popular by the end of the 18th century.

In the late 18th century most illustrations for geological works were made using copperplate, making them expensive and time consuming to create. For that reason, illustrations were limited. Hamilton's 1776 - 1779 *Campi Philegraei* had engravings of Vesuvius and de Saussure's *Voyages dans les Alpes* in 1779 - 1796 also had engravings (Rudwick, 1976, p154). Desmorest created a map of the volcanic rocks in the Auvergne in 1799. He was actually more interested in the temporal pattern of the volcanism in the area as indicated by the layering of the lavas than in the spatial patterns (Rudwick, 1976, p163). By 1809 a small geological map of the United States had been created and the 1830's and 1840's saw the creation of maps of the eastern states by Rogers and Hitchcock (Raisz, 1938, p285).[5]

In the 1810's two competing techniques to show outcroppings were developed. Cuvier used plain colors for outcrops and included a legend showing the colors used (Rudwick, 1976, p162-163). This is the technique that is used in the present day. It tends to include cross sections to assist with interpretation. In 1815 Smith created the classic *Delineation of the strata of England and Wales,* which used an innovative technique to show outcrops. The technique required hand coloring and used lines of color that shaded from intense along the scarp face to more muted tones along the dip slope (Rudwick, 1976, p162). The complexity of this technique precluded its wide adoption. The 1820's saw the development of two less expensive techniques - wood engraving and lithography - which made it easier to include maps in publications. Wood engraving was used for small drawings and had the advantage that it didn't require special paper for printing (Rudwick, 1976, p157). Lithography allowed shading and fine grained detail and was used in scientific journals starting in the 1820's (Rudwick, 1976, p156). Panoramic illustrations also reached a peak with the 1827 publication of Scrope's *Memoir on the geology of central France.* It is thought that these idealized views may also have influenced Lyell's work due to the impact of the

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[5] For a history of geology, and geologic maps in this era see Mott Greene, *Geology in the nineteenth century: changing views of a changing world*. Cornell history of science series. (Ithaca, N.Y.: Cornell University Press, 1982).

landscape portrayals (Rudwick, 1976, p176-177). By the1840's, geological maps were central to scientific publications. Lyell's 1845 account of his travels in North America in1841 and 1842 was accompanied by a *Geological map of the United States, Canada, etc., compiled from the State Surveys of the U.S. and other sources*. The formation of the U.S. Geological Survey in 1882 led to systematic mapping of the United States, and especially the western states. Improvements continued with the publication of the *Geologic map of North America of 1912* and a revised version of the map in 1932. The map continued to be used for the next 40 years (King and Beikman, 1974, p10).

Meteorology

Meteorological research involves manipulating vast amounts of data. There are a number of techniques for making this easier. The first, and oldest, method is to simply list the values in a table. Showing the data in a graphical form such as a contour plot or x/y plot improves understanding and summarizes the data at the cost of precision. This display was sufficient during the "synoptic era" when data collection was two-dimensional (Schiavone and Papathomas, 1990, p1013). The advent of radiosondes to collect three-dimensional data, massive datasets from models, and computers to process them, added 3-D plots to these tools. Three-dimensional viewing compresses time and makes it possible to view large amounts of data (Grotjahn and Chervin, 1984, p1201). The collection of space borne data, where 2-D image data can actually provide four-dimensional information, required advanced visualization tools (Schiavone and

Papathomas, 1990, p1013). Weather maps are assumed to be synoptic views of conditions such as temperature, winds, relative humidity and barometric pressure. Brandes in Breslau created the first map prepared from observations in 1820.[6] The map showed the observations taken during a storm in 1783. Elias Loomis made a similar map in a series of five charts presenting conditions during a storm in 1842 in the United States. The advent of telegraphic records made the production of weather maps easier and a daily weather map was attempted in England in 1851. Daily maps in France started in 1863 (Wallis and Robinson, 1987, p157). Precipitation maps provide a synoptic view of rain or snowfall either from observed points or via remotely sensed data. An atlas of the climate of Italy in 1839 is given by Wallis and Robinson as the first example of a precipitation map. One map showed the data points while the other map showed seasonal amounts. Maps for the world were created in1841 by Berghaus and in 1848 by Johnston. These types of maps became common after the early 1840's (Wallis and Robinson, 1987, p153)

Wind maps are similar to current maps in that they show the direction of flows, but in the atmosphere. Wind roses were used in Greco-Roman times to determine wind directions. Ptolemy's Geography, from the 13th century, is thought to contain data from these sources. Hondius' map of the world in 1611 included wind data. Edmond Halley's map of 1686 is thought to be the first true wind map showing conditions during

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[6] For a history of meteorological mapping see Mark Monmonier, *Air Apparent*. (Chicago: University of Chicago Press, 1999).

the monsoon season. Dampier produced a similar map in 1699 for wider areas of the Atlantic, Indian and Southern oceans. Matthew Fontaine Maury produced Monsoon and Trade Wind charts from 1846. Unlike most data sets, maps of terrestrial winds developed after those for marine areas. Astruc produced maps of winds for Languedoc in 1737 (Wallis and Robinson, 1987, p158).

The invention of the telegraph in the 1800's allowed the gathering of synoptic 2-D measurements of surface features. The first newspaper weather "telegraphic daily weather report" was printed as an experiment by the *London Daily News* in 1848. The regular printing of such reports started in 1849, utilizing railway company telegraphs to transmit the data (Monmonier, 1999, p154). The first newspaper map was in the *Times* of London. The map included data and reports from the Continent and was a map of conditions, not a forecast (Monmonier, 1999, p156). The *New York Herald* printed a weather chart as a part of celebrations for the International Exposition in 1876 and a map was shown in 1879. By 1882, the Signal Office (the precursor to the Weather Bureau) was producing a daily weather map in its New York City office (Monmonier, 1999, p160). In 1891 the Signal Office was transferred to the Department of Agriculture and civilian dissemination of its products started (Monmonier, 1999, p167). The regular printing of a newspaper weather map started in the United States in 1910, in part due to the development of photoengraving, which made map reproduction easier (Monmonier, 1999, p154). This date also marked the shift from a government-printed weather map to the maps being printed by newspapers (Monmonier, 1999, p167). The production of weather maps languished during WWI due to a lack of resources for their printing and the need to concentrate on military mapping. The newspaper weather map was not to return on a regular basis until 1935 when the Wirephoto network was used to disseminate maps (Monmonier, 1999, p168). The development of radio technology in the 1930's allowed the development of radiosondes and balloons, which could now collect three-dimensional data (Schiavone and Papathomas, 1990, p1014).

Oceanography

Ocean current maps were first created by Hondius in Amsterdam in 1618 when he published a map of the world ocean currents.[7] Charts with currents, winds, soundings and magnetic variation were found in Dudley's world atlas *Dell' Arcano del mare* in 1646 (Wallis and Robinson, 1987, p151). Thematic current maps started with Kircher in 1665 with his *Mundus subterraneus* where currents are shown with shaded lines, but without any indication of the direction in which they flow. Bolland created a text map of ocean currents in the 1660's. Arrows to show the direction of the current were added starting in the 18th century. William De Brahm and Benjamin Franklin used patterns of gently undulating lines to show currents for the Gulf Stream and the Atlantic (1786).[8] The U. S. Coast Survey under Alexander Dallas Bache added indications of

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[7] For histories of marine cartography and charting see A.H.W. Robinson, *Marine cartography in Britain: a history of the sea chart to 1855*. (Leicester: Leicester University Press, 1962); Adam Kerr, *The Dynamics of oceanic cartography*. (Toronto: University of Toronto Press, 1980).
[8] See Joyce Chaplin, *The first scientific American: Benjamin Franklin and the pursuit of genius*. (New York: Basic Books, 2006).

temperature variations using shading in the 19th century. Velocities of the flow were added by the end of the 19th century. (Wallis and Robinson, 1987, p152)

Isobaths are used to indicate lines of constant depth - the precursor to the modern bathymetric chart and to the grids of bathymetric data used for 2.5-, three- and four-dimensional maps and visualizations. Briunsz, a Dutch surveyor, first used an isobath in a chart of the river Sparne in 1584. A similar map of the river Maas was produced in 1697. An early marine isobath was on a chart of the “Golfe du Lion” produced by Marsigli in 1725. The first chart with a complete set of isobaths for various depths was created by Cruquius in 1730 for the river near Gorichem. Marine charts with multiple isobaths were also created during the 18th century and a manuscript chart of the coast of Nova Scotia created in 1715 by Blackmore may be the first maritime chart with isobaths (Wallis and Robinson, 1987, p225).

The creation of isobaths required the taking of soundings. While individual soundings have been collected for centuries on an *ad hoc* basis by mariners, recording the soundings was not seen until the 15th century on a German chart of the French coast. The earliest English chart of soundings is a manuscript chart of the river Humber around 1569 (Tyacke and Huddy, 1980, cited in Wallis and Robinson, 1987, p243). At a similar time, Dutch charts also showed soundings. By the first third of the 17th century, soundings were frequently seen on charts, both in Europe and around the world.

As with terrestrial topographic mapping, the development of the bathymetric portion of oceanic mapping and visualization is a function of data collection. The first deep sea sounding was taken by Sir James Clark Ross in 1840 at 27S, 17W. By 1849, the Coast Survey was making soundings in support of Bache's studies of the Gulf Stream.[9] The first submarine canyon was discovered by Alden in Monterey Bay in 1857. An operational wire sounding machine, to replace hemp based sounding machines, was developed in 1872 (NOAA, p3). The machine was both faster and more accurate in determining depths due to the decreased stretching of the wire as opposed to a hemp line. It was used for a trans-Pacific survey from Cape Flattery and Japan in 1873. The Coast Survey Steamer *Blake* made a detailed survey of the Gulf of Mexico and the results were used to compile what is seen to be the first modern bathymetric map (NOAA, p4). Surveys using the wire sounding machine continued to expand available data for the next 40 years. In 1914, the Fessenden Oscillator was used to reflect a signal off of the sea floor and also off of an iceberg (NOAA, p6). This was the first use of acoustic techniques to determine depth. Development of acoustic techniques accelerated during WWI. The acoustic echo sounder was used for survey transects of the Atlantic after WWI. The improved Hayes sounding equipment was eventually installed on most Coast Survey ships. At the same time radio ranging techniques for navigation were being developed. The improved navigation improved the accuracy of the location of soundings. The interwar years saw the running of a number of surveys, both in US and foreign waters. Bathythermographs to measure water temperature and current meters to measure current speeds were also developed (NOAA, p8). During

[9] See http://www.oceanexplorer.noaa.gov/history/timeline/timeline.html (hereafter NOAA) for a timeline of developments in surveying and charting.

WWII most of the electronic tools were improved and new technologies such as deep-ocean camera systems, baseline navigation for towed instruments and magnetometers (originally developed to detect mines) were created.

After WWII various military tools were released for civilian government use.[10] Navigation improved with the development of SHORAN (NOAA, p1). Academic oceanography also developed, taking advantage of war surplus ships and developments in electronics. Magnetometers were used to measure the magnetic inclination of the sea floor - contributing to the theory of plate tectonics, and the precision depth recorder (PDR) was developed.[11] These tools provided datasets for mapping, and also created challenges as the detailed datasets, frequently created with military funding, were also classified due to their military uses. In this case, the need, the technology and the real advantages of the new data were confounded by policy.

An important multi-dimensional map of the sea floor, developed in 1957, was the Heezen and Tharp physiographic map of the Atlantic Ocean.[12] The map was drawn as a perspective diagram rather than a planar map in part to get around security

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[10] See Naomi Oreskes. "A Context of Motivation: US Navy Oceanographic Research and the Discovery of Sea-Floor Hydrothermal Vents," *Social Studies of Science*. 33 (5) (2003):697-742 for how these developments affected one aspect of marine research and surveying. See Helen Rozwadowski, *Fathoming the ocean: the discovery and exploration of the deep sea*. (Cambridge, Mass: Belknap Press of Harvard University Press, 2005) for a history of the exploration of the deep ocean.

[11] The ozone producing graphical recorder of the PDR was to nauseate generations of graduate students required to annotate the continuous profiles created - TCV

[12] See Ronald Doel, Tanya Levin, and Mason Marker, "Extending Modern Cartography to the Ocean Depths: Military Patronage, Cold War Priorities, and the Heezen-Tharp Mapping Project, 1952-1959," *Journal of Historical Geography*, 32(3) (2006): 605-626. for a complete history of this development.

restrictions on using detailed bathymetric soundings. Since a perspective diagram blurs the precise location of the data, the diagram escaped security restrictions (Doel et al., 2006, 606). In the process, a three-dimensional representation was created and viewers became familiar with these types of views. While the Heezen and Tharp diagram became a part of the popular literature, it was also used by scientists and contributed to their skills in interpreting future visualizations.

Conclusions

This chapter has explored the history of multi-dimensional plotting and mapping up to 1960 for the disciplines of cartography, geology, meteorology, and oceanography to set the scene for Henry Stommel's development of new multi-dimensional graphical techniques. The maps and charts described were all a product of the data available for their creation, the goals of their creators and the graphical fashions of the time. Each reflected a need to portray a phenomenon, the technology available both to collect the needed data and to create the graphical depiction, and the abilities of the viewer to understand the new chart or map. The needs included seeking ways to represent both space and time, the need to represent data from three spatial dimensions, military needs to represent terrain in a way that could be quickly created and equally quickly comprehended, and the need to represent the "invisible" data collected in the atmosphere and in the deep ocean. The data gathering technologies included tools such as improved surveying equipment, drilling equipment for geological sampling, airplanes for taking air photos, and sensors for both the ocean and the atmosphere resulting from WWII. The display technologies included artistic techniques for portraying perspective, mechanical methods of creating terrain models, and graphical techniques to both present and hide classified data. With each new graphical development, the viewers became familiar with seeing the world simplified in new ways.[13] As the detailed two-dimensional map became familiar, it was then possible to create perspective maps. As these three-dimensional representations became familiar, it was possible to add more attributes and to increase the detail of the representation. Most of the maps described here also share the quality of being created by non-digital technologies. Doel et al. observed that "the Heezen-Tharp maps thus have additional significance by being among the last large-scale twentieth-century maps drawn by hand rather than produced by mechanical or computerized processes" (Doel et al., 2006, 621). This part of the technology would soon change and would produce the precursors to computer cartography and ultimately lead to the development of GIS. In the meantime, researchers able to straddle the worlds of creative graphical methods and efficient digital methods would develop techniques to represent the results of the new data collection tools.

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[13] For a critical view on whether these new techniques were improvements see M.J. Blakemore, J. B. Harley, and Edward H. Dahl, *Concepts in the history of cartography: a review and perspective* (Downsview, Ont., Canada: B.V. Gutsell, 1980).

Rapid acceptance of new data gathering techniques led scientists to express frustration with the inadequacies of two-dimensional plots and the need for multi-dimensional representations. The pitfalls of collecting large datasets without a clear plan, just simply because one could collect them, led to the call for tools to better describe datasets and their uses. The need for better planning for data collection, especially for major campaigns or long cruises, drove the development of tools. While many scientists still chose “not to 3-D” and increasing number chose “to 3-D”. The next chapter will describe the development of the Stommel diagram – a classic use of a three-dimensional diagram to understand multi-dimensional data – that built upon many of the techniques described in this chapter.

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Chapter 3: Henry Stommel and the emergence of multi-dimensional plotting: transferring techniques across scientific disciplines

Introduction

In 1945, a printing press from the Kelsey Company in Connecticut arrived at the Rectory of the Church of the Messiah in Woods Hole, Massachusetts. The Rectory by then was a residence, home to several junior oceanographers at the Woods Hole Oceanographic Institution, including Henry Melson Stommel. Over the next few decades Stommel used the press to produce party invitations, humorous seminar announcements, and newsletters for a variety of scientific societies. Even more innovatively, Stommel also employed it to publish broadsheets on a number of topics in physical oceanography.

One of these occasional publications carried the provocative title, “Why do our ideas about ocean circulation have such a peculiarly dream-like quality? or Examples of types of observations that are badly needed to test oceanographic theories” (1954, hereafter the “dream-like” pamphlet). Handed from scientist to scientist within the physical oceanographic community, the pamphlet was quickly recognized as path-breaking, much like earth scientist Harry Hess’s informal “Geopoetry” broadsheet the following decade.[14] In 1963, writing in *Science*, Stommel used the ideas that he had developed in this pamphlet to create to a new graphical depiction of time and space, one that eventually spread beyond physical oceanography to ecology, geography, meteorology and plankton biology. The "Stommel Diagram," as it came to be known, was one of the most significant achievements in the application of graphical methods to science in the mid-twentieth century.[15]

The Stommel diagram, and its diffusion within the physical and biological science communities, was the product of three distinct influences. The first was Stommel's interest in visual models of phenomena. In contrast to many of his colleagues, Stommel was a skilled sketch artist and painter, and his pamphlets frequently included three-dimensional diagrams and small sketches. As one of Stommel's biographers later noted, Stommel had "insatiable curiosity, extraordinary

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[14] See Homer E. LeGrand, *Drifting continents and shifting theories* (Cambridge: Cambridge University Press, 1988). The use of informal, non-peer-reviewed communications is a woefully underexplored issue in the history of recent science; for important insights on this issue see Sharon Traweek, "Generating High-Energy Physics in Japan: Moral Imperatives of a Future Pluperfect," in David Kaiser, ed., *Pedagogy and the practice of science: Historical and contemporary perspectives* (Cambridge, MA: MIT Press, 2005): 357-392.

[15] Another remarkably influential graphical method introduced at this time was the Feynman diagram in particle physics, developed by Richard Feynman; see David Kaiser, *Drawing theories apart: The dispersion of Feynman diagrams in postwar physics* (Chicago: University of Chicago Press, 2005).

intuition (he was relentless in stripping problems down to their most elemental levels), and the ability to visualize physical processes fully in three dimensions."[16]

The second influence was Stommel's early exposure to computers and computing - whose application to the earth sciences stemmed from World War II - and his interest both in the modeling of oceanographic phenomena and the visual display of large oceanographic data sets. These interests were reflected in Stommel's late-night forays to Maynard, Massachusetts for computing time[17] on the Digital computers located there, and his 1963 paper on machine plotting of oceanographic data.[18]

Finally, the third influence was the postwar development of oceanographic instrumentation that made it possible to measure turbulent and transient processes in the oceans. As the Cold War took hold, federal and military funds to accelerate research in geophysics and oceanography poured into major institutions such as Woods Hole and Lamont Doherty, aiding the development of new oceanographic instruments and

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[16] His artistic skills were not limited to scientific pursuits. His "skill as a painter was considerable ... [producing a] refrigerator ... with tropical birds and animals on a brilliant yellow backdrop." Carl Wunsch, "Henry Stommel", National Academy of Sciences Biographical Memoir. Hereafter "Wunsch-NAS". Available at http://www.nap.edu/readingroom/books/biomems/hstommel.html. See also "Employee Portrait Gallery: Henry Stommel," http://www.whoi.edu/75th/gallery/week25.html.

[17] Dennis Moore, pers. comm., and Henry Stommel. "The Sea of the Beholder". (1984) reprinted in Henry M. Stommel, Nelson G. Hogg, and Rui Xin Huang. *Collected works of Henry M. Stommel*. (Boston, MA: American Meteorological Society, 1995) Hereafter "Stommel autobiography". p I-48.

[18] Malcolm Pivar, Edward Fredkin, and Henry Stommel, "Computer-Compiled Oceanographic Atlas: An Experiment in Man-Machine Interaction." *Proceedings of the National Academy of Sciences U.S.A* 50(2) (1963): 396 - 398.

opportunities to work more frequently in the deep ocean, far from shore.[19] The rise of large-scale measuring programs depended upon these technical advances. The Stommel diagram reflected and summarized Stommel's thoughts on how new spatially extensive and temporally detailed data sets of oceanographic phenomena might best be utilized by his colleagues and employed to develop large, new multi-institutional research programs.

Between the mid-1960s and the late-1970s the Stommel diagram had a circuitous career. Diffusion of Stommel's ideas and graphics was certainly aided by his use of his printing press to produce informal pamphlets, as well as his highly visible *Science* article. Perhaps more importantly, the rise of models in a variety of environmental science disciplines and the need by biologists for a simple graphical summary of the phenomena they were recording—as their burgeoning datasets focused their attention on understanding larger scale patterns—aided its adoption in scientific fields remote from Stommel's own areas of expertise.

Two key questions provide the focus for this work. First: to what extent did the Stommel diagram become an established tool within physical oceanography, the community in which it originated? Second, to what extent was this innovation adopted

[19] On the rise of oceanography as a discipline in the postwar years see Jacob Hamblin. *Oceanographers and the Cold War: Disciples of marine science*. (Seattle: University of Washington Press, 2005); Naomi Oreskes, "A Context of Motivation: US Navy Oceanographic Research and the Discovery of Sea-Floor Hydrothermal Vents." *Social Studies of Science* 33 (5) (2003):697-742; and Ronald E. Doel, Tanya J. Levin and Mason K. Marker, "Extending Modern Cartography to the Ocean Depths: Military Patronage, Cold War Priorities, and the Heezen–Tharp Mapping Project, 1952–1959." *Journal of Historical Geography* Volume 32 Issue 3 (July 2006):605-626

outside the earth sciences, and why did this occur? This chapter explores Stommel's early career, the experiences and research that led to the genesis of the Stommel diagram, its emergence within the scientific context of the early Cold War period (when military funding for oceanography reached unprecedented heights), and its diffusion to other scientific communities. It is simultaneously an exploration of the Stommel diagram itself, its contribution to the physical environmental sciences, and its enthusiastic adoption within the biological sciences.

Henry Stommel: Education, training, and background

Hank Stommel, as he was known to friends and colleagues, was an oceanographer of unusual intellectual breadth and even more remarkable artistic bent. As one colleague later described him, Stommel was a "raconteur, explosives amateur, printer, painter, gentleman farmer, fiction writer and host with a puckish sense of humor . . . [who] entered oceanography when the field still had much of the atmosphere of an avocation for wealthy amateurs . . . he left it at a time when it had been transformed into a modern branch of science, often driven by perceived needs of national security, and of global, organized, highly expensive programs requiring government funding."[20] From the 1940s through his death in 1992, Stommel's work touched on almost all aspects of physical oceanography. Already by 1959, the eminent geophysicist Jule Charney, noting that oceanography remained "one of the last remaining strongholds of

[20] Wunsch-NAS, 1.

the all-embracing naturalist," declared that Stommel and the Scripps Institution of Oceanography scientist Walter Munk were its two most versatile practitioners.[21]

Stommel graduated from Yale in 1942 with a degree in astronomy. He then began wartime service, spending the next two years teaching analytic geometry and celestial navigation in Yale's Navy V-12 program, designed to provide a short, but thorough, college education to potential officers. Stommel's upbringing as a Methodist pacifist made him reluctant to serve in the military; he later cited his role as a teacher as "not a consistent or logical moral position, but at least I was not personally killing anybody."[22] A brief enrollment in the Yale Divinity School and graduate work in astronomy did not suit him. In 1944, the Yale astronomer Lyman Spitzer recommended him for a post at the nearby Woods Hole Oceanographic Institution, at the southern tip of Cape Cod, then largely on wartime research footing. There he worked with visiting geophysicist Maurice Ewing on acoustics and anti-submarine warfare.[23]

After the war ended, Stommel remained at Woods Hole. He soon began working on an increasingly wide range of problems in physical oceanography, extending from modeling tides to atmospheric convection to Langmuir cells. To a considerable extent, Stommel's ideas were shaped by a wide collection of friends and colleagues,

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[21] Charney, letter of recommendation for Walter Munk, no date [Mar. 1959], Box 14, Frank Press collection, MIT Archives.

[22] Stommel autobiography, pI-16

[23] Gary Weir. *An ocean in common: American naval officers, scientists, and the ocean environment*. (College Station: Texas A & M University Press, 2001).

with whom he remained in close contact. An early influence was the classic 1942 book *The Oceans* by Harald Sverdrup, Martin Johnson and Richard Fleming, which served as his introduction to oceanography. He remained in contact with Lyman Spitzer at Yale. While first at WHOI, Stommel came into contact with the Harvard biologist Jeffries Wyman who had spent WWII working at WHOI on the detection of submarines and the use of smoke screens. Seeing Stommel floundering without a clear research direction, Wyman suggested that he work on entrainment in clouds, work that led him to a lifelong interest in convection in the atmosphere and especially in the ocean. A semester spent at the University of Chicago in 1946 exposed him to two leading meteorologists, Carl-Gustav Rossby and Victor Starr.[24] While pursuing theoretical studies, Stommel also gained experience with oceanographic instruments early in his career, spending the fall of 1947 doing experiments with geophysicist Lewis Fry Richardson on eddy diffusion, using carefully weighted slices of parsnips as drifting buoys.[25]

Stommel also soon met oceanographers at other institutions, including the Scripps Institution of Oceanography, at the time the only other major oceanographic research facility in the United States. There he met the influential physical oceanographer Albert Defant in 1949, and they "spent happy hours walking the

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[24] Stommel autobiography, p I-18.

[25] Stommel autobiography, p I-18. Their paper [L. F. Richardson and H. M. Stommel, "Note on the Eddy Diffusion in the Sea." *Journal of Meteor*ology 5(5) (1948): 238–240] starts with one of the more intriguing first lines seen in a journal article - "We have observed the relative motion of two floating pieces of parsnip, and have repeated the observation for many such pairs at different initial separations"

beach."[26] Even more important for his subsequent career was his interactions with the young oceanographer Walter Munk. Though Stommel seemed to feel that Munk's interest in waves did not coincide with his interests, and his correspondence suggests he was diffident towards Munk, they subsequently exchanged many letters. Many of ideas about scale in the oceans that Stommel pursued apparently originated from his correspondence with Munk.[27]

Stommel's future research was influenced even more directly by his Woods Hole colleagues. With Arnold Arons, he worked on salt fountains and the installation of deepwater sensors off Bermuda, the latter contributing to his future work on time scales in the ocean. John Swallow earned his lifelong respect as "the greatest and most dedicated oceanographer of [his] time" for developing what became known as the neutrally buoyant Swallow floats for determining circulation patterns.[28] Another major local influence was a seminar at Brown in the 1950's arranged by Raymond Montgomery that involved future colleagues and friends of Stommel's, including the oceanographers Nick Fofonoff, George Morgan and George Veronis.[29]

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[26] Stommel autobiography, p I-19.

[27] While Stommel's correspondence collection at WHOI is incomplete, the Munk papers at the Scripps Institution of Oceanography archives contain many letters between the two from 1947 until Stommel's death.

[28] Stommel autobiography, p I-37

[29] Stommel autobiography, p I-32.

Interactions with these colleagues led Stommel to consider getting a Ph.D. as this degree was becomingly increasingly standard in the oceanographic research community. Although Stommel thought seriously of earning a Ph.D. at Brown University in the early 1950s, in the end he did not do so.[30] He also approached other institutions. After a pleasurable summer spent at Scripps, he applied in 1950 to do a Ph.D. there. Munk and his senior colleague Roger Revelle argued that Stommel should receive the degree "sight unseen".[31] In contrast, Columbus Iselin, WHOI's director, counseled that his getting a Ph.D. was unnecessary.[32] This argument—and his continued achievements in research—led him to finally decide against getting a degree anywhere. While he was one of the last of the generation of non-Ph.D. researchers, this lack did not hinder either his thinking or his renown. He and other non-Ph.D. leaders in their field formed a group called So-So, for the Society of So-called Oceanographers.

Even before he considered earning his Ph.D., Stommel had made his mark as a talented, broad-minded oceanographer with interest in experiment and theory. Stommel's first major study addressed the westward intensification of wind-driven

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[30] Montgomery to Stommel, Mar. 23, 1950. Raymond B. Montgomery (1928 – 1988) Papers, MC-30, Box 16, Data Library and Archives, Woods Hole Oceanographic Institution.

[31] Munk to Stommel, April 18, 1950. Walter Munk Papers, MC-17, Box 19, Scripps Institution of Oceanography Archives [hereafter Scripps archives], UCSD.

[32] Iselin to Stommel, April 30, 1950. Henry Melson Stommel (1920-1992) Papers, 1946-1996, MC-6, Box 2, Folder 3, Data Library and Archives, Woods Hole Oceanographic Institution.

currents, which he published in the *Transactions of the American Geophysical Union* in 1948. This oft-cited paper established Stommel's ability to create simple models of idealized situations that required limited mathematics. As Arnold Arons, a frequent collaborator of his, later put it, "in Henry Stommel's papers you can almost invariably tell the lion by his claw. He is diffident, almost apologetic, for what he regards as his "limited mathematical capacity" in dealing with the complexity of oceanographic problems. . ."[33]

Stommel began his work in oceanography just as technical advances—and funding for extended voyages, provided primarily by Navy patrons—made possible many new areas of study. A research cruise in 1950 involving six ships working between Cape Hatteras and Newfoundland provided Stommel and his colleagues one of the first detailed looks at the variability and detail of flow in the ocean.[34] By the early 1950's, he began stressing the need for time-series of pressure, temperature, and currents in the deep oceans; working with the British oceanographer John Swallow and his Swallow floats, Stommel began investigating fluctuations of flow in the deep oceans.[35]

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[33] Arnold Arons, "The Scientific Work of Henry Stommel" in Henry Stommel, Bruce Alfred Warren, and Carl Wunsch. *Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel*. (Cambridge, Mass: MIT Press, 1981), hereafter "Arons", p xv.

[34] George Deacon, "The Woods Hole Oceanographic Institution: An Expanding Influence" in International Congress on the History of Oceanography, Mary Sears, and Daniel Merriman. *Oceanography: The Past*. (New York: Springer-Verlag, 1980) p 25 – 31.

[35] Arons, p xvi

In 1954, he started a series of hydrographic station measurements, the *Panulirus* series, in deep water off of Bermuda.[36] As he reported in a round-robin letter to oceanographers in 1955, he had gotten thermistor cables installed after two tries and could now see internal waves generated by distant storms.[37] From 1952 to 1955, employing these cables, he obtained measurements of the voltage difference between Halifax – Bermuda – Turks Islands, which allowed him to compute tidal velocities and transports.[38] As a time series, these data provided a view of variability in the ocean. This work later contributed to his classic book-length study *The Gulf Stream, A physical and dynamical description*, published by the Cambridge University Press in 1958.

In arguing that new forms of measurement were on the horizon, Stommel shared the concerns of many that modeling efforts might be conducted without subsequent verification by observation. The Woods Hole physical oceanographer William von Arx commented in 1955 that “we lack the necessary insight to extend our thinking very far without observations to verify our progress.”[39] As Stommel himself noted in *The Gulf Stream*, “Too much of the theory of oceanography has depended upon purely

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[36] George Veronis, “A Theoretical Model of Henry Stommel”, in Henry Stommel, Bruce Alfred Warren, and Carl Wunsch. *Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel*. (Cambridge, Mass: MIT Press, 1981), hereafter “Veronis”, p xx-xxi.

[37] Stommel to Leipper, May 1, 1955. Leipper Papers, 92-17, Box 1, Scripps Archives, UCSD.

[38] Stommel autobiography, p I-29.

[39] W.M. Ewing, handwritten note, undated [circa 1955]

hypothetical physical processes. Many of the hypotheses suggested have a peculiar dreamlike quality, and it behooves us to submit them to especial scrutiny and to test them by observation."[40]

It was a kind of argument that Stommel would return to again and again, including when he developed his new graphical methods for representing the physical properties of the ocean across large scales of time and space. His abiding interest in visual displays of data—nurtured during the 1950s as well—played an equally formative role in his quest to portray the complexity of what he would later term a "physical understanding" of oceanic circulation, both as a pedagogical tool to convince his colleagues and as a new approach to making it easier to order and grasp closely interrelated physical processes.[41]

The influence of post-war computers on Henry Stommel

Henry Stommel's interest in the use of computers for the analysis and display of oceanographic data began soon after the end of the Second World War, when he and Walter Munk visited John von Neumann at the Institute for Advanced Study at

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[40] Henry Stommel. *The Gulf Stream; a Physical and Dynamical Description*. (Berkeley: University of California Press 1965), 178.

[41] The oceanographer Bob Reid commented "Hank was into computer graphics early, especially interested in three dimensional stuff, and that may have led to the space-time-energy diagram" while George Veronis cited his "lifelong interest in maps and charts" Veronis, p xxiii. Stommel even co-authored a book on oceanographic atlases – H. Stommel and M. Fieux, *Oceanographic atlases* (Falmouth, Massachusetts: Woods Hole Press 1980).

Princeton in 1946.[42] There, and in subsequent discussions, Stommel, Munk, and von Neumann discussed how the use of high-speed electronic computers in oceanography might make it possible to solve previously unsolvable problems, including understanding diffusion and calculating eddy viscosity.[43] They commented that "… [the] EDVAC (electronic discrete variable automatic computer) is being developed as a research instrument. The long range possibilities behind its development are (a) to improve methods of weather forecasting and (b) to explore the possibility of influencing the weather by means of properly spaced and timed trigger actions [e.g. cloud seeding]. Since problems in meteorology over the oceans are at least 30% oceanographic, it appears that a simultaneous investigation of certain oceanographic and meteorological problems would be absolutely essential to the ultimate goal."[44] Stommel went to the Institute for Advanced Study in 1955 for four months to work on various problems, including the ascertaining the reasons why the main thermocline existed. In a letter to

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[42] Harry Wexler to Francis Reichelderfer, Nov. 15, 1946, Wexler papers, Library of Congress.

[43] Munk to Stommel, Mar. 1, 1949. Walter Munk Papers, MC-17, Box 13, Scripps Archives, UCSD.

[44] Vine to Munk, November 7, 1972 enclosing a copy of a report written by Munk and Stommel on December 17, 1946 reporting in a visit to the Institute of Advanced Studies on the "Possible Uses of Electronic Computing Machines to Problems in Oceanography". Walter Munk Papers, MC-17, Box 19, folder "Stommel 1966, 1969, 1972, 1977," Scripps Archives, UCSD. For more detail on the project see "Finding Aid for the Records of the Electronic Computer Project" http://www.admin.ias.edu/library/hs/ECPfindingaid2004.pdf and an oral history interview with Herman Goldstine, associate director of the Institute for Advanced Study (IAS) computer project from 1945 to 1956 at http://www.cbi.umn.edu/oh/pdf.phtml?id=129 .

fellow oceanographers, he described the time he spent working with the meteorologist Jule G. Charney, "who, you probably know, is the weather computer extra-ordinary." Stommel commented that Charney was able to fully develop a purely inertial Gulf Stream theory with no friction, an issue which "I was futilely playing with for a year."[45]

Convinced of the value of von Neumann's computing project for physical oceanography, Stommel sought other recruits to work with him at Princeton. He particularly urged Munk to do so, writing that, "together under the loom of The Computer," they could tackle crucial problems of oceanic circulation.[46] Munk, comfortably settled at Scripps, declined to join him. Nevertheless, Stommel reported to Iselin at WHOI that he had made what he felt were major steps forward by brainstorming with Charney at Princeton (and also George Morgan) about Charney's two-layer, quasi-geostrophic theory of the growth region of the Gulf Stream and Morgan's work on the boundary stream. Stommel found this reassuring: while he knew that the Swedish-American meteorologist Carl-Gustav Rossby had never felt that Munk's wind-driven circulation theory could give a detailed picture of the filament-like structure of the Gulf Stream, he was glad to discover new ways to approach equations of motion. As he reminded Iselin, "You will recall the bombshell that Neumann quietly cast into the arena last spring, when he suggested that variations in depth of the moving

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[45] Stommel to Leipper, May 1, 1955. Leipper Papers, 92-17, Box 1, Scripps Archives, UCSD.

[46] Stommel to Munk, September 17, 1954. Walter Munk Papers, MC-17, Box 19, folder Stommel 1954, Scripps Archives, UCSD.

surface layer might alter the picture of the central oceanic wind-driven circulation used by Sverdrup, Reid, Munk, and myself."[47] The Meteorology Project not only made numerical weather prediction possible, but demonstrated anew that important issues at the interface of the oceans and the atmosphere could be addressed and explored by the modern computer.[48]

When the Electronic Computer Project at the Institute closed in 1956, Charney and Phillips moved to MIT. Stommel was excited to have them close to WHOI so that they might continue their collaboration.[49] At the same time, Stommel continued his computer related collaborations with Munk, and arranged for Munk to run spectra on hydrographic records he was collecting at the Bermuda hydrographic station. In 1956, Munk commented that he had "not forgotten offer to run spectrum of Bermuda temp records," and was working on getting the temperature data into the computer. This work was completed in 1957.[50] They also considered whether it would be worth it to "take hourly sea levels for a station for 3-10 years, pass it through Gordon Groves tide killing convolution, and end up with 1000-3000 mean daily levels, good to about 1cm.

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[47] Stommel to Iselin, March 12, 1955. Walter Munk Papers, MC-17, Box 19, folder "Stommel 1955 - 1957," Scripps Archives, UCSD.

[48] On this development see Kristine C. Harper, *Weather By the Numbers* (Cambridge: MIT Press, forthcoming in 2008).

[49] Stommel to Leipper, no date, 1955. Leipper Papers, 92-17, Box 1, Scripps Archives, UCSD.

[50] Munk to Stommel, September 19, 1956 and Munk to Stommel, October, 10, 1956. Walter Munk Papers, MC-17, Box 19, folder Stommel 1955- 1957, Scripps Archives, UCSD.

From these I can get meaningful spectra for all periods between 2 days to 2 months. The spectrum has about 60 values, each good to few percent."[51] The spectra calculated here formed part of a joint paper on "thermal unrest in the ocean".[52] These calculations would have provided the basis for one of the axes of the Stommel diagram.

The second aspect of Stommel's explorations of computers and computing came several years later. It involved using computers to display oceanographic data. In 1963, the same year he was drafting the paper that came to include his influential diagram, Stommel wrote an article with M. Pivar and E. Friedkin, collaborators from Information International in Maynard, Massachusetts, on the machine display of oceanographic data. Their paper described a program to create a computer-compiled oceanographic atlas. They argued that the increasingly huge amounts of data being gathered by oceanographers could only be plotted by a computer, since individual scientists would want specific displays based upon what questions each was addressing. Stommel and his colleagues demonstrated that a cathode ray tube, light pen, input-output typewriter and control switches could produce a display of data stored on magnetic tape. The output was a two-dimensional plot showing the location of data points; points could be interrogated for more information by pointing at them with the light pen. While only a first step towards visualizing oceanographic data, the publication revealed Stommel's

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[51] Munk to Stommel cc to Arthur, December 27, 1956. Walter Munk Papers, MC-17, Box 19, folder "Stommel 1955-57 ", Scripps Archives, UCSD.

[52] Bernard Haurwitz, Henry Stommel, and Walter Munk, On the Thermal Unrest in the Ocean, *Rossby Memorial Volume*, (New York: Rockefeller Inst. Press, 1959) 74–94.

strong and growing interest in arranging complex data in visual ways.

Thinking about scale, measurement, and representations: Stommel's pathway to visual representation

It was amid this work on physical oceanography, informed by his ever-expanding appreciation of the role that computers were about to play in assess data in the physical environmental sciences, that Stommel began to work on diagrammatic representations that could adequately capture the complexity of natural phenomena at sea. In many respects, Stommel's work in this period marked a cumulation of the nearly twenty years of research he had done at Woods Hole. It reflected his growing familiarity with geophysical fluid dynamics, which he came to know through weekly seminar series at MIT and WHOI that involved numerous meteorologists and oceanographers, including Charney, von Arx, and personnel from the Geophysical Research Directorate of the nearby Air Force Cambridge Research Center.[53]

It also reflected his growing interest in gathering time-series observations of pressure, temperature and current in deep ocean regions, after he had initiated studies of

[53] In the late 1950's, a weekly geophysical fluid dynamics seminar, held at MIT and WHOI, involved Charney, Phillips (ex-Institute for Advanced Study), Stommel, Malthus(s), Fuglister, Stern, vonArx, Fuller (WHOI), Howard, Lin, Kuo, Lorenz, Stuart (MIT), Harvard, and personnel from the Geophysical Research Directorate, Cambridge Air Force Research Center [Veronis, pxxi]. At the same time, a summer course in "Theoretical Studies in Geophysical Dynamics" was started at WHOI. The course included Stommel, Willem Malkus, George Veronis, Louis Howard, Melvin Stern and Edward Spiegel. Topics included "geophysical fluid dynamics, meteorology, oceanography, and radiation" in 1959 with the lecturers listed as George Veronis and Others and the more general "fluid dynamics" with Louis Howard and Others in 1960. Stommel autobiography, p I-38.

ocean temperatures near Bermuda and began using submarine cables in the early 1950s to estimate ocean currents from potential differences. He perceived a way to do this by using strings of moored instruments and recoverable instrument packages containing automatic recorders, particularly after becoming aware of the neutrally buoyant float system for tracking deep currents developed by the British oceanographer John Swallow. During a 1957 cruise of the new WHOI research ship *Aries*, Stommel further tested his ideas about deep-water circulation, discovering that it displayed a wide spectrum of motions.[54] From 1958 to 1960 Stommel and his Woods Hole collaborator Arons intensively studied deep currents in the vicinity of Bermuda. These studies dovetailed with Stommel's efforts to install thermistors and other deep-sea instruments off of the islands, making use of new forms of electronic instruments that until then had not been applied to physical oceanography.[55] These new time series would provide additional data for one of the axes of what would later become the Stommel diagram.

Stommel's work in developing higher dimension diagrams of natural phenomena in the oceans represented a summit of his creative efforts. Nevertheless, it did not take place at Woods Hole. In 1958, Paul Fye succeeded Columbus Iselin as WHOI director. When Fye sought to coordinate research efforts at Woods Hole by appointing a director of research, his controversial plan led several researchers,

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[54] Deacon, p xxv

[55] Arons, p xvi

Stommel included, to resign.[56] In 1960 Stommel moved to Harvard to accept a teaching position. His time at Harvard was not entirely pleasurable, and he missed having daily conversations with observational oceanographers and access to oceanographic data.[57] While at Harvard Stommel worked with Paul Stimpson on a 1962 cruise on the WHOI ship *Atlantis* to test newly developed moored current meters. Stommel quickly appreciated that an array of these meters might provide quantitative measurements of the eddy motions seen qualitatively during the *Aries* studies.[58]

The flood of new data, the development of new instruments, and the challenges of understanding phenomena at varying scales in the oceans over long periods of time were all on Stommel's mind by the very early 1960s. Indeed, they had begun to coalesce in his thoughts several years before, which Stommel captured in one of his most influential self-published papers. In many respects Stommel's "dream-like" pamphlet, written in 1954, pointed the way towards what later became known as the Stommel diagram.[59] Stommel himself described it as a "polemical pamphlet," "a little memo about types of observations needed in oceanography."[60] The polemical label was

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[56] Walter Munk OHI [Ronald E. Doel], Sept. 17, 1997, Scripps archives, pp. 313-4.

[57] Veronis, p xxii. In his autobiography, Stommel describes "being called to Harvard" as a disaster.

[58] Stommel autobiography, p I-46.

[59] Arons, p xvi

[60] Stommel to Munk, Arthur, Knauss and Montgomery, June 1, 1954 and Stommel to Munk, May 10, 1954. Walter Munk Papers, MC 17, Box 19 folder "Stommel 1954", Scripps Archives, UCSD.

apt. To a large extent, it was his way to creatively deal with a mounting frustration he felt over the lack of widespread systematic data collection that he believed necessary to gain "an accurate idea of the mean distribution of properties in the ocean."[61] He had then raised anew an idea he had strongly promoted the year before to his WHOI colleagues Columbus Iselin and Ray Montgomery, as well as with Walter Munk: that thermal structures in the oceans now could be measured by buoys. Buoys and related new instruments under development, he believed, could also measure very large storm waves in the oceans.[62]

Though privately printed, the pamphlet was widely distributed and had a great influence on physical oceanographers. As one oceanographer later recalled, the 'dream-like' pamphlet was a "penetrating, incisive critique of the status of ocean current theory [which] made the rounds of active theoreticians and deeply influenced the direction of their thinking. I recall it being referred to repeatedly in seminars and colloquia of that period."[63]

What Stommel particularly wanted to do with the "dream-like" pamphlet, which ran some eleven pages of tightly argued text, including quantitative arguments, was to convince fellow physical oceanographers that the 'exploration phase' of oceanography

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[61] Stommel, "What Do We Know about the Deep Ocean Circulation?", text for talk at Deep-Sea Research Symposium, no date [circa 1955], Box 57, W. Maurice Ewing papers, Center for American History, University of Texas at Austin.

[62] Stommel, memo to Iselin, Montgomery, Munk [and others], Dec. 24, 1953, Walter Munk Papers, MC 17, Box 13, Scripps Archives, UCSD.

[63] Arons, p xvi

was over—and that new electronic instruments and improved understanding of what was required to advance physical theory required new approaches and new ways of thinking about experimentation. Among the sections of his paper were "Can oceanographic theories be tested?" and an extended review of how wind-driven current theories in the Gulf Stream could be tested. Some of these ideas had long been in circulation at Woods Hole. Already in 1939 Columbus Iselin, reflecting on the state of physical oceanography, had argued that key theories in the field, particularly Wilhelm Bjerknes's circulation theorem and Walfrid Ekman's wind current theory, "are too often used as though no questionable associations were involved."[64] But for Stommel the time to rethink oceanographic research had become critical. "I should like to make clear," he wrote, "that I am not belittling survey type of oceanography – nor purely theoretical speculation. I am pleading for more attention to be paid to a difficult middle ground: the testing of theories." He ended, "Much of the thinking and theory of oceanography depends on purely hypothetical physical processes (e.g. lateral mixing). They have a peculiar dream-like quality—and it behooves us to submit them to special scrutiny and to test them by observation."[65] Less than a decade later, Stommel found an occasion to recast the arguments in this paper in a more general form, one that included,

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[64] Columbus Iselin, circulating letter to biological oceanographers and fisheries scientists, undated [Dec. 1939], Columbus Iselin (1904 – 1971) Papers, MC-16, Box 9, folder 'Scientific, 1940, 1 of 2,", Data Library and Archives, Woods Hole Oceanographic Institution.

[65] Stommel, "dream-like" paper, p. I-134 of collected works.

for the first time, his effort to represent four dimensions of physical phenomena in graphical form.

"Varieties of oceanographic experience:" Stommel creates the Stommel diagram

In 1962, Stommel traveled to Moscow. The occasion of the visit—partly a result of his interaction with Soviet oceanographers during the International Union of Geodesy and Geophysics meeting in 1958—was to discuss a new Soviet proposal to begin large-scale repeated hydrographic studies of the world oceans, submitted to UNESCO by the Soviet Academy of Sciences and the State Hydro-Meteorological Agency.[66] Together with John Swallow and a number of U.S. colleagues, Stommel used the opportunity to reiterate now-familiar arguments. Western scientists were convinced, he argued, that ships should not be used for these kind of extensive and repetitive surveys.[67] The American team argued that turbulence played such a major role in ocean properties that repeated sections would be hopelessly aliased and unproductive. Instead, they argued for the ships to be used for studies of the role of eddies rather than for conducting standard ocean sections.

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[66] Stommel, Autobiography, p I-46.

[67] Interestingly, this type of repeated global survey of ocean properties to consider the role of the oceans in climate was the centerpiece of the World Ocean Climate Experiment (WOCE) conducted from 1990 – 1998 [http://woce.nodc.noaa.gov/wdiu/] and the Geochemical Ocean Sections Study (GEOSECS). [http://iridl.ldeo.columbia.edu/SOURCES/.GEOSECS/]

Following his Moscow visit, Stommel decided to write up another polemical statement on experimental practices in physical oceanography, this time for publication. "Varieties of Oceanographic Experience" – his "valedictory to Harvard," as he later put it[68]--appeared in *Science* in March of 1963. In contrast to his "dream-like" paper from nine years before, "Varieties" was largely qualitative. But it contained his strongest assertion until that time of what he now considered the key challenges of physical oceanography: the design of expeditionary programs that took into account the "whole spectrum of phenomena" on both periodic and geometric scales (Stommel 1963: 572).

Why Stommel chose to publish his review in *Science* is uncertain, but in choosing the journal of the American Association for the Advancement of Science, rather than a specialized earth sciences journal, Stommel clearly wished to reach a wide range of professional researchers and planners. In 1947 he had missed a significant paper by Harald Sverdrup published in the *Proceedings of the National Academy of Sciences*, another multi-professional journal, but one he later dismissed as one read only by "its aging members."[69] He may also have been aware that *Science*'s new editor, the physicist Philip H. Abelson, was deeply interested in scientific practice, was about to publish the geophysicist M. King Hubbert's lengthy indictment of U.S. university

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[68] Stommel, Autobiography, p I-47.

[69] Stommel, Autobiography, p I-18.

science practice, "Are We Retrogressing in Science?"[70] In any event, Stommel had a wide audience in mind.

Stommel's 1963 article primarily addressed the problems of making measurements in a turbulent environment, specifically addressing the scales of phenomena that could be described by samples collected at a given interval in time and space. In laying out an approach and rationale for conducting oceanographic research, Stommel also provided insights into the role that scale, in time and space, acts in the oceans. He cited two examples: temperature fluctuations in the deep sea, where a relatively small number of measurements spread over a long time period are sufficient, and tidal variation in the South Pacific, where a large number of measurements at short time intervals are necessary to define the short wavelength tidal signal (Stommel, 1963). "A single net does not catch fish of all sizes," Stommel wrote, and "the existing net of tide-gauge stations does not suffice for a study of geostrophic turbulence" (Stommel 1963: 573). He sought to convince oceanographers that these problems were fundamental: "the coexistence of different periods and scales leads not only to contamination in measurement programs but that the scales also interact. To achieve 'physical understanding' we must map not only the variables but also their interactions." He concluded with a mix of exhortation and optimism:

> "In the past there were very few points of contact between the ocean as visualized by conventional analysis of serial observations on the one hand and the ocean as portrayed by simplified laminar theoretical

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[70] M. King Hubbert. "Are We Retrogressing in Science?" *Science* 139(3558) (1963), p. 884-490.

> models on the other. I think the reason is not hard to find: neither model has been developed to a level of sophistication corresponding to the essential complexity of the oceanic phenomenon it was trying to describe. From the scattered pieces of evidence that are at present available it appears that the dynamics of the oceanic circulation, and the transport of various properties in the sea, may actually be dominated by the large-scale, transient, turbulent processes which hitherto have been ignored by observers, and which theoretical workers had been hoping to bypass. There is no harm in thinking at first about the ocean in various simple ways, to see how satisfactory a model one can devise, but a time comes when consideration of the next stage in complexity can no longer be postponed. Happily, we have the technological means to begin oceanographic observation of the new type, and we can look forward to a time when theory and observation will at last advance together in a more intimately related way." (Stommel 1963: 575)

To further illustrate these arguments, Stommel provided a diagram of the spectral distribution of sea level, as well as two diagrams of the velocity spectra for currents in the deep oceans. The first of these diagrams is what later became known as a "Stommel diagram." It supported Stommel's argument that scales mattered in understanding oceanic phenomena, and that experiments needed to be carefully designed to investigate specific phenomena. This "scale" aspect of *Stommel's* Science article is probably the more widely cited aspect of this seminal paper. This now-classic Stommel diagram (Figure 1) is a "schematic diagram of the spectral distribution of sea level."[71] It is a three-dimensional plot with time versus space as the axes of the horizontal surface and the power of the spectrum as the vertical axis. Short time period-short wavelength phenomena were represented near the X-Y origin; very long term variations, for

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[71] Henry Stommel. "Varieties of Oceanographic Experience". (*Science*. 139, 3555 1963): pp. 572-576.

example ice age changes in sea level, appeared at the extremes of X and Y. Tidal terms were depicted as two peaks, with long wavelengths and high power at a diurnal and

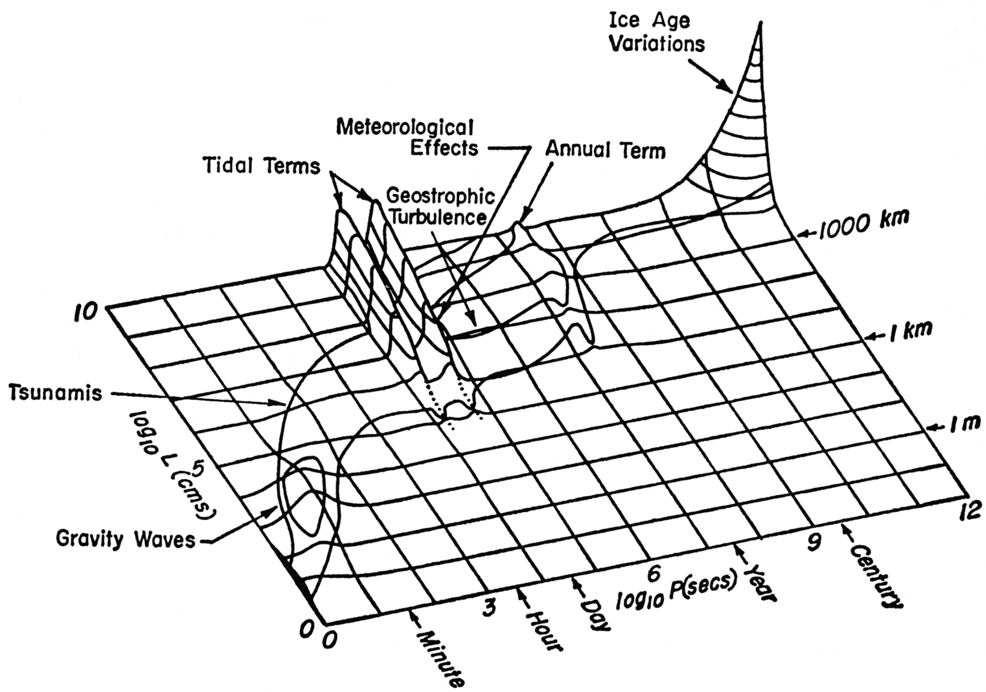

Figure 4 The original Stommel diagram. "Schematic diagram of the spectral distribution of sea level". Reproduced from Henry Stommel. "Varieties of Oceanographic Experience", Science 139 (1963): 373. Used with permission from AAAS.

semi-diurnal timing. While intending to illustrate a general point, Stommel went on to provide a practical example of using the plot to evaluate the results of a research cruise in the Indian Ocean (Figure 5). On this plot he indicated the expected spectra, the spectra for another part of the ocean, and the spectra *actually* observed on the cruise.

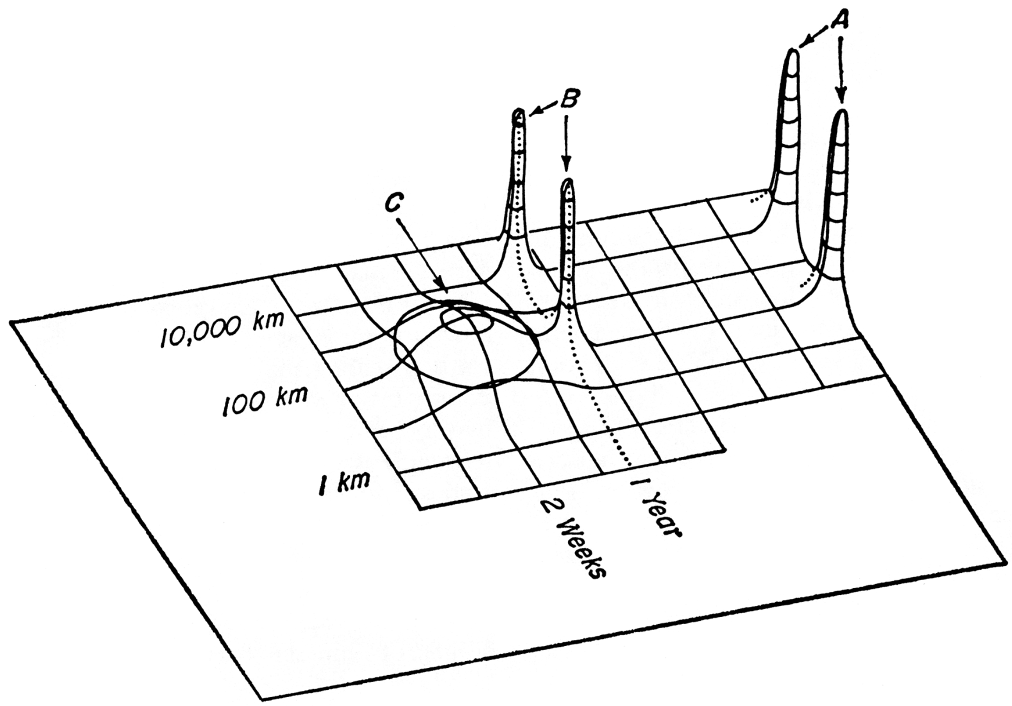

Figure 5 Application of the Stommel diagram to the sampling strategy for a cruise in the Indian Ocean From Henry Stommel. “Schematic diagram of velocity spectra, showing (A) the two peaks associated with the Pacific equatorial undercurrent; (b) the two annual peaks which the Argo expedition expected to find for the Indian Ocean at the equator and which it planned to map; and (C) the probable actual peak for velocity that was revealed to be present but that could not be mapped by the procedures, appropriate for mapping B, that were employed in the expedition. Coordinates are the same as in Fig. 1.” Reproduced from Henry Stommel, “Varieties of Oceanographic Experience”, Science 139 (1963): 373. Used with permission from AAAS.

By doing this he showed how the data collected during a cruise designed to measure one set of spectra were aliased with respect to another set of spectra due to the mismatch in the timing and spacing of the samples taken. Moreover, the diagram illustrated this at a careful glance.

Stommel's *Science* article—together with another co-authored publication with Malcolm Pivar and Ed Fredkin titled "Computer-Compiled Oceanographic Atlas: An Experiment in Man-Machine Interaction"— certainly attracted the attention of oceanographers. His Brown University colleague Raymond Montgomery, although irritated by what he perceived as Stommel's brash dismissal of much contemporary oceanographic research methods, commented, "I am glad that you are devoting attention to the development of machine methods of data processing, and I look forward with interest to the publication of the Kuroshio Atlas. And I am glad that you are exploring the possibilities of machine display of oceanic distributions. I hope that your personal activity in these directions will receive adequate support."[72] Over the next several years Stommel continued to emphasize the importance of careful planning of future expeditions, stressing, as he had in 1963, that achieving "physical understanding" of the oceans would require mapping phenomena at a wide range of periods and scales (Stommel 1963, 575).[73]

Despite having achieved this breakthrough in employing graphical methods, Stommel himself seemed to have limited interest in this approach. The only other time

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[72] Montgomery to Stommel, April 15, 1965. Raymond B. Montgomery (1928 – 1988) Papers, MC-30, Box 16, Data Library and Archives, Woods Hole Oceanographic Institution.

[73] This commitment is no less apparent in Stommel's correspondence; see for instance Stommel to Pritchard, Fofonoff, Munk, McLellan, July 19, 1966; Munk to Isaacs, July 26, 1966; Munk to Stommel, Pritchard, McLellan and Fofonoff , July 26, 1966; Isaacs to Munk, August 3, 1966; all Walter Munk Papers, MC 17, Box 19, folder "Stommel 1966, 1969, 1972, 1977", Scripps Archives, UCSD.

Stommel published a Stommel diagram was in a 1965 article on planning research on the Kuroshio Current. In it, he returned to the approach he had utilized two years earlier, using this critical diagram to drive home the point that oceanographers needed to carefully consider the varieties of phenomena they wished to measure and to plan their experiments accordingly (Stommel 1965, 30).

Why was this? One reason was likely professional. In 1963, the year he published in *Science*, Stommel left Harvard for MIT. The move brought him once again into closer contact with researchers developing oceanographic instruments. While at MIT, Stommel met M.J. Tucker, an oceanographer working on the tracking of floats by use of the sound fixing and ranging (SOFAR) channel. He also had contact with Phil Bowdwich at MIT's Draper Laboratory, which led to the successful development of a high precision deep-sea thermometer in collaboration with a graduate student, Alex Gilmour. Although other attempts to develop the instrumentation necessary to detect microstructure in the oceans were less fruitful, Stommel again found himself in an intellectual environment where he had less need than before to stress the fundamentals of instrument and experiment design.[74]

Another, and perhaps more significant, reason may be that Stommel saw the diagrams primarily as tools of persuasion rather than as a new instrument in their own right. Stommel's 1963 paper reveals his predominant concern with the proper design of

[74] Stommel autobiography, p I-58. Stommel stayed at MIT until Fye retired from the directorship of Woods Hole in 1977, creating an opportunity for him to return to the research community he most dearly missed. He remained there until his death in 1992.

large-scale, multi-institutional expeditionary programs at a time when funding for such research was burgeoning. Rising concern about Soviet submarine advances, and an ever-growing recognition of the importance of understanding the oceans as an environment in which the U.S. military needed to operate, had greatly increased funding for large-scale oceanographic research programs.[75] In his *Science* article Stommel expressed his concern that past—and proposed future expeditions—would take place without sufficient planning and hence miss precious and unprecedented opportunities to make measurements that would enhance physical theory. He criticized the recently concluded International Geophysical Year of 1957-58, noting that “there is a need for more sophisticated and more physically oriented observational programs than the geographical surveys” it had achieved. Calling attention to emerging oceanographic programs, including the MOHOLE drilling project, Stommel suggested that a coordinated national program might be required to make necessary observations (Stommel 1963, 575). Since Stommel, in particular, and Woods Hole, in general, had played an important role in jumpstarting the International Indian Ocean Experiment, he was particularly sensitive to the question of experimental design, an issue clearly reflected in his 1965 article on the Kuroshio Current study. In short, Stommel sought to use his new graphical tool, not simply to structure data or influence fellow

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[75] See also Jacob Hamblin. *Oceanographers and the Cold War: Disciples of marine science*. (Seattle: University of Washington Press, 2005); Ronald E. Doel. “Constituting the Postwar Earth Sciences: The Military’s Influence on the Environmental Sciences in the USA after 1945”. *Social Studies of Science* 33 (2003): 635 – 666.

oceanographers about the interrelation of physical processes at differing scales, but also as a pedagogical tool that would influence science policymakers.[76] Stommel appreciated its utility within physical oceanography, but not necessarily its broad applicability to the environmental sciences in the broadest of terms.

Dispersion and diffusion: Migration of the Stommel diagram into biological oceanography

Although Stommel was in close proximity to biological oceanographers at Woods Hole, with the campus of the Marine Biology Laboratory just over a mile away from WHOI, a shared geography did not lead to an immediate dispersion of his graphical methods into adjoining fields. Indeed, it would take more than a decade before other researchers would pick up key aspects of his "Stommel diagram." The first scientists outside physical oceanography who made use of Stommel's graphical methods did cross physical paths with Stommel, at least in terms of institutions. In 1978, the biological oceanographers Loren Haury, John McGowan and Peter Wiebe published a paper entitled "Patterns and processes in the time-space scales of plankton

[76] Stommel's interest in tools such as the Stommel diagram for planning research campaigns was not simply academic. In the 1960's he became increasingly involved in the planning for, and execution of, large oceanographic projects. He became involved in one capacity or another with GEOSECS, MODE and MEDOC 1969. (1969); for further background see Wallace S. Broecker oral history interview [Ronald E. Doel], June 6, 1997, pp. 108-9, Oral History Research Office, Columbia University, NY.

distribution."[77] Their paper included a three-dimensional version of the Stommel diagram, tailored to plankton biology. It depicted zooplankton biomass variability and the physical phenomena that contributed to this variation, with axes of space-time-biomass variability (Figure 6). As with the Stommel diagram, it featured peaks due to factors such as ice ages, annual cycles and daily changes. Haury, McGowan and Wiebe then identified these peaks with characteristic physical oceanographic forcing factors such as eddies and currents. The height of the peaks was originally a qualitative estimate, though later versions had a stronger quantitative basis. Precisely how Haury, McGowan and Wiebe became familiar with the Stommel diagram and perceived its utility for marine biology is unclear. Later McGowan recall that he had created the plot as an illustration for classes he was teaching. In these courses he presented three lectures: one on the original Stommel diagram, a second on spatial scales in the oceans, and a third on temporal scales. A student of his, Patricio Bernal, asked why it wasn't possible to create a biological version of the Stommel diagram?[78] The result was the plot used in their 1978 paper.

Stommel's original paper and Haury *et al.* remain the main three-dimensional versions of the Stommel diagram in the literature. The meteorologist Isidoro Orlanski

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[77] Loren Haury, John McGowan, and Peter Wiebe. "Patterns and Processes in the Time-Space Scales of Plankton Distributions". In *Spatial pattern in plankton communities*. Edited by J.H. Steele. (New York: Plenum Press 1978), p. 277-327.
[78] John McGowan, pers. comm., 11 January 2007.

created a similar plot for atmospheric processes plotting space-time-vertical distance.[79] Physical oceanographers Kuragano and Kamachi have looked at space-time scales in

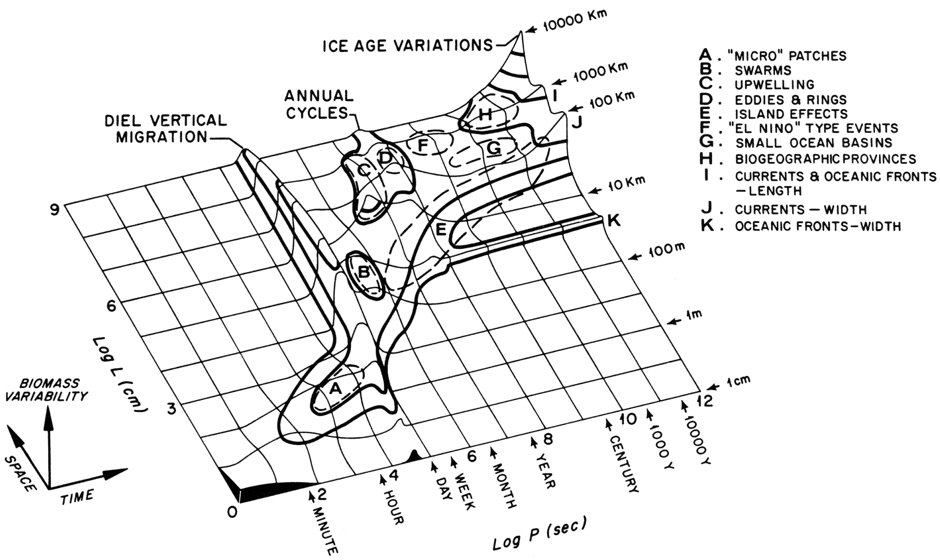

Figure 6 The Haury et al. version of the Stommel diagram. "The Stommel diagram, a conceptual model of the time-space scales of zooplankton biomass variability and the factors contributing to these scales." From L. Haury, J. McGowan and P. Wiebe. Patterns and processes in the time-space scales of plankton distributions. In John H. Steele. 1978. Spatial pattern in plankton communities. New York: Plenum Press. p 277 – 327. With kind permission of Springer Science and Business Media

oceanic variability, and created a plot of correlation coefficients in latitude-longitude-time lag space.[80] Most other researchers have collapsed the three-dimensional plot into a two dimensional Time-Space diagram (Figure 7). In these plots the relative power of

[79] I. Orlansky, I., "A Rational Subdivision of Scales for Atmospheric Processes." *Bulletin of the AMS.* 56(5) (1975): 527 – 530.

[80] See T. Kuragano and M. Kamachi. "Statistical Space-Time Scales of Oceanic Variability Estimated From the Topex/Poseidon Altimeter Data." *Journal of Geophysical Research-Oceans.* 105(C1) (2000): 955-74.

the phenomenon is not represented, the plot is quantitative in space and time, and does not specify the power or importance of the phenomenon.

Most known adaptations of the Stommel diagram have occurred in the West, suggesting that this innovation has diffused by individual-to-individual contact as much as from researchers becoming acquainted with it solely through Stommel's 1963 and 1965 publications. But by the early 1990s interest in the Stommel diagram also spread to Russia, where researchers, despite *Glasnos*t, remained somewhat isolated from their western colleagues. A posthumous paper by the Moscow State University oceanographer Oleg Ivanovich Mamayev, published in 1995, bore the title "On Space Time Scales of Oceanic and Atmospheric Processes." In it he argued, "Investigations of the space-time scales of variability of processes in the ocean and in the atmosphere, from the most short-lived ones to planetary scale processes, as well as the interdependence of these processes are important for understanding trends in climate changes, at least for the future."[81]

The situation in ecology and biological oceanography was quite different: there, the diagram seemed to be an important analytical tool for representing complex data. David Schneider looked at the rise of the concept of scale in ecology.[82] In the process, he explored the adoption of space-time diagrams in ecology. He argues that Steele's

[81] See O. Mamayev, "About Space-Time Scales of Oceanic and Atmospheric Processes." *Okeanologiya.* 35(6) (1995): 805-8.

[82] For a more complete discussion see David Schneider, "The Rise of the Concept of Scale in Ecology." *BioScience* 51(7) (2001): 545-53.

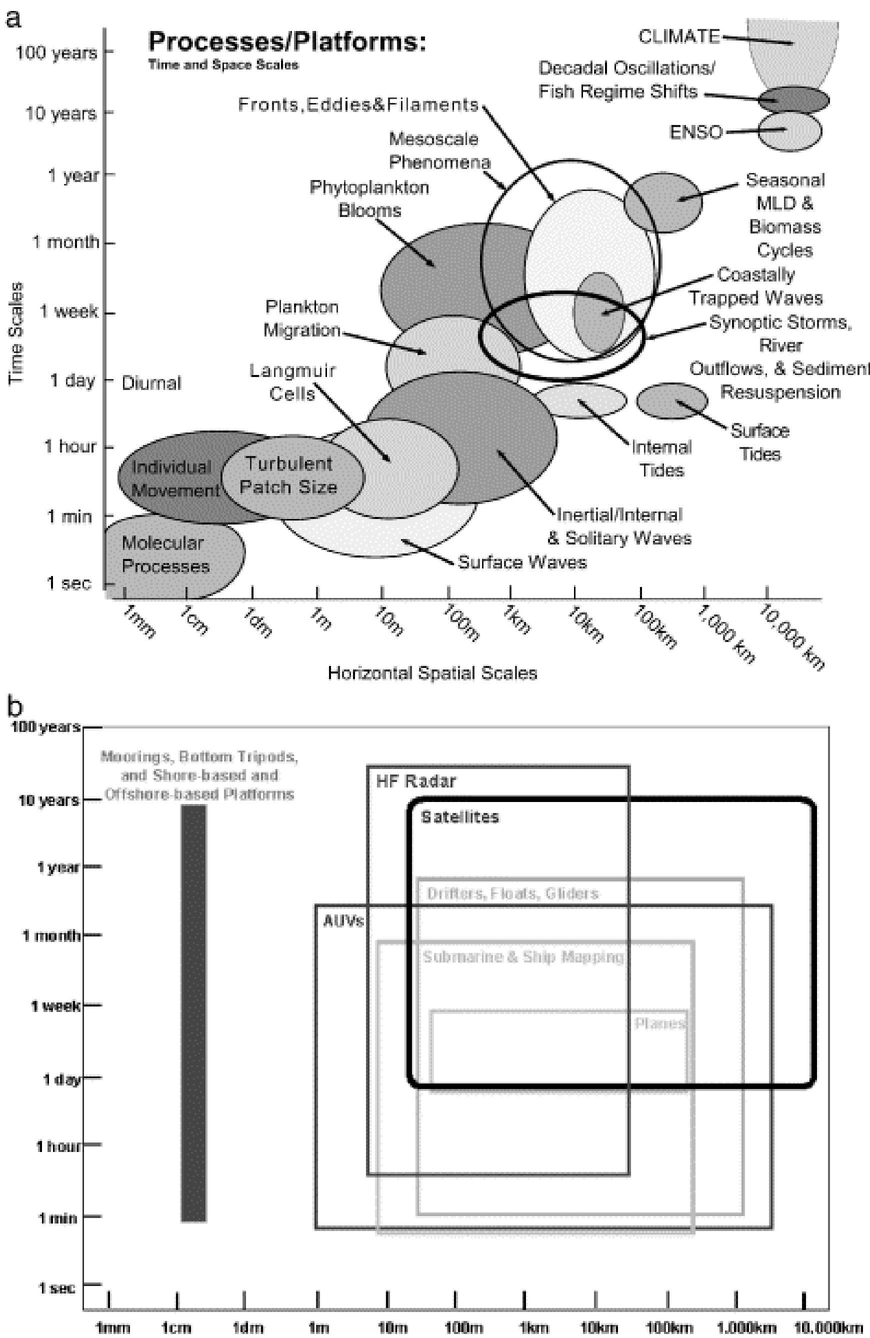

Figure 7 Example of a 2-D Stommel diagram being used both for phenomena and for the capabilities of sampling technologies. Reprinted from Journal of Marine Systems, Vol. 40-41, Tommy Dickey, Emerging ocean observations for interdisciplinary data assimilation systems, p 5 - 48, 2003, with permission from Elsevier

1978 article[83] was the first to use a space-time diagram in the ecological literature. Steele's article uses the two-dimensional space-time version of the Stommel diagram. It was in the same volume of conference proceedings that Haury, McGowan and Wiebe, as discussed above, first used a complete three-dimensional Stommel diagram to describe plankton dynamics.

Since the early 1980s, this version of the Stommel diagram appears in a number of other articles in the ecological literature. Others have commented on the adaptation of the space-time diagram in various disciplines. Perry and Ommer wrote of works on scale-dependent processes in physiology, island biogeography and metapopulation dynamics.[84] In 1985, Clark wrote of the ecological literature and also of more general oceanography and climate change and fisheries and he used Stommel type plots to look at climate impacts.[85]

Conclusions: On the nature of intra- and cross-disciplinary scientific communication

Two key questions require an answer. First: to what extent did the Stommel diagram become an established tool within physical oceanography, the community in

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[83] John Steele, "Some Comments on Plankton Patches." In *Spatial pattern in plankton communities*. Edited by J.H. Steele. (New York: Plenum Press 1978), p. 1- 20.

[84] See R. Perry and R. Ommer, "Scale Issues in Marine Ecosystems and Human Interactions." *Fisheries Oceanography*. 12(4-5), (2003): 513-22.

[85] See William Clark, "Scales of Climate Impacts." *Climatic Change.* 7(1) (1985): 5-27.

which it originated? Second, to what extent was this innovation adopted outside the earth sciences, and what explains why this occurred?

The Stommel diagram does not seem to have become widely used in physical oceanography. Several factors may account for this. By publishing his pioneering paper in *Science,* Stommel succeeded in placing it before a wide audience, but not in a journal central to physical oceanographers at the time.[86] Moreover, the article itself was primarily qualitative, and thinly sourced. Stommel may well have hoped the diagram would serve primarily to buttress his arguments about the need to carefully design large-scale oceanographic experiments, rather than to convince oceanographers about the need to adopt graphical representations. Moreover, the arguments Stommel made in *Science* concerning the challenges of verifying oceanographic theories, as Carl Wunsch had suggested, were already made in his "Dream-like" paper, which contained many more quantitative arguments and thus may have appealed more to physical oceanographers.[87]

The situation in the biological and ecological sciences was markedly different. With the collection of long time series such as the CalCOFI dataset[88] and terrestrial datasets such as those collected at Hubbard Brook and other Long-Term Ecological

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[86] Dennis Moore, pers. comm., 7 September 2006.

[87] Carl Wunsch, pers. comm, 20 May 2006.

[88] http://www-mlrg.ucsd.edu/calcofi.html, accessed 16 November 2007.

Research (LTER) sites[89] it became not only possible, but necessary, to use graphical summaries to understand the data. While some researchers limited themselves to a qualitative description of intensity and used the two-dimensional version of the diagram. Others used the fully three-dimensional version of the diagram and made an attempt to quantify the relative magnitudes of the various phenomena.[90] Further investigation of the dissemination of the Stommel diagram will provide both an understanding of how it was adapted for these new uses and an exploration of the possibilities of a "new Stommel diagram" to serve future generations of scientists.

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[89] See John J Magnuson, "Long-Term Ecological Research and the Invisible Present: Uncovering the Processes Hidden Because They Occur Slowly or Because Effects Lag Years Behind Causes," *Bioscience* 40(7), (1990): 495-501.

[90] See Lee Benda, Leroy Poff, Christina Tague, Margaret Palmer, James Pizzuto, Scott Cooper, Emily Stanley, and Glenn Moglen. "How to Avoid Train Wrecks When Using Science in Environmental Problem Solving." *BioScience* 52, no. 12 (2002): 1127-36; George Hunt, and David Schneider. "Scale Dependent Processes in the Physical and Biological Environment of Marine Birds" in J. Croxall, *Seabirds: Feeding Biology and Role in Marine Ecosystems*. (Cambridge: Cambridge University Press, 1987); M. Kaiser, "Pelagic Ecosystems." Web page, Available at www.st-andrews.ac.uk/~perg/06_Kaiser_Chap06.pdf , accessed 16 November 2007.

Chapter 4: Diffusion of the Stommel diagram and the possibilities for a 'new Stommel diagram'

Introduction

The spread of the Stommel diagram and its leap to biology and ecology follows a somewhat atypical route. While it was created by a widely respected physical oceanographer, it was published in the AAAS flagship journal *Science* and not in a more purely oceanographic journal. It gained its widest adoption as the result of being adapted for use in plankton biology, and is still cited and used in a wide variety of disciplines including marine biology, terrestrial ecology and plankton ecology. Given this complex dispersion, it is necessary to consider the process from a variety of perspectives beyond geography, including history and sociology. A number of techniques can be used to study the spread of ideas and techniques in a scientific environment. Among them are models that use analogies with epidemiology, studies of innovation diffusion, studies of invisible colleges and tacit knowledge, and studies of the mechanics of the creation of graphics or inscriptions. Each of these tools provides clues to the spread of the Stommel diagram, and how a "new Stommel diagram" might be developed and promulgated.

This chapter is intended to briefly describe some of the techniques to study the spread of scientific techniques, describe how the data illustrating the adoption of the diagram were gathered and analyzed, and to show the results of the analysis. Understanding this process can then be used to both identify the possibilities for a "new

Stommel diagram" and to describe the hurdles that the creation and adoption of such a plot might face.

Understanding the spread of techniques and tools

Models

The industrial economist Paul Geroski (2000) describes the common observation that the spread of a new technology tends to follow an S-curve, with slow adoption followed by a period of rapid uptake and culminating in a slow decline of the rate of new adoption. The curve tends to be asymmetric with a long upper tail. If there are two populations adopting a tool, e.g., physical oceanography and plankton biology, the S-curve can be the result of the vertical summation of two sources. The asymmetry is a product of adoption by heterogeneous populations, adoption via both a common source and word of mouth, an 'infection' rate that declines with time, or a pool of potential users that increases with time. Everett Rogers, a sociologist of communications and innovation diffusion, proposes that the adoption of new technology is a combination of hardware and software, where hardware is the new tool or technique and the software is the information base (Rogers, 1983). Software is passed on via word of mouth, which requires an existing user base. A mixed information source model includes common source information and word-of-mouth information. The mixed information model assumes a population with similar beliefs, levels of education and social status. This would be the case of oceanographers and plankton biologists but might be less the case with a transfer from oceanographers to terrestrial ecologists. In agreement with the arguments of historians of science, Geroski (2000) concludes that some of the knowledge that is a part of this process will be tacit.

Geroski proposes four main models to explain patterns of technique diffusion: the *epidemic* model, which uses analogies from disease vectors in medical studies to describe the process; the *probit* model, which suggests that potential users adopt at times based upon their own needs and when the benefits exceed the apparent and hidden costs; *density dependent* models, involving legitimation and competition; and *information cascade* models, where a single technique wins out over a number of variants. All of these models reflect the fact that social phenomena are complicated, people tend to think for extended periods before they act, their actions can be slow and unpredictable, and there are seen and unseen interdependencies (Geroski, 2000).

Researchers who model the spread of scientific ideas through the use of epidemiological models start with the premise that there is an “infected” population of existing users of a technique or tool and an uninfected population that is susceptible to infection in that they could use the tool. The transition from uninfected to infected requires exposure to the tool. The process can be stable - the rate of infection is not changing, or unstable - the rate of infection is increasing or decreasing. The uninfected population may also be increasing through time due simply to the increase in the number of practitioners in a discipline. The appeal of this conceptual approach is that is can be used both to model the importance of past events and tools or techniques and the emergence of new ideas and tools. William Goffman, a mathematician studying communication theory and information systems, was one of the first to use this technique. In 1966, he used it to model the spread of knowledge about mast cells, which are important in allergic reactions and wound healing. As his data he used a bibliography of papers from 2195 contributors on the subject ranging from the discovery of the cells in 1877 to a then-current cutoff point in 1963. With these data he was able to model the rise in studies of mast cells with a system of differential equations, and could predict directions that the research might take in the future. This was a first attempt to use mathematical techniques to analyze and *predict* the directions of research in a discipline (Goffman, 1966). As such, it is the precursor to mathematical analyses of patterns in scientific literature.

More recently, a multi-disciplinary team of historians of science, mathematicians and physicists used similar techniques to look at the spread of Feynman diagrams within theoretical physics (Bettencourt et al., 2006). They see the spread of ideas as an intentional act with no easy way to become uninfected but with major advantages to becoming infected and acquiring new ideas. Feynman diagrams provide a tool for making scattering calculations in quantum physics. They are a "diagrammatic representation of particle interactions that [can] be used to organize a series expansion"[91] for modeling interactions in high-energy physics. The diagrams were

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[91] L. Bettencourt et al., "The Power of a Good Idea: Quantitative Modeling of the Spread of Ideas from Epidemiological Models," *Physica A -Statistical Mechanics and Its Applications* 364 (2006): 515.

formalized, expanded, and described by Feynman's colleague Freeman Dyson and his descriptions led to wider acceptance and understanding of the diagrams. As the early use of Feynman diagrams required apprenticeship and familiarization, transmission was preceded by personal contact. Only in later years were textbooks and lecture notes on the use of the diagrams available. Bettencourt et al. use data collected by historian David Kaiser on the spread of the diagrams from 1949 to 1954. The network of scientific contacts is reconstructed through the use of correspondence, interviews, and the exchange of preprints and papers that cited the original Feynman paper or the subsequent Dyson papers on the technique.

The Kaiser data display the expected S-curve with a lazy tail as the technique spread to new parts of physics and as textbooks started to spread the idea to new groups of susceptible scientists. As with epidemics of disease, there were geographical barriers to transmission: in this case the spread of the use of Feynman diagrams to the Soviet Union during the Cold War was limited by restrictions on travel and scientific exchange. This can be contrasted with the spread to Japan, where the barriers were more systemic and social (Traweek, 2005). The Bettencourt study found that authors early in the study cited Feynman or Dyson but did not use the diagrams, and authors towards the end of the study period used the diagrams without citing the seminal papers. Bettencourt et al. (2006) also observed that this kind of data gathering can underestimate the number of infected persons, but that it is the only practical approach to creating a model. Many of the same techniques have been used here to study the diffusion of the Stommel diagram.

The other three models mentioned by Geroski are not commonly used in the analysis of the diffusion of scientific ideas. The probit model analyses the individual adoption decisions affecting diffusion and requires that the profit from implementation exceeds a threshold. While a user may simply recognize a need, the probit model is concerned with quantifying costs for characteristics that are frequently unavailable for decisions about research tools. The legitimation versus competition models look at density-dependent growth models and include limits on the number of organizations and the erosion of barriers to acceptance. Finally, the information cascade model looks at the interaction of two competing technologies and how the transmission of information leads to the dominance of one over the other. This type of competition does not seem to be a factor in the acceptance of new graphical techniques, thus this model can be ignored in this analysis.

Innovation diffusion

Geographical studies of innovation diffusion have traditionally considered the spatial pattern of the spread of a new idea or technique, while more systems-oriented studies place less emphasis on spatial patterns and more emphasis on social factors. Rogers (1983) proposes five phases of the diffusion of an innovation. *Knowledge* exposes the new idea and leads to its being understood by potential adopters.

Persuasion involves the formation of a favorable response to the idea, while *Decision* is a commitment to its adoption. *Implementation* puts the new idea or tool to use, and *Confirmation* reinforces the decision to use the new idea by producing positive results. The characteristics of an innovation include the advantage it provides, how compatible it is with previous experiences, how easy it is to use, how easily a small example can be tested and whether the improved results are easily visible. While Rogers' approach is purely qualitative, it can describe and compare innovations. The future outlook for an innovation can be predicted based upon its current phase in the process.

Sociology of Science

The sociologist of science Robert Merton has described the Matthew Effect in the communication and acceptance of new ideas. In his now-classic formulation, he proposed that a contribution by a highly ranked scientist will have higher visibility and the reputation of the author will serve as a cue when readers are deciding what to read in a large and overwhelming literature. He argues that "Science is public" and that "innovation must be effectively communicated to others". He also argues that "only work that is effectively perceived and utilized by other scientists, then and there, matters."[92]

Similarly, the science policy expert Diana Crane (1972) has looked at the social structure of science and the ways in which scientists communicate about research and

[92] Robert Merton. "The Matthew Effect in Science". *Science* 159 (1968): 5.

deal with change over time. In considering "invisible colleges," she places a greater emphasis on *how* scientists communicate as opposed to *what* they communicate. Crane proposes a four-stage model for the rise and fall of new ideas. In the first stage a new paradigm (or technique) appears and there is little social organization to its practitioners. In the second stage Kuhn's normal science is occurring and there are groups of collaborators and the formation of invisible colleges of acceptors and practitioners (Crane, 1972). In the third phase there is a divergence. If the new idea is a solution to major problems then there is increasing specialization in its use. If anomalies appear that challenge the effectiveness of an existing paradigm, then there are increasing controversies about its use. Finally the idea either runs its course and becomes a part of the standard body of knowledge, or it fails and a crisis occurs. In either case, the number of practitioners actively touting its use declines.

History of science

Historians of science have considered the role of research schools, the interactions between scientists and the role of tacit knowledge in the spread of new ideas. Research groups are defined as small geographically co-located groups while a research school is a geographically dispersed community of researchers, which may, or may not, have a geographic center. These two scales of research spread new ideas in different ways. In a research group ideas are spread by personal contact and ideas spread to the larger world as personnel migrate to new jobs and institutions. The physical tools of the discipline may complicate this type of migration. While the spread of a mathematical technique can be easily transported in the mind of a researcher, the physical equipment of a complicated laboratory is much harder to transport. In some cases, a local characteristic or discovery may become so dominant that it becomes universal. Research schools tend to exchange information via more impersonal means and the interconnections between researchers may be invisible (Geison, 1993). The clearest example of this invisible exchange is a paper being read by researchers who have never had personal contact with the author(s).

Other historians have looked at the role of tacit knowledge in creating research schools and spreading their new techniques. Tacit knowledge is knowledge that makes up the assumed expertise within a lab or discipline. It may be as simple as understanding the way that a recalcitrant piece of laboratory equipment works and how that affects data production or as complicated as the assumed format for presenting data and discoveries. In any case, it is not formally described but is dispersed informally. Utilizing these approaches, David Kaiser (2005) has traced the spread of Feynman diagrams both via formal written processes and by informal sharing of tacit knowledge and the resulting dispersion of researchers. In some cases, multiple types of dispersion can be identified based upon whether the scientists in question are able to travel and gain access to the printed literature or whether their travel and access are limited due to political considerations such as the Cold war.

Information technology

The information scientist Albert Tabah (1999) provides a summary of the approaches used in literature dynamics to understand the diffusion of an idea. He argues for four methods for studying patterns in the way a literature evolves. The first is an historical focus, to follow the movement of people and ideas. The second is sociological, and considers the structures of networks and the social processes associated with science. The third is philosophical, and follows truth claims; while the fourth involves activities in the information sciences to follow the published literature. This approach argues that it is possible to make inferences about the movement of ideas by following the growth of the literature. The newer techniques of visualizing the links between papers, such as those shown by CiteSpace, are an extension of this approach (Chen, 2004).

Tabah argues that there is much confusion in the usage of the terms “diffusion” and “epidemic” in the information sciences literature. He defines diffusion as the spread of an idea or technology without a vector, while an epidemic *requires* a vector. Tabah discusses fitting curves to the growth curve for a literature. These curves include linear, exponential and power models and curves such as Gompertz curves. The best fitting curve is a function of the specialty, the time period and the scale of measurement and may vary over the lifetime of a literature. As a generality, if diffusion is propagated by an external source the curve is an inverted “J”. If it includes interpersonal contact, it follows an “S” curve.

Approaches used in this analysis

Because of the relatively small number of citations that exist to look at the spread of the Stommel diagram, the more rigorous modeling techniques used in some analyses would seem to be unwarranted. A qualitative approach, enhanced by some of the visualization techniques used in the information sciences seems most germane. Data were gathered by locating as many papers and other writings that cited Stommel 1963 as could be found through extensive literature searches as well as queries made to individual researchers. While there are known problems with the use of references and citation lists, for the purposes of this research they seem to be a straightforward and manageable way to gather data. Laird et al. (2007) have explored these techniques and their potential problems while looking at publication productivity and impacts in the geosciences. The analysis involved categorizing the papers both by subject area and by the type of time-space diagram used. To explore the spread of the diagram, a rough web of citations was created by starting with the first paper in each discipline that cited Stommel and seeing how it was, in turn, cited by other papers.

Methods

To trace the diffusion of the Stommel diagram, both in its three-dimensional version and the simplified two-dimensional space-time version, into other disciplines, I looked for articles that cited Stommel's 1963 paper. This was done in a number of ways. The first was to look in the printed Science Citation Index (SCI), and the subsequent on-line ISI Web of Science, for references to the paper. The printed SCI was used for 1955-1964, 1965-1969, 1970-1974, and 1975-1979. The on-line Web of Science was used for citations from 1980 to the present. These searches produced a list of 65 references.

Aware that these citation indices might not have captured all of the possible references, I also made Google searches under a variety of possible phrases. The most fruitful were "Stommel 1963", "Stommel diagram", "Stommel plot", "Stommel graph", and "Stommel Science 1963 139 572". The last search includes the volume number and page number for the article. I made similar searches in GoogleScholar and Scirus [http://www.scirus.com/srsapp/]. These searches turned up a few new references. They also turned up web pages and other grey literature references to Stommel and the Stommel diagram. I also looked in the articles located by SCI/ISI for references to others who might have been working on space-time questions. Another resource is books and textbooks. As these are not indexed in any coherent manner, finding these uses of Stommel diagrams was problematic. Some uses appeared through the Google and Scrius searches. Colleagues suggested others and some were simply found by chance.

The end result of my various searches was a list of 125 articles, books, and other materials that cited Stommel, used a Stommel diagram or included a verbal description equivalent to a diagram. Once I had this list, I sought out copies of the complete article.

These came from a combination of printed journals and on-line archives. A few came from web sites of the authors. Almost all of the articles could be located. The exceptions tend to be older articles from more obscure journals. Each article was read and coded for discipline, type of diagram used, whether Stommel was cited directly, and what related articles were cited. The coding was entered into a spreadsheet for further analysis and a bibliography was created.

A phenomenon became apparent while exploring the journals looking for the articles. As Bettencourt et al. (2006) observed in their analysis of the spread of Feynman diagrams, in the early years authors cited Stommel but did not use a diagram, and in later years authors used Stommel diagrams and did not cite Stommel. The diagram had become a standard enough tool that it did not warrant a citation. To some extent, for the biological literature, a citation of Haury et al. (1978) can be used as a proxy for Stommel's paper. For other disciplines, finding the users of the Stommel diagram who do not cite the original paper is problematic. Bettencourt et al. simply did a page-by-page review of the fairly small number of physics journals that were publishing Feynman diagrams. This technique is impractical given the wide range of disciplines using Stommel diagrams. One problem that has been noted with relying on publications as a measure of adoption of a technique is the danger of underestimating adopters (Bettencourt et al., 2006 and Tabah, 1999). However, this has become a standard measure of adoption for practical reasons, and so is used for this study.

For a first analysis I simply divided the articles by era and then into arbitrary sub- categories by discipline. I was interested in seeing the overall balance between physical oceanography, marine biology/ecology, the geosciences (including geography and hydrology) and climate studies. I categorized both the articles in the original citation search and those located via more indirect means. What became immediately apparent was that the references I located do not include a large number of citations to articles in the oceanographic literature. Of the original 125 articles, I only categorized 23 as being ‘oceanography’, where this to refers to physical oceanography and is differentiated from marine biology and plankton biology.

The first rough analysis of the references also pointed up some challenges. Stommel’s 1963 paper is noted for two key contributions, the Stommel diagram and for its exploration of the role of scale in research and sampling. Many of the references I located were more concerned with the latter aspect of the paper and didn’t include any sort of diagram. To untangle this, I divided the papers into seven categories: 1) papers that referred to the scale aspect only, 2) papers that use the term Stommel diagram or Stommel plot but did not include a graphic, 3) papers that used a 2-D version of the diagram, 4) papers that used a 3-D version of the diagram, 5) papers that used a 4-D version of the diagram, 6) papers that used a Stommel diagram but neither cited Stommel nor called the diagram a Stommel diagram, and 7) papers that used the diagram and also discussed the history of the use of the diagram or its diffusion. The first category was set aside and not used for further analyses. From an original list of 125 references, 77 were used for the final analyses.

The condensed set of references was explored in a number of ways. The cumulative frequency and the number of articles per 5-year period as a percentage of the total number of citations were plotted. The citations were divided up by discipline and by type of diagram. The tool CiteSpace [http://cluster.cis.drexel.edu/~cchen/citespace/] was used to create a co-citation diagram (presented in the Results section) for the Stommel (1963) article based upon references given in the Web of Science. Additionally, a network of contacts was constructed manually by looking at the articles and the references they cited. This was done to understand the spread and evolution of the diagram and to trace the links between disciplines. A number of prominent users of the diagram were contacted via email or phone conversations to inquire about their use of the diagram, where they first encountered it, and their perceptions of its use and diffusion.

Results

In summary, the count of papers using a Stommel diagram, based upon data from the Science Citation Index, Web of Science entries, and citations from other sources for Stommel (1963) is shown in Figure 8. As expected, the curve follows a lazy S but the leveling off point has not been reached. This pattern is identical in the three curves: for all papers, for papers that explicitly cite Stommel (1963), as well as for those

Table 1 Papers citing Stommel (1963) and/or using a Stommel diagram, by year

	all	cumulative	cite Stommel	cumulative	use Stommel diagram	cumulative
1963 - 1967	3	3	3	3	1	1
1968 - 1972	3	6	3	6	2	3
1973 - 1977	1	7	0	6	1	4
1978 - 1982	4	11	3	9	2	6
1983 - 1987	13	24	11	20	4	10
1988 - 1992	18	42	6	26	10	20
1993 - 1997	26	68	11	37	13	33
1998 - 2002	36	104	26	63	26	59
2003 - 2007	21	125	12	75	18	77

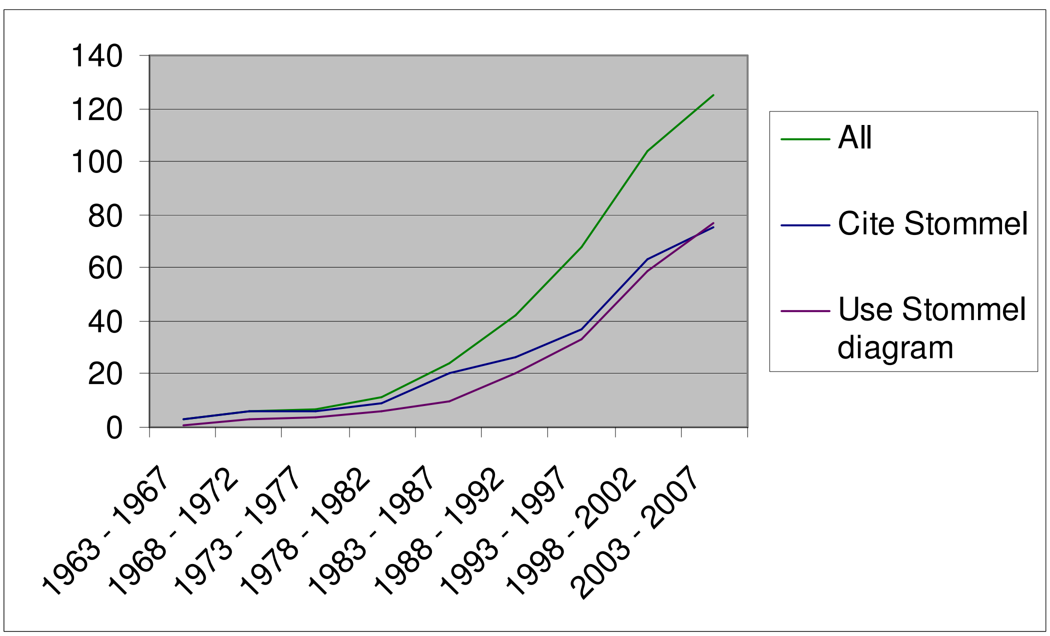

Figure 8 Numbers of papers, books, and other materials studied to understand the diffusion of the Stommel diagram. "All" refers to all materials located, "cite Stommel" refers to those materials that cite Stommel's 1963 paper and "Use Stommel diagram" refers to those papers that use some version of the diagram.

that may or may not cite Stommel but use some form of a Stommel diagram. The expected leveling off of the curve with saturation, or the end of epidemic spread, is not apparent. This could be due to the fact that the paper and the diagram are still seen as very usable and are still being adopted by new users. It could also be a function of the expansion of disciplines (such as ecology) that have adopted the diagram. This is the functional equivalent of an ever-increasing uninfected population keeping an epidemic alive and spreading.

The equivalent curve for a search through just ISI/Web of Science does show a hint of leveling off, which might be an artifact of the fact that the diagram is being used but it has become so well integrated that the original paper is no longer cited (Figure 9). A very similar curve is seen for citations of Haury et al. (1978) [hereafter HMW] which is the intellectual successor to the Stommel paper. In fact, researchers locating the HMW paper first and then following its references to find the Stommel paper may be a partial explanation for the continued references to the Stommel paper. In an example of the Matthew effect, a researcher seeing the name Stommel in the references of a paper would be likely to search out that paper simply based upon Stommel’s reputation.

Dividing the citation up by discipline showed a number of patterns (Figure 10 and Figure 11). As might be expected, the first adopters, who used a Stommel diagram and cited the 1963 paper, were in physical oceanography and climate studies. Since

Table 2 Count of references to Stommel (1961) in Science Citation Index and Web of Science

Publication Year	Record Count		Percent of Total	Cumulative Percent
1963	1	1	1.54%	1.54%
1965	1	2	1.54%	3.08%
1966	1	3	1.54%	4.62%
1969	1	4	1.54%	6.15%
1970	1	5	1.54%	7.69%
1971	1	6	1.54%	9.23%
1980	1	7	1.54%	10.77%
1984	2	9	3.08%	13.85%
1985	5	14	7.69%	21.54%
1986	2	16	3.08%	24.62%
1987	2	18	3.08%	27.69%
1988	2	20	3.08%	30.77%
1990	2	22	3.08%	33.85%
1991	1	23	1.54%	35.38%
1992	1	24	1.54%	36.92%
1993	2	26	3.08%	40.00%
1994	2	28	3.08%	43.08%
1995	3	31	4.62%	47.69%
1996	5	36	7.69%	55.38%
1997	2	38	3.08%	58.46%
1998	1	39	1.54%	60.00%
1999	5	44	7.69%	67.69%
2000	3	47	4.62%	72.31%
2001	4	51	6.15%	78.46%
2002	5	56	7.69%	86.15%
2003	4	60	6.15%	92.31%
2004	1	61	1.54%	93.85%
2005	1	62	1.54%	95.38%
2006	2	64	3.08%	98.46%
2007	1	65	1.54%	100.00%

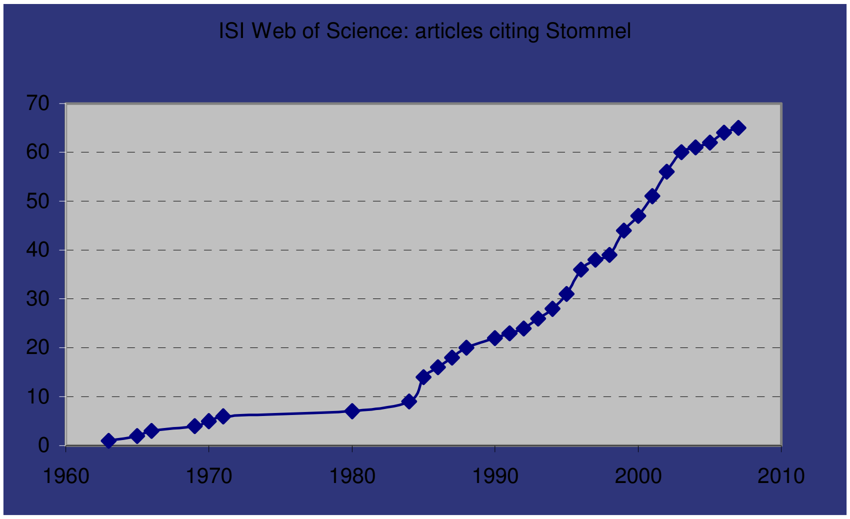

Figure 9 ISI/Web of Science references for “Stommel 1963”

Stommel was a member of the Meteorology department at MIT at the time, the spread into climate studies seems logical. The next fields to adopt the diagram were plankton biology (via the Haury et al. paper), marine biology and ecology. Geography followed soon after, and there were later expansions into hydrology, geology, limnology, and management of ecosystems. Ecology was the biggest source of users of the Stommel diagram, due in part to the rapid expansion of the discipline at the time. One challenge to drawing conclusions about the spread to disciplines is the fact that papers may fit equally well into two or more categories. Hence, any categorization is subjective.

One final graphical analysis performed was to take the entries found in the Web of Science and use CiteSpace to create a co-citation diagram (Figure 12). This diagram shows papers that were co-cited with Stommel (1963), the date that the two papers were

Table 3 Papers citing Stommel (1963), by discipline

by discipline all papers	plankton biology	marine biology	oceanography	ecology	geography	hydrology	geology, pale-biology	limnology	management	climate
1963 - 1967			3							
1968 - 1972			1				1			1
1973 - 1977										1
1978 - 1982	3			1						
1983 - 1987	2	4	2	2				1		2
1988 - 1992	2	1	4	9	2					
1993 - 1997	7	6	4	3	1			1	1	3
1998 - 2002	7	6	2	13	3		2		3	
2003 - 2007	3	2	7	4	1	1		1		2
Total	24	19	23	32	7	1	3	3	4	9

Table 4 Papers using Stommel diagrams, by discipline

by discipline, verbal, 2D, 3D, 4D	plankton biology	marine biology	oceanography	ecology	geography	hydrology	geology, paleobiology	limnology	management	climate
1963 - 1967			1							
1968 - 1972			1				1			
1973 - 1977										1
1978 - 1982	2									
1983 - 1987	1	1		1						1
1988 - 1992		1	2	5	2					
1993 - 1997	3		4	1			1	1		3
1998 - 2002	3	4	2	10	5				2	
2003 - 2007	3	2	5	4	1	1				2
Total	12	8	15	21	8	1	2	1	2	7

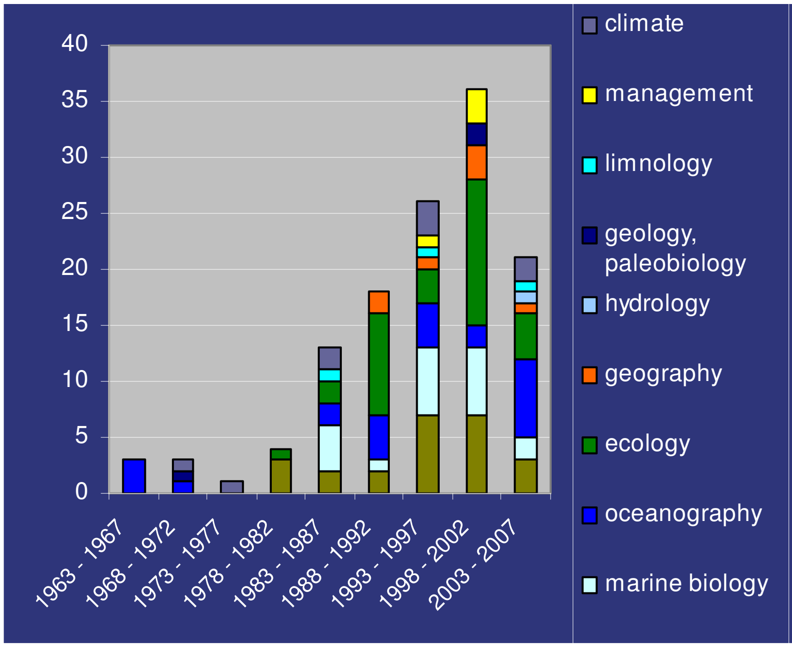

Figure 10 All papers sorted by discipline

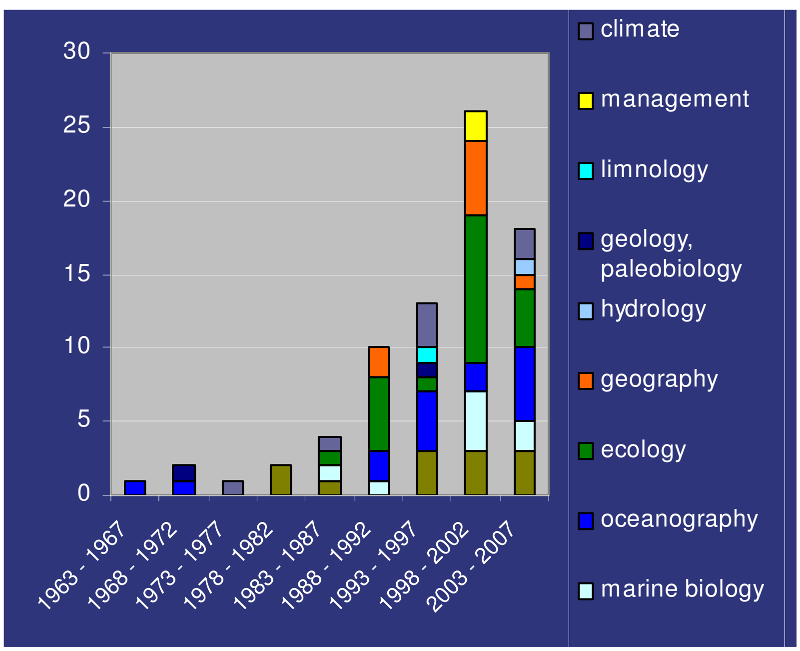

Figure 11 Papers using a Stommel diagram, by discipline

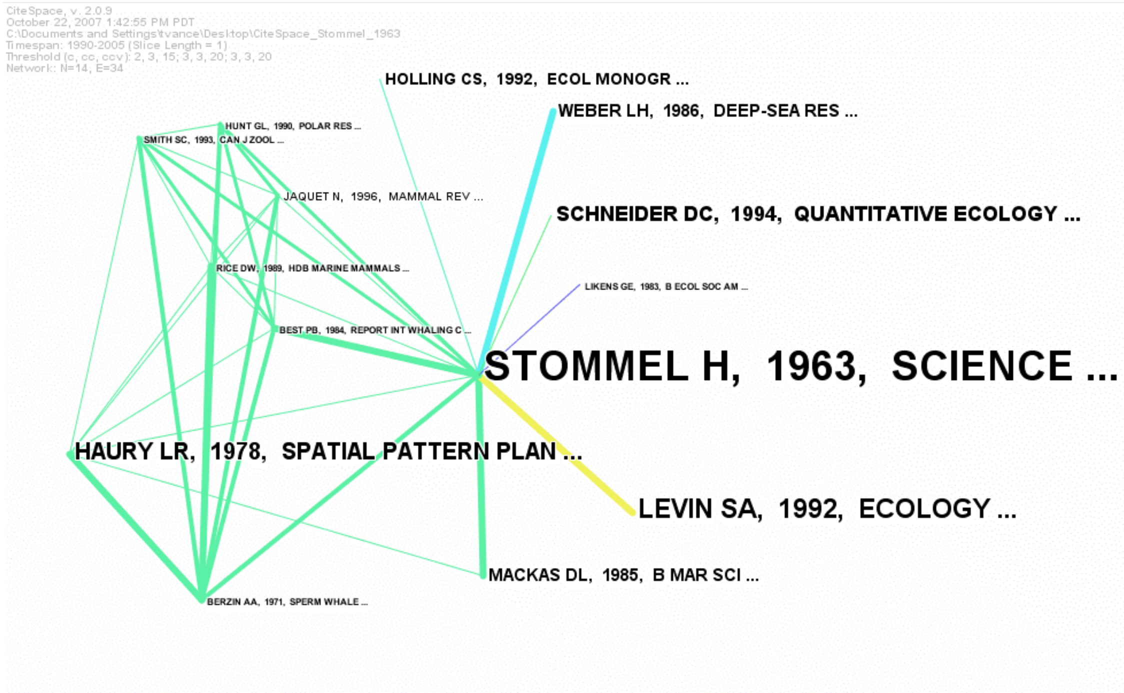

Figure 12 CiteSpace diagram of co-citations with Stommel (1963)

first co-cited and the number of papers that cited the two papers. While this diagram is not based upon the full dataset gathered, due to a number of the citations not being found in the Web of Science, it does support some of the observations made. The two strongest co-citation links are with Haury et al. (1978), as expected, and Levin (1992). The Levin paper is a seminal work on pattern and scale in ecology that uses both the three-dimensional HMW version of the Stommel diagram and a two-dimensional Steele diagram of the sampling limitations of using ships. Other papers that showed up strongly in the co-citation analysis were Weber et al. (1986) and Mackas et al. (1985). Mackas et al. (1985) is a paper on plankton patchiness that does not cite Stommel

(1963), but does cite Haury et al. (1978). Weber et al. (1986) is a paper on the variance spectra of water temperature and plankton near Antarctica. It cites neither Stommel nor Haury at al. (1978) and uses no diagrams.

Analysis

David Schneider (2001) has looked at the rise of the concept of scale in ecology. As a part of this, he has explored the adoption of space-time diagrams in ecology. While he considers a variety of plots, not just self-titled Stommel diagrams, his observations are relevant. Schneider proposes a taxonomy of time-space plots, dividing them into conceptual and instrumental plots.[93] Conceptual plots are those that indicate the space and time scales of phenomena, for example internal waves or hurricanes, while instrumental plots show the space and time scales that can be measured by a specific instrument or by a sampling strategy for a cruise. Schneider argues that the phenomenological or conceptual plots are basically qualitative as they are really a graphical depiction of a verbal concept. In his work he was unable to create a quantitative phenomenological plot but felt he was able to "plot the space and time scales of measurements within the axes and so put the instrumental plot on a sound footing".[94] In all these examples he created two-dimensional plots with no attempt,

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[93] Schneider, pers. comm., 2 January 2007.

[94] Ibid., p2.

qualitative or quantitative, to represent the power of the phenomena, as Stommel did in his original diagrams.

Schneider cites Steele's (1978) article as the first to use a space-time diagram in the ecological literature. Steele's article used the two-dimensional space-time axes of the Stommel diagram. In the same volume as the Steele article is the Haury et al. article that used the three-dimensional version of the Stommel axes. Schneider argues that these were primarily used as a way to "organize a confusing body of literature around the concepts of space and time scales, using defined regions within the space time axes of Stommel (1963)."[95] The Stommel diagram, by providing a clear visual organization to space and time, provided a framework to organize the data and conclusions of the new ecological research. In many ways, it was a visual shorthand to the data.

Others have commented on the adaptation of the space-time diagram in various disciplines. Perry and Ommer (2003) write of works on scale dependent processes in physiology, island biogeography and metapopulation dynamics. Clark (1985) writes of the ecological literature and also of more general oceanography and climate change and fisheries. He is using Stommel type diagrams to look at climate impacts. Several of these articles also discussed the diffusion of the Stommel diagram into other disciplines or the way is which similar analyses were carried out in other disciplines. These include climatology, hydrology, various types of ecology and general oceanography.

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[95] Ibid., p1.

A hand-built 'Stommel web' to describe the diffusion of the diagram is shown in Figure 13. The Stommel web starts with the use of a three-dimensional version of the diagram by Haury et al. (1978) and the simultaneous creation of a two-dimensional version by Steele (1978). The Haury et al. (1978) version substitutes a biological axis for the power axis Stommel used. Steele leaves out the third axis and simply presents temporal versus spatial scales of phenomena and sampling techniques. From then there are four main paths that the diagram takes. Users in a few disciplines, including oceanography and marine ecology, use the original Stommel diagram. A much larger group - in marine ecology, terrestrial ecology, and oceanography - use the Haury et al. (1978) version of the plot. Some of these users cite only Haury et al. (1978), others cite Stommel as well. There is a continuing pattern of a steady level of citations extending to the present day. Most of these plots are phenomenological, but Kaiser (2005) has combined the phenomenological and sampling plots into a single diagram. The largest group of users - in geography, climate, oceanography, ecology, and fisheries - use a two-dimensional version of the plot modeled after Steele's version. As with the Haury et al. (1978) plot, the use of two-dimensional plots continues to the present at a steady rate. Finally, there is a group of researchers, especially those looking at scale and at new sampling technologies, who have developed new types of Stommel diagrams that plot time and space scales versus a variety of axes in three and four dimensions. Bauer et al. (1999) present three-dimensional diagrams through time for a four-dimensional tool.

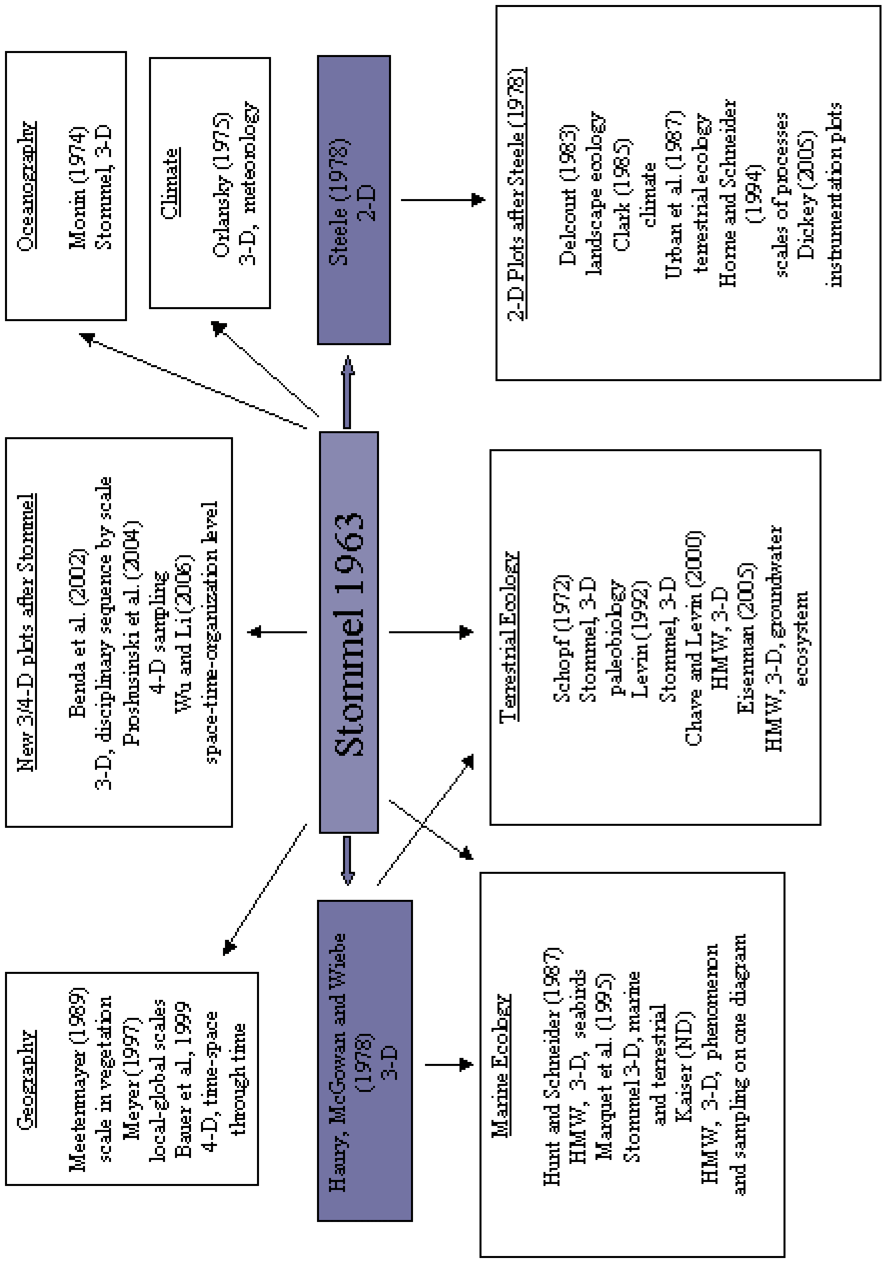

Figure 13 The "Stommel web" showing papers that cite Stommel (1963) by discipline

Proshutinski et al. (2004) look at sampling for long-term ice observatories in three spatial dimensions and add seasonality and the type of sampling to the diagram.

The possibilities for a 'new Stommel diagram'

Understanding the creation and spread of the Stommel diagram is valuable in two ways. The first is that the diagram itself can serve as a model for the creation of a new diagram that would present a four-dimensional phenomenon in a three-dimensional view for greater understanding. The second is as a model for improving the spread and acceptance of new multi-dimensional methods. Two-dimensional versions of the Stommel time-space diagram have been created for a large number of disciplines. More interestingly, a number of researchers have explored new ways to use the three-dimensional diagram, and even variants to the three-dimensional diagram. While the two-dimensional diagrams are qualitative in the third dimension, increased sampling possibilities have made it possible to take the qualitative third intensity dimension that Stommel represented and develop quantitative axes.

When Henry Stommel originally created his diagram, he used it for two purposes. The first was as a summary of the scales of phenomena in the ocean and hence as a guide to the sampling regime needed to detect a specific phenomenon. The second was as a guide to the scales that could be measured by a specific type of instrument. In looking to create a new Stommel diagram it is necessary to first define one's goals. If the goal is simply to illustrate the sampling range of a new piece of equipment in space and time, then a simple 2-D "Dickey-type" Stommel diagram will suffice.[96] While such a graphical summary would provide a quick illustration of the capabilities of a new device, it is not a particularly informative or unique diagram. On the other hand, a new diagram in three dimensions that relates the scale and intensity of a biological phenomenon to the underlying physical phenomena could be important.

The Stommel diagram worked, and spread, due to a number of factors. All are pertinent when considering creating a new Stommel diagram. The diagram itself is a clear visual - the diagram is simple, easily understood, and intuitive once directly examined. Given this, it is interesting that many users of the diagram sought to collapse it to a 2-D version, which is even easier to understand but loses Stommel's innovative contribution. The diagram, and the Stommel (1963) paper, met a need. It was produced at a time when there was just enough data to construct such a diagram, and there was a need for such a diagram to understand the large datasets. Biologists were working with physical oceanographers and were exposed to the oceanographic literature. The diagram was graphically simple to construct and adapted well to other disciplines and data sets. The diagram was a product of, and necessitated by, good timing. There was development of new instruments to collect time series data, oceanography was expanding and changing, and the rise of computers made it possible to process time series data and create graphics including 3-D fishnets

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[96] Tom Dickey, of UC Santa Barbara's Department of Geography, is the most prolific current user of the Stommel plot to describe the capabilities of new instrumentation. See his website at http://www.opl.ucsb.edu/tommy/publications.html for examples [accessed 2 November 2007].

Deconstructing the Stommel diagram

Marquet et al. (1995) provide a guide to creating one's own Stommel diagram that also serves as a deconstruction of the plot. For one axis it is necessary to have a time series of data that can be analyzed to create a time spectrum of phenomena. For another axis it is necessary to have the same sort of data over enough spatial scales to create a power spectrum of spatial phenomena. These two spectral plots are combined graphically to create the Stommel diagram. In each case the spectra are continuous and provide enough amplitude information to create a quasi-quantitative third axis. So, to create a 'new Stommel diagram' it is necessary are to have at least two plots of a power spectrum or other continuous variable. Since the purpose of the Stommel diagram is to represent 4-D phenomena, the plots should represent the spatial and/or temporal aspects of an entity. Examples might include chlorophyll measured at a series of depths by a fluorometer on a mooring, a continuous plankton sampler used to measure plankton diversity over either a vertical or horizontal extent, salinity and temperature measurements taken either by a CTD or a SeaCat, temperature or ocean color measured by satellite, and measures of the genetic diversity of organisms along a transect. A number of researchers have used these new types of data to create new Stommel diagrams, as described below.

Examples of new Stommel diagrams

Examples of these new Stommel diagrams include work being done by Sergey Piontkovsky to create a quantitative version of the Haury et al. (1978) variant of the Stommel diagram. This work is based upon long time series of plankton data and new types of sampling tools that show vertical structure. An example of the kind of measurements needed to construct such a plot is found in Piontkovski (1985). For further details on the types of equipment used see the proceedings of the International Congress on the History of Oceanography held in 1980.[97]

Marquet et al. (1995) have used Stommel diagrams to compare the species richness in benthic, terrestrial and pelagic systems. They have also proposed comparing Stommel diagrams of species richness and intraspecific genetic variation to look at the evolutionary consequences of patchiness. They argue that genetic bottlenecks, such as glaciation, should show up as a peak in the variance at a suitable time scale due to the depletion of variance just after the removal of the bottleneck.

A very few researchers have actually created new types of three-dimensional diagrams to represent various time-space-space or time-space-intensity patterns. The new Stommel-type diagrams included Orlanski's (1975) diagram for atmospheric processes showing space-time-vertical distance and Kuragano and Kamachi's (2000) diagram of correlation coefficients in latitude-longitude-time lag space.

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[97] See M. Sears and D. Merriman, eds., *Oceanography: The past*. (New York: Springer-Verlag, 1980).

A "new Stommel diagram"

Ideas of new Stommel diagrams that are derivatives of the original plots include the application to new (sub)disciplines, e.g., a diagram of geological phenomena for mid-ocean ridges. This diagram might portray spreading rate versus the relative isolation of the ridge segment and the z-axis might represent biological diversity or the speed of genetic divergence. While spreading rates are well known, it would be necessary to create a measure of the isolation or separation of ridge segments. Biological diversity could simply be a measure of species richness or diversity or could be a more complicate measure based upon genetic analysis of the organisms present.

A second idea would be the creation of a 4-D Stommel diagram. The original Stommel diagram depended upon the ability to measure an oceanic parameter, such as temperature, that showed the passage or size of a physical feature. The Haury et al. (1978) biological plot was a qualitative plot of biomass variability versus time and space scales. Newer technologies such as continuous plankton samplers and fluorescence meters that can be mounted on a current meter mooring would allow for the creation of a quantitative plot. A variation of this would be to create a plot that differentiated between the scales seen horizontally in features and those seen vertically. In this case the plot would be horizontal spatial scales versus temporal scales with a z-axis of vertical scales. The intensity of the biological parameter - be it biomass variability or genetic variability or species diversity - would be represented by the intensity of clouds in the 3-D diagram. If data in the z-dimension were to be collected via repeated soundings or a network of moorings, then a plot might show time versus horizontal scale versus vertical scale. Intensity of the phenomena would be represented by the color and density of 'clouds' in the plot. A challenge to interpreting this diagram would be the likelihood that a casual viewer would make the incorrect assumption that the z-axis represents depth rather than the spectrum of measurements taken vertically. The intensity could be biomass variability, but Peter Wiebe argues that a new plot should really show species abundance.

A Stommel diagram could also be created for the spatial and temporal distribution of scientific research projects showing the range from small science to big science. The third axis could be a suitable time interval, possibly decades - to show temporal changes or latitude - to show changes in the geographic areas of interest, or production of papers from the project - to see if 'big science' really produces better science.

A Stommel diagram could also be created as a data quality tool in data access software. Tools such as Ocean Data View and Java Ocean Atlas allow rapid access to large oceanic data sets such as the WOCE and World Ocean Atlas datasets. With this ability to rapidly locate data comes the danger that the data selected might not be appropriate for the question being studied. In this case a data selection tool such as ndEdit, which shows plots of data over latitude, data over longitude, and data over time, would include a Stommel diagram highlighted to show the spatial and temporal spectra of the data selected. This would provide a useful tool to verify the correct extents of data are selected. One could also calculate spectra for x/y and t, and then have a Stommel plot with peaks for research concentrations creating a z-axis as scientific output measured by number of papers. Another representation might label peaks by the research questions of the data, e.g., egg production or freon in the ocean. This would both quickly show the critical scales for the phenomena being researched but might also point out important scales that are not being fully explored.

An intriguing new diagram could use the traditional three-dimensional Stommel diagram, but animate it through time to show how the importance of various phenomena changes as the base conditions of the environment shift. For example, a Stommel diagram for the importance of environmental effects on the early life history of pelagic fish might show eddies and seasonal temperature regimes currently having the greatest importance for determining recruitment and survival. However, under a climate change scenario where the intensity and variability of storms is greatly increased, these shorter scale phenomena might turn out to be the most important. Creating an animated diagram where the height of the various peaks changes with the climate change scenario being represented would be a powerful way to illustrate the effects of changes upon individual species, or assemblages of species. The current Stommel diagram depicts the relative strength of influences such as meteorological effects and annual terms. While Stommel depicted the strength as the effect upon sea level, others have presented this as showing effects upon organisms. As climate change occurs, the relative importance of these various factors may change, e.g., if the variability of storms greatly increases then the day to week time scale may gain importance over annual scales. Creating an animated Stommel diagram where the height of the individual peaks varies with the climate scenario chosen would provide a visual summary of these possible effects.

Conclusions

The spread of the Stommel diagram can be measured against a number of models and techniques. The epidemic model for the spread of a new idea predicts a logistic curve. As shown in the results both from the Web of Science and the expanded Stommel paper collection, the pattern follows an ‘S’ curve but does not level off. This could be due to there being an ever-expanding pool of potential adopters. While oceanographers were already exposed via the "Dream-like" paper and so serve as a resistant population, other disciplines were unexposed and uninfected. There is also an ever expanding pool of the uninfected due to the rapid growth of science in the past three decades, the expansion of new fields, such as ecology, which make great use of the Stommel diagram, and the development of new data collection techniques in many disciplines. These new techniques create more datasets needing a Stommel type summary. The publication of the Haury et al. (1978) provided a second pulse of infection as it exposed the Stommel diagram to a new population of plankton biologists and ecologists interested in patchiness.

Analyzing the diffusion using traditional spatial diffusion techniques is less straightforward. The true spatial spread is hard to locate because the ISI so centered on

US and western papers/journals. Stommel's ideas did get to Russia via his 1963 visit and collaboration with Monin. Tracing its spread after the initial contact is limited by the lack of information on Soviet science during that period. The spatial diffusion of the paper is also not purely geographic. To understand the spread it would be necessary to calculate an *intellectual* distance measure rather than just simple geographic distance. For example, Scripps is much closer to WHOI intellectually that mere geographic distance suggests. For a true analysis, it would be necessary first to create a map of the intellectual connections within oceanography and associated sciences in the early 1960's.

By the same token, the role of research schools and invisible colleges is less easily determined without more research into the intellectual setting in oceanography. What is apparent is that, following Crane's ideas, the Stommel diagram became a part of the standard part of the body of knowledge to the point that it was used with citation to the original paper. It was not even necessary for it to become a part of tacit knowledge as the construction of a diagram was so simple that Marquet et al. could construct a one page "how to build a Stommel diagram" (Marquet et al., 1993).

The role of the Matthew effect is evident in the co-citation web and the way the technique spread directly to other disciplines. Memoirs, citation patterns, and anecdotal stories make clear how well respected Stommel was, and how widely his ideas were used. Testaments to the range of Stommel's influence include the *festschrift* in honor of his 60^{th} birthday[98] and the posthumous publication of all of his formal and informal works in N. G. Hogg and R. X. Huang's *Collected Works of Henry Stommel* published by American Meteorological Society (1996). He also published in a broad array of journals and on a wide array of topics, adding to his exposure and importance. He wrote well and his works were read outside of his discipline. The 1963 paper also served as seminal work on scale in oceanic phenomena and was read for that reason alone. Both the Stommel (1963) paper and the Haury et al. (1978) paper were seen as seminal contributions to the literature, and the authors were seen as very important thinkers. The papers are still frequently cited.

Plots of the networks of uses of Stommel diagrams in the published literature, both via CiteSpace and the creation of the Stommel web, show that the spread of the Stommel diagram followed paths based both upon personal interactions and upon professional links. The spread of the scale aspects of Stommel's work and the diagram itself can be differentiated in the CiteSpace diagram. Logical paths of diffusion can be constructed into a Stommel web.

One can make a number of observations from studying the articles using Stommel diagrams. The first is the fact that almost all of the articles use a two dimensional diagram. So while Stommel took four-dimensional phenomena and represented them in three dimensions, those who followed him took these four dimensions and reduced them to two dimensions. Only within the climate studies and

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[98] See B. Warren and C. Wunsch, *Evolution of physical oceanography, scientific surveys in honor of Henry Stommel* (Cambridge Mass.: MIT Press, 1981)

Haury et al. (1978) was the original three-dimensional diagram retained. This raises the question of why this is done? Possible answers are that four and three dimensions are hard to visualize. The authors may also less be interested in the spectrum or power of a phenomenon than in its place in space and time. Some of this may be related to the way that the data used for research are gathered. Physical oceanographers frequently use time series at a point, leading to a time series analysis, not to a spectral space-time analysis. Another possibility is related to what can be visualized from analogy in the physical world versus concepts that are basically abstract. For example, a climatologist can see cloud patterns and can draw analogies with plumes of smoke. An ecologist may be able to see at least surface representations of plankton patches, or can study growth in laboratory experiments. An urban historian can look at the current geographic layout of a city and mentally extrapolate back to an earlier city form. For a physical oceanographer the patterns may be less tangible, less imaginable and therefore more in need of being reduced to simpler dimensional representations.

A challenge to the idea of creating a new Stommel diagram is the fact that visualizations have become so good that summaries like the Stommel diagram may no longer be necessary. As the following chapter will detail, developments in computer hardware and software have made it possible to view data easily, and well, in 4-D. Users are better trained to interpret these types of displays due to the popularity of video games and other high-end graphics. Data selection is so fast and easy and time series analysis so rapid that can one can easily analyze fully dimensioned datasets. But, some users still more comfortable with reduction of dimensions seen in maps and diagrams such as the Stommel diagram.

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Chapter 5: History of 3-D graphics as a precursor to developing a multi-dimensional GIS

Introduction

While the creation of the Stommel plot is a case of a pedagogical need driving a development, and the spread of the plot is a case of the gathering of multi-dimensional data creating a need to summarize the data, the slow development of multi-dimensional GIS illustrates a different balance between need, technology and acceptance. Even relatively early in the development of more general geographical information systems, there was a perceived need for multi-dimensional tools.[99] By the 1970's data collection techniques such as air photos and terrain models, well drilling and seismics, and oceanographic and atmospheric sounders were providing three- and four-dimensional data sets. Computer scientists were creating data structures for the storage of multi-dimensional data. Computer hardware and graphics display devices were starting to be able to represent multi-dimensional data. There have also been examples of multi-dimensional GIS's coded and published, and in the 1980's there was a working version of a commercial multi-dimensional GIS in the System 9 package, and later in another package called Voxel Analyst. Development of theoretical GIS's to handle 3- and 4-D data has continued but, in 2007, there are still very limited examples of either a

[99] For a description of a multi-dimensional proto-GIS for studying lobster habitat see A. Collin, D. Monahan and A. Kerr, "Navigators Aren't the Only Sea Chart Users." In International Cartographic Conference, Adam J. Kerr and A. Kordick. *Oceanographic cartography - cartographie oceanographique : papers presented at the sixth technical conference on oceanographic cartography held in Ottawa, Ontario, Canada, August 1972*. (Lonneker, Netherlands: International Cartographic Association, 1972).

commercially available or a widely used open source, truly multi-dimensional GIS. This is due to a combination of technical, user/human and organizational factors.

This chapter will provide the background to the development of a prototype of a multi-dimensional scientific GIS, which started with an application called OceanGIS and has evolved to a package called GeoModeler (described in chapter 6). It will complete the history of three-dimensional plotting and mapping started in chapter 2. A brief history of recent developments in multi-dimensional plotting, and specifically in GIS is included. After that, I will describe the state of technologies for data gathering, storage and graphical display at the time of the first attempts to create a multi-dimensional GIS. A description of attempts to create a multi-dimensional GIS will follow. This chapter also details the multiple narratives put forward to explain the development of GIS. Both commercial and more theoretical tools will be described and the current state of multi-dimensional GIS will be detailed. Finally, I will summarize the state of the art in multi-dimensional GIS when we began to develop OceanGIS, the prototype multi-dimensional GIS described in chapter 6.

Geography

One of the first mentions of the multi-dimensional possibilities of "Automation and Cartography" is in Waldo Tobler's 1959 article of the same name. While he mentioned "a large number of difficulties in any attempt to automate cartographic procedures" he also saw the possibility of using computers to make calculations such as the intersection of planes and surfaces to create contours (Tobler, 1959). While cartographers had reservations about the ability of automated processes to imitate the artistic judgments of cartographers, other parts of geography embraced multi-dimensional representations more quickly. As noted in Friendly and Denis (2003), much of the development of multidimensional visualization has come from the world of statistics. This contribution has continued in the work of those who visualize multivariate multidimensional data. Wong and Bergeron (2007) have provided a history of the last 30 years of development in this area. Though multivariate visualization started in 1782 with Cromme's use of point symbols to show the distribution of commodities, most techniques used nothing more than colored pencils and graph paper (Wong and Bergeron, 2003). Pickett and Grinstein computerized texture mapping in 1988[100]. Datasets were small and the output was two-dimensional. Tukey's 1977 book on exploratory data analysis[101] proved to be a turning point and the late 1970's and early 1980's were the start of visualization of more than two dimensions. Higher speed computers and color graphical displays enhanced the visualizations (Wong and Bergeron, 2003). The "grand tour" was introduced by Asimov as a way to view projections of multivariate data in a series of two-dimensional planes. In 1987, the NSF

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[100] See Ronald M. Pickett and Georges G. Grinstein. "Iconographic Displays for Visualizing Multidimensional Data." In *Proceedings IEEE Conference on Systems, Man, and Cybernetics*, Beijing and Shenyang, PRC, (May 1988): 514–519

[101] John Tukey. *Exploratory data analysis.* (Reading, Mass: Addison-Wesley Pub. Co., 1977)

formalized the need for multidimensional visualization by holding a workshop entitled "Visualization in Scientific Computing".[102] Research shifted from data exploration to high-speed color graphics requiring considerable processor power. Some efforts worked toward presenting all the variables in a single multidimensional display, while others aimed for interactivity (Wong and Bergeron, 2003).

In cartography, the 1960's and 1970's brought changes in the types of maps desired, which led to technical advances, and newer types of maps led to enhanced analyses of spatial and temporal patterns. Developments in computer graphics made computer cartography possible (Foley and Van Dam, 1984, cited in Kraak, 1988). The Harvard Lab for Computer Graphics was started in 1967 and it produced SYMAP for general mapping, CALFORM for choropleth maps, SYMVU for 3-D wireframe diagrams, POLYVRT for the conversion of coordinate systems, and GRIDS for raster analyses[103]. ODYSSEY was a very early GIS also created at the Harvard Lab. Other packages included the Calcomp libraries of graphics primitives and DISSPLA, which was a complete mapping package for 2- and 3-D maps. SURFACE II was developed by John Davis at the University of Kansas to produce contour maps. Given his background in statistics, it provided robust interpolation to grids and was flexible in handling

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[102] B. McCormick , T. DeFanti and M. Brown, "Visualization in Scientific Computing," available as http://www.sci.utah.edu/vrc2005/McCormick-1987-VSC.pdf

[103] For a complete history of the Harvard Lab see Nicholas Chrisman, *Charting the unknown: how computer mapping at Harvard became GIS*. (Redlands, Calif: ESRI Press, 2006).

multiple data formats[104]. The Cartographic Automated Mapping (CAM) system was created by the CIA in the late 1960's and later used to create maps from the CIA World Data Bank.[105] In 1973, Thomas Poiker at Simon Fraser reported to the Office of Naval Research on work he did for them creating TINs as the surface representation of solids but he had been thinking about the idea since at least 1969.[106] Peter Haggett created a geographical data matrix, which plotted spatial scale versus system of interest (attribute) versus time. This work built upon the earlier efforts of Berry (1964) and Bullock et al. (1974) (Cited in Haggett, Cliff and Frey, 1977). Turnkey cartographic systems included the various Intergraph systems tied to proprietary hardware.[107] Synercom provided a system based upon a DEC VAX/VMS (Digital Equipment Corporation Virtual Address eXtension/Virtual Memory System) with a few hundred megabytes of disk storage, dedicated cartographic workstations and a vector plotter. Systems for environmental analyses included the early ESRI systems, COMARC (created in 1977), and Intergraph and Synercom systems.[108] Major changes came with the massive

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[104] John Davis, "Contour Mapping and SURFACE II," *Science* 237 (1987): 669-672.

[105] See James Carter, *Computer mapping: progress in the '80s*. Resource publications in geography. (Washington, D.C.: Association of American Geographers, 1984): 49 - 51.

[106] David Mark, http://www.ncgia.buffalo.edu/gishist/GISLIS97.html.

[107] See J. Ulc, "Intergraph System Overview," In Kolb, Otto. *Photogrammetrie et systemes d'information du territoire - Photogrammetry and land information systems*. (Lausanne, Suisse: Presses polytechniques romandes, 1990). 193 - 205.

[108] Carter, p 28 - 35

datasets resulting from the launch of Landsat, GOES and Seasat in the late 1970's. Programs such as ODYSSEY were developed to analyze and display these datasets. The programs were specifically designed to combine and compare these types of datasets.[109] The technologies available with the start of microcomputers in the early 1980's made it possible for individuals to easily create their own maps using tools such as Arc/Info, which was released in 1982 for workstations and in 1986 for PCs.[110]

Geology

The use of computers to generate geological maps started in 1946 with an article by Margaret Parker on the use of punched cards to store drilling data (Larsgaard, web page).[111] In the 1950's the Canadian government started creating digital files of geological data. The 1960's saw the start of computer programs and algorithms to process the data with Sampson and Davis' (1966) FORTRAN programs to create surfaces being an early development. In 1969, a system for the automated creation of

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[109] E. Teicholz, and B. Nisen. "Geographic Information and the ODYSSEY Project." In C. Vandoni, ed. *Eurographics 80*. (Geneva: University of Geneva, 1980) 149 - 166

[110] http://www.esri.com/company/about/history.html
http://www.intergraph.com/about/history/default.asp

[111] M. Parker, "Use of International Business Machine Techniques in Tabulating Drilling Data." *Ill. State Acad. Sci. Trans.* 39 (1946): 92–95. Cited in Larsgaard, M. "History of computer use in geologic-map production". http://www.sdc.ucsb.edu/~mary/computer.html. See also Daniel F. Merriam, "The Quantification of Geology: From Abacus to Pentium: A Chronicle of People, Places, and Phenomena, *Earth-Science Reviews*, Volume 67, Issues 1-2, (2004): 55-89.

geological maps was developed at the Royal College of Art's Experimental Cartography Unit. Boundaries between geological units were digitized from field sheets and the results used by a scribing machine to create masks. The process took two to three weeks for a single geological map (Bickmore, 1969). In the same journal issue, the use of anaglyph contour maps to represent three-dimensional features in weather maps and nautical charts was detailed (Adams, 1969). A rapid rise in the use of computers occurred in the 1970's and articles on multi-color geological maps and automated geological cartography appeared (Larsgaard). The Kansas Geologic Survey, where Davis worked, started producing maps from digital datasets. Programs to handle the increasing amounts of data being collected were created. The algorithms included contouring, creation of topology, display of point data and general data storage and handling routines. Wider application of computer techniques was limited by the relatively small memory available on computers and the slowness and expense of digitizing data (Larsgaard).

Digital data gathering techniques were still not considered cost effective in the 1980's and digital data gathering in field geology consisted primarily of transferring hand written field notes and drawings into a digital format, rather than collecting the information digitally. The exception to this situation would be petroleum exploration where digital data for seismic work was widespread. The 1980's saw “innovations” such as the creation of a digital version of Cuvier's map of Paris. It was also the start of the creation of programs for personal computers, as opposed to mainframes. Larsgaard also makes an interesting argument about the delay in embracing digital methods in geology as this time. She argues that geological maps are a bit different in that the maps are created once, and rarely updated. Since one of the major cost savings of digital maps is the ability to easily make corrections and updates and to reprint the map, this cost saving is lost to geological maps. Instead, they only see the high cost of the initial digitizing of data. For this reason, digital techniques are relatively unhelpful for geological mapping (Larsgaard).

The rise of GIS did provide a situation where the benefits of becoming digital outweighed the initial costs. Standardized base maps could be reused in a series of maps and field data were increasingly recorded using digital means. The mid-1980's saw the start of the use of GIS by state geological surveys. There were also discussions of multidimensional maps and plots and the " . . . use of software and hardware to display geological information in three dimensions was increasingly being mentioned, with the next step being the ability to manipulate and analyze that three-dimensional display" (GIS Symposium, 1988, p40-41and p46-47, cited in Larsgaard). Software started to be developed to create these three-dimensional plots. MacSection II created two-dimensional plots such as cross sections and fence diagrams and three-dimensional block and fishnet diagrams. As processing power improved, it became possible to create increasingly complicated geological models that included multiple spatial dimensions and temporal changes. EarthVision was developed in the 1990's to allow the building and sharing of complicated geological models that included structure, stratigraphy and temporal development (Larsgaard). Parallels between the GIS structures of vectors and rasters were drawn by researchers such as Boulding who wrote, "From a computer perspective, the geometry of irregular geological volumes is equivalent to vector information, and the spatial variation of variables to raster information. Information of these two information types in a 3-D context provides a platform for effective geological characterization on a computer" (Boulding 1995, p2, cited in Larsgaard). Challenges to the acceptance of digital techniques included the perception that the reading of geological maps is a linguistic skill that must be learned. Geology is a social community that accepts the rules of communication and the conventions that are necessary to create the maps (Rudwick, 1976). Digital maps, and their production, must adhere to these conventions.

Meteorology

The 1950's and 1960's brought the arrival of television and with it television weather reports that used government produced facsimile charts along with locally produced graphics (Monmonier, 1999). The 1960's brought the rise of weather prediction, models and an explosion in the amount of data collected.[112] Scientific interest in making animations for meteorological data may have started with a 1968 article in the *Bulletin of the American Meteorological Society* (Grotjahn and Chervin, 1984). The 1980's saw the use of digital representation on television, animated forecast

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[112] See Kristine Harper, *Weather by the numbers: The genesis of modern meteorology* (Cambridge, MA: The MIT Press, forthcoming 2008).

maps and the advent of "engaging" weather graphics. Scientific research into visualization was being carried out at the National Center for Atmospheric Research (NCAR), which developed early plotting packages, and still produces some of the best software for scientific visualization. In 1984, NCAR completed a two-year project to produce animated movies of data created by models at the European Center for Medium-Range Weather Forecasts (ECMWF). The animations included the use of trajectories, contour lines, shading patterns and 3-D surfaces viewed in perspective. The data included model and in situ data (Grotjahn and Chervin, 1984). In 1987, NSF produced a widely read report on the "Physical Simulation of Visual Representation of Natural Processes". The report, along with increased access to supercomputers, triggered the development of 4-D graphics for meteorological data (Schiavone and Papathomas, 1990). The McIDAS system was used at the University of Wisconsin-Madison to create images of 4-D meteorological data.[113] Three-dimensional graphics reached television with the development of various types of animations and graphical displays by private companies such as WSI. These became prevalent in the 1990's, along with the multi-color *USA Today* weather maps (Monmonier, 1999). More recently, the National Center for Atmospheric Research (NCAR) has a Geographic System Initiative with the goal to "to promote and support the use of GIS as both an

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[113] William Hibbard, "Computer-generated Imagery for 4-D Meteorological Data," *Bulletin of the American Meteorological Society.* 67(11) (1986): 1362 - 1369. This project led to the subsequent development of Vis5D and VisAD, which are the premier tools for visualizing meteorological data.

analysis, and an infrastructure tool in atmospheric research and to address broader issues of spatial data management, interoperability, and geoinformatics research in atmospheric sciences. The Initiative aims to make atmospheric data sets compatible with GIS tools and create a bridge between the atmospheric sciences, geography, ecology, other more spatially-based sciences, and the natural resource management and planning communities."[114] The project explicitly includes time dependent, real-time and volumetric data.

Oceanography

Up to 1950, there we so few soundings of the deep ocean that they could be published in a tabular form. The deployment of precision echo sounders, with a 5 meter accuracy and navigational accuracies of 3 nautical miles, led both to the ability to create more detailed maps and the need for new visualization techniques. The advent of supertankers and other deep draft vessels made it necessary to create accurate charts to greater depths and to greater accuracies.[115] There were still problems with gathering the data, and some maps had only a 50% data density. Additionally, datasets were held as secret for various reasons. In 1971, the Scientific Committee on Oceanic Research

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[114] http://www.gis.ucar.edu/initiative.html

[115] G. Ritchie, "Surveyors of the oceans," *The Geographical Magazine* XLII(1) (1969): 13 - 21.

(SCOR)[116] set up a committee on mapping the ocean floor. The was in response to the fact that the GEBCO charts, seen as the most complete bathymetric charts of the oceans, included sheets that had not been revised since 1928 (Laughton, 1980). This rapid increase in bathymetric data led to the creation of more detailed charts and the possibility of creating three-dimensional representations. One approach was the physiographic diagram, such as the Heezen and Tharp maps, first published in 1959, with the advantages mentioned in chapter 2.

Anaglyph charts were also created to provide three-dimensional views of the sea floor. The data were manually contoured, the line work was scribed automatically and the anaglyph was produced using automated equipment (Adams, 1969). The technique was also applied to weather maps and mention was made of the potential for using the digital data created in making these maps for other types of analyses (Laughton, 1980). At the same time, researchers in other oceanic disciplines began to combine their observed data with bathymetric data. While charts were still important for navigation, mariners were no longer the only ones making use of these tools.

More recently advances such as the use of seismic refraction and reflection, sidescan sonar and swath bathymetry sensors have provided 2- and 3-dimensional datasets for large areas of the sea floor. Seismic techniques provide a three-dimensional view of the sea floor[117] and software developed for terrestrial geological applications,

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[116] http://www.scor-int.org/

[117] See J. Mutter and G. Moore, “Opportunities for 3-D Seismic Reflection in

such as the Interactive Volume Modeling tool (IVM) can be used equally well for marine applications. These kinds of tools are especially good for handling faults and other discontinuities. Sidescan sonar provides a three-dimensional picture but the results tend to be more visual than quantitative so image processing tools are more used for these data. Swath bathymetry provides detailed bathymetric data and can be used for surveys of large areas. Early swath bathymetry for the United States exclusive economic zone was still sometimes withheld due to national security concerns. In recent years the datasets have been more widely available.[118]

Developments in computer hardware and software

The computer hardware and software developments that supported the creation of a 3-D GIS reflect patterns in other technological developments of the time. Military funding supported the first phase of development, with commercial expansion and refinement following. Hardware developments led the way, but operating systems and software to take advantage of the new hardware followed quickly. With the post-Cold War decreases in military spending, commercial development eventually was in the forefront, or at least in the publically announced forefront. GIS development depended upon hardware to support advanced graphical operations and analysis of large data sets. Operating system developments moved GIS from dedicated central machines to the

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Geoscience Research," *Eos* 86(49) (2005): 509 and 513 - 514.

[118] See http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html for data and technical details.

user's desktop and to grids of PC's. Algorithms, graphics accelerators, and cards first developed for the military simulation and high-end gaming industries enabled the creation and rapid display of complicated visualizations.

The invention in 1951 of Whirlwind, a real time computer for air defense, is usually cited as the beginning of the development of computer graphics.[119] The system drew symbols on a CRT to show aircraft locations superimposed over a map of the Massachusetts coast. A light gun could be used to query a database for the aircraft ID, speed and direction. A similar hardware configuration would be used in the oceanographic atlas described in the Pivar, Freedkin and Stommel paper of 1963.[120] In 1954, FORTRAN was developed as the first computer language to easily handle mathematical formulas by translating them into machine code. While later languages have been optimized for various tasks, FORTRAN is still a language of choice for large numerical models that provide the multi-dimensional output to be analyzed in a scientific GIS. The development, in 1957, of a digitizing tablet for handwriting recognition would lead to the development of tools to easily digitize analog material for

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[119] Sources: A Critical History of Computer Graphics and Animation http://design.osu.edu/carlson/history/lesson4.html; A Brief History of Computing, http://trillian.randomstuff.org.uk/~stephen/history/timeline.html; The Future of Spatial Data and Society: Summary of a Workshop, 1997. Good sources for GIS history include Unit 23 (History of GIS) in Michael Goodchild, and K.K. Kemp, eds. 1990. NCGIA Core Curriculum in GIS. National Center for Geographic Information and Analysis, University of California, Santa Barbara CA. Also see Nicholas Chrisman, http://chrisman.scg.ulaval.ca/ite/Lec27old.html

[120] Malcolm Pivar, Edward Fredkin, and Henry Stommel, "Computer-compiled Oceanographic Atlas: An Experiment in Man-machine Interaction," PNAS **50 (1963): 396 - 398**.

digital representation. In the same year, IBM marketed the dot matrix printer. Early mapping packages such as SYMAP would use these printers to create choropleth and other types of maps. Hardware developments continued with the development of the integrated circuit in 1958 and the TX-2 computer for interactive graphics at MIT's Lincoln Labs in 1959. Computer aided design (CAD) began with the development of DAC-1 by General Motors and IBM in the same year. CAD and GIS remain interrelated to this day.

While having a name for something does not guarantee its success, the coining of the term 'computer graphics' by a designer for Boeing Aircraft in 1960 did provide an identity for these early hardware and software developments. The next major hardware development was the PDP-1, the first of a long line of machines from what later became DEC. Ken Olsen, who had earlier worked on the TX-2 project, created the PDP-1. Henry Stommel and others were to make use of the DEC resources in Maynard, Massachusetts for after-hours explorations of using computers to analyze oceanographic data.[121]

In 1963, Ivan Sutherland created the Sketchpad program, which he called "a man-machine graphical communication system."[122] Sketchpad included one of the first

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[121] Dennis Moore, pers. comm. and Henry Stommel, "The Sea of the Beholder" [1984] reprinted in Nelson Hogg and Rui Xin Huang, *Collected works of Henry M. Stommel*. (Boston Mass.: American Meteorological Society, 1995). Hereafter 'Stommel autobiography'. p I-48.

[122] See Ivan Sutherland, "Sketchpad, a Man-machine Graphical Communication System," Thesis (Ph. D.)--Massachusetts Institute of Technology, (1963), reprinted as

graphical user interfaces, a light pen, and anticipated advances such as clicking to highlight an action and dragging to modify an object. The tool was developed at Lincoln Labs and is an important example of a technique migrating from a military laboratory to civilian engineers. At the same time, the first hidden line algorithm was also developed at Lincoln Labs.[123] The next year Ruth Weiss supported the viewing of three-dimensional surfaces by writing some of the first algorithms for converting their equations to orthographic views on an output device.[124]

More general developments included the creation of the BASIC programming language in 1964. This was the first freely available, simple language. The same year the PDP-8 was developed as the first minicomputer and an early system for general users. In contrast, the IBM-380 was developed that year as a centralized computing system. SYMAP was developed as a general mapping package, using line printers for output, as a part of work by Duane Marble and Howard Fisher on transportation in Chicago.[125] In 1965, the Canada Geographic Information System (CGIS) was created to support land management plans in rural Canada. The CGIS was an example of a system tuned to a specific need, rather than a general purpose software application.

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http://www.cl.cam.ac.uk/techreports/UCAM-CL-TR-574.pdf

[123] See L.G. Roberts, "Machine Perception of Three Dimensional Solids," *MIT Lincoln Lab. Rep.*, TR 315, May 1963

[124] See Ruth Weiss, "BE VISION, a Package of IBM 7090 FORTRAN Programs to Drive Views of Combinations of Plane and Quadric Surfaces, " *Journal of the ACM* 13(4) (1966): 194-204. Cited in http://design.osu.edu/carlson/history/lesson4.html

[125] See Chrisman (2006) and Goodchild and Kemp (1990).

Other developments at this time included the first supercomputer, the Control Data CD6600 and the Tektronix direct view storage terminal 4002A, a classic graphical display device. The following year Ivan Sutherland (of Sketchpad fame) and Robert Sproull began virtual reality (VR) research as part of a "remote reality" project for Bell Helicopter. The first published research project deploying the VR display "addressed problems of representing hemodynamic flow in models of prosthetic heart valves. The idea was to generate the results of calculations involving physical laws of fluid mechanics and a variety of numerical analysis techniques to generate a synthetic object that one could walk toward and move into or around (Greenfield et al., 1971)."[126] The development of GIS expanded with the formation of the Harvard Laboratory for Computer Graphics in 1967 and the Environmental Systems Research Institute in 1968. To display these new graphics, tools such as the DEC 338 intelligent graphics terminal were developed out of work at the Electronic Systems Laboratory at MIT, another military support and research entity. Interactions between humans and computers were greatly enhanced by the invention of the computer mouse in 1968. Scientific visualization on computers saw its start in color visualization of energy spectra of spacecraft plasma by Louis Frank in 1969.

Hardware developments continued with the first PDP-11, using UNIX, in 1970 and the invention of the RAM chip, which allowed the construction of frame buffer for

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[126] Cited in http://design.osu.edu/carlson/history/lesson4.html

holding a screen's worth of data and rapid updating. This led to the rise of raster graphics as an alternative to the earlier vector graphics of CRT displays and the Tektronix 4nnn line of terminals. The DEC VT-52, released in 1974, had the first addressable cursor in a graphics display. The same year, Xerox's PARC development lab developed the first workable GUI. Computer hardware improvements continued with the VAX 11/780, a 32-bit machine with virtual memory first sold in 1976. The IBM-PC started the personal computer world in 1981. High-end graphics machines were created with the invention of the Geometry Engine for rapid processing. This became Silicon Graphics, which was generally seen as the best image and graphics generation hardware. Further graphics improvements came with the development, in 1987, of graphics accelerator boards, which added a coprocessor to take the load of graphics creation off of main CPU. Graphics software improvements led to the X-Windows system in the same year. Software applications included the Application Visualization System (AVS), a modular system developed in 1989 and Iris Data Explorer, developed in 1991, with a visual programming and data flow approach. Iris Explorer supported multi-dimensional explorations by implementing points, lines, areas, and volumes as data types.

By the early 2000's all of the technical resources necessary for the creation of a commercial multi-dimensional GIS were available. Computer hardware, in the form of personal computers and centralized resources such as supercomputers, could support the calculations necessary for multi-dimensional analyses. Graphics co-processors and display cards could support the rapid creation of output. Databases could store the necessary number of dimensions in various structures. Programming languages and algorithms for advanced graphical techniques were available. Visual objects and modular tools were available in a variety of scientific visualization packages and theoretical exercises had explored the possibilities of a multi-dimensional GIS. There were even sensors available to collect the multi-dimensional data that warranted analysis in a GIS. What was still missing was the package that took advantage of all of these possibilities.

History of three-dimensional GIS – precursor systems

The 1950's and 1960's were the start of the development of what would become civilian GIS. While multiple theme maps had been in use for a long time, three factors contributed to the rise of GIS - computer technology, theories of spatial processes and the need to tackle social and environmental problems (NCGIA, web page). One of the challenges to creating a history of multi-dimensional GIS is simply choosing which story to tell about these times. The history of GIS as a larger topic is told in at least four quite different ways. The first is based upon military developments at the end of the Cold War. In this narrative, GIS develops out of the MGIS system in the ways described in chapter 2. The second major school of thought on the history of GIS traces its development from the Canadian Geographic Information System (CGIS). The third version is based upon the rise of academic GIS and marks the start with the mapping applications developed at the Harvard Lab for Computer Graphics. The fourth approach traces the development by considering the agencies and companies that developed GIS systems, and how the various packages were interrelated.[127]

The CGIS was developed in the mid 1960's to analyze data collected by the Canadian Land Inventory and to assist with land management. The CGIS provided land classifications based upon a variety of attributes. While the CGIS ran into technical and financial difficulties, it did lead the major advancements in techniques and technologies such as scanning, vectorization, the use of data layers, and various polygon overlay techniques (NCGIA).

GIS development also occurred at the Harvard Laboratory for Computer Graphics and Spatial Analysis. The Harvard lab served as a testbed for a variety of techniques and was also the training ground for a large number of the faculty and students who went on to form the core of the discipline - Nick Chrisman, Jack Dangermond, Scott Morehouse, Howard Fisher and others. The Harvard lab developed programs for general purpose mapping, 3-D perspective mapping, raster mapping and analysis and a variety of polygon operations that would speed future GIS development (NCGIA). The ODYSSEY project created a GIS with analytical capabilities such as polygon overlay and manipulation of the database containing the geographic data (Teicholz and Nisen, 1980).

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[127] For a series of chapters on the four schools see Timothy Foresman, *The history of geographic information systems perspectives from the pioneers.* Prentice Hall series in geographic information science. (Upper Saddle River, NJ: Prentice Hall PTR 1998).

After the groundwork for GIS was laid by these projects further development came through commercial packages such as ArcInfo (ESRI), MapInfo (Intergraph) and government packages such as GRASS (USDA). Coppock and Rhind traced this development and used Cooke's diagram of the interconnections between products[128] to show the complex relationships between packages, as well as those between the individuals and institutions who created the products.

The U.S. government also played a role in the development of GIS due to the need to represent and analyze Census data. The need to match population data to addresses and geographical location led to the development of DIME files. DIME files built upon the polygon and arc structures of both the CGIS and the Harvard POLYVRT programs (NCGIA). Importantly for future development in GIS and in multidimensional visualization, the DIME files included topology so that the relative positions of objects and relationships such as "inside" and "outside" became a part of the data structure. DIME files were used starting with the 1970 Census of Population.

Examples of multi-dimensional GIS

Multi-dimensional GIS's can be classified as theoretical exercises, visualization tools that might better be called GIS data viewers, geospatial analysis tools for specific disciplines, e.g. geology, and working examples in both the commercial and open-

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[128] Another view is in J. Coppock and D. Rhind, "The History of GIS, " In David Maguire, Michael Goodchild, and David Rhind, (editors) *Geographical information systems: Principles and applications*, London: Longmans Publishers, 1991): 21-43.

source sectors. There is also a large literature on the data structures needed to support multi-dimensional GIS, but that is not the focus of this work.[129]

Theoretical exercises include both toolkits and philosophical explorations. In 1988, Visualizing in Perspective (VIP) created perspective maps from rasterized DTMs and explored visualization tools and menus for various graphical operations, but did not perform analyses.[130] At the same time, Davis and Davis discussed a theoretical marine GIS.[131] The posited five dimensions - three spatial, one temporal, and one attribute dimension. The paper touched upon the paucity of surface data available for the deep ocean and the challenges of developing a GIS to describe a dynamic environment. They argued that the marine realm was so fundamentally different from the terrestrial one that it required new concepts and perceptions but, they also pointed out that computer technology was inadequate to analyze and display fully five-dimensional data. They saw stacked two-dimensional layers of attributes as disregarding the continuous nature

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[129] See Donna Peuquet, "Making Space for Time: Issues in Space-time Data Representation," *GeoInformatica*. 5 (1) (2001): 11-32 and Rita de Caluwe, Guy de Tre, and Gloria Bordogna. *Spatio-temporal databases: flexible querying and reasoning.* (Berlin: Springer, 2004).

[130] See B. Lafargue, "VIP: Visualizing in Perspective," In GIS/LIS. 1988. *GIS/LIS '88: proceedings: accessing the world: third annual International Conference*, Exhibits, and Workshops, San Antonio, Marriott Rivercenter Hotel, San Antonio, Texas, November 30-December 2, 1988. (Falls Church, VA: American Society for Photogrammetry and Remote Sensing, 1988): 100 - 110.

[131] B. Davis, and P. Davis, "Marine GIS: Concepts and Considerations," In *GIS/LIS. 1988. GIS/LIS '88: proceedings : accessing the world : third annual International Conference,* Exhibits, and Workshops, San Antonio, Marriott Rivercenter Hotel, San Antonio, Texas, November 30-December 2, 1988. (Falls Church, VA: American Society for Photogrammetry and Remote Sensing, 1988): 159 - 168.

of phenomena and the perspective view was seen as lacking in its inability to portray more than 2.5-dimensional views. They called for four-dimensional displays or multi-perspective views, or possibly holographic displays. The paper also observed that analysis was typically conducted in two dimensions and draped over a third dimension. While the authors provided no technical solutions, they posed a number of questions that are still valid, and unanswered.

Kavouras and Masry created Daedalus in 1987 to display ore bodies and other mineral resources.[132] The 3D Geoscientific Resource Management System (GRMS) was developed by Bak and Mill in 1989 to combine vector and raster data. While the prototype was promising, it was not developed further.[133] An urban multidimensional GIS was a part of the 1989 National Capital Urban Planning Project to visualize urban planning and transportation patterns.[134] Scott extended Tomlin's cartographic modeling methods to three dimensions using the IBM Visualizaton Data Explorer. The system concentrated on voxels as a way to extend two-dimensional raster techniques to datasets such as the output of global circulation models. The functions included LocalMean, LocalSum, LocalMaximum, LocalMinimum and similar computations. As with most of

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[132] See M. Kavouras and S. Masry, "An Information System for Geosciences: Design Considerations," In N. R. Chrisman, (ed.) *Proceedings, 8th International Symposium on Computer Assisted Cartography, (Auto-Carto 8).* Baltimore, MD. (1987): 336-345.

[133] P. Bak and A. Mill, "3-D Representation in a Geoscientific Resources Management System for the Minerals Industry," In J. Raper, ed. *Three Dimensional Applications in GIS*. (Bristol, PA: Taylor and Francis, 1989): 155-182.

[134] L. Batten, "National Capital Urban Planning Project: Development of a 3-D GIS," *Proceedings of GIS/LIS '89*. (Falls Church: ACSM/ASPRS, 1989): 781-6.

these projects, development stopped after the first prototype.[135] GeoNet is billed as a web based 4-D GIS. It is an attempt to link a traditional GIS with web content and multimedia. It is based upon the ESRI MapObjects and data are stored in an Access database. It is more of a data display enhancement for a GIS than an analytical tool.[136] Geotouch is a tool for data analysis in three and four dimensions. Intended primarily for geological applications, it includes focal mechanisms and wire frame representations of sub-surface structures. It is written in C and uses X-Windows under Unix and Linux. Editing of data is done externally and output included arbitrary cross-sections, three-dimensional objects that can be rotated in space and animations.[137] GeoToolKit is a library of C++ classes to add spatial and temporal functionality to applications. It supports 3- and 4-D geological applications in an object-oriented database.[138]

In the mid to late 1990's, linking GIS with virtual reality (VR) was used as a way to create a multi-dimensional GIS. Faust argued that a true 3-D GIS required "(1) ... a

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135 M. Scott, "The Extension of Cartographic Modeling for Volumetric Geographic Analysis," http://www.spatial.maine.edu/~onsrud/ucgis/testproc/scott_m/scottm.html. accessed 8/14/07.

136 B. Thomas, "The GeoNet Project - A Web Based 4D GIS," In Strobl J. and C. Best (Eds.), *Proceedings of the Earth Observation & Geo-Spatial Web and Internet Workshop '98*, Salzburger Geographische Materialien, Volume 27. Instituts für Geographie der Universität Salzburg (1998).

137 J. Lees, "Geotouch: Software for Three and Four Dimensional GIS in the Earth Sciences," *Computers and Geosciences*. 26 (2000): 751 - 761.

138 B. Balovnev, T. Bode, B. Breunig, A.Cremers, W. Mueller G. Pogodaev; S. Shumilov; J. Siebeck, A. Siehl, and A. Thomsen, "The Story of the GeoToolKit - An Object-oriented Geodatabase Kernel System," *GeoInformatica*, 8(1) (2004): 5 - 47.

very realistic representation of the three-dimensional nature of real geographic areas. (2) a user would have to have free movement within and outside the geographic terrain. (3) a user should be able to perform all normal GIS functions (search, query, select, overlay, etc.) within the three-dimensional database and view the results from any vantage point. (4) visibility functions ... should be natural functions integrated with the user interface ..."[139] Germs et al. created an example of a 3-D GIS linked with VR in creating Karma IV for the Dutch Land Water Environment Information Technology foundation. (Germs et al., 1999) The tool included three linked viewers - a "plan view" providing traditional GIS capabilities, a 2.5-dimensional "model view" providing analyses such as line-of sight and extruded 2-D geometries and a full 3-D "world view" with virtual reality and analyses such as shadows and scenario creation. When a user was in the 3-D world, it was possible to send queries back to be answered by the 2-D GIS-based plan view. The Spatial Data Engine was used to pass data and queries between an ESRI based GIS and the Sense 8 VR-system. Development of the Karma IV system seems to have stopped in 1999 and further development has concentrated on the VR side of the tool to create immersive visualization for rural and urban planning.[140]

Virtual Reality Modeling Language (VRML) was used as another way to create 3-D representations of GIS data. Starting in 1995, VRML provided a way to create

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[139] N. Faust, "The Virtual Reality of GIS," *Environment and Planning B. Planning and Design*, 22 (1995): 257-268.

[140] www.k2vi.com

immersive realities that could be displayed and interacted with on desktop systems. Unlike earlier GIS-VR tools, which required a high end workstation or supercomputer to handle geometric and rendering computations, VRML could be created on inexpensive desktop systems. In a survey in the late 1990's, half of the systems for creating visual reality from a GIS used VRML (Haklay, 2002). ESRI's ArcScene could create VRML output for use within various VRML viewers. One of the problems of standard VRML was its use of a Cartesian coordinate system. GeoVRML was proposed as an extension of VRML to handle coordinate transformations and non-Cartesian coordinates (Rhyne, 1999). GeoVR was developed as a tool to create 3-D VRML scenes from ESRI ArcView 3DAnalyst layouts.[141]

GIS data viewers are a relatively new development, and include tools such as Google Earth, NASA's WorldWind, and the various ArcGIS data viewers. These tools allow the integration of GIS data with other types of spatial data, but do not provide analytical tools beyond spatial searches and simple analyses. Google Earth is primarily a viewer, though it does allow for searches and for the addition of GIS data layers. Its main strength is in the ability to rapidly add new data sets and the high-resolution data inherent in the product. Like Google Earth, World Wind is primarily intended to serve as a viewer for high-resolution satellite data.

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[141] B. Huang and H. Lin, "GeoVR: a Web-based Tool for Virtual Reality From 2D GIS Data," *Computers and Geosciences.* 25 (1999): 1167 - 1175.

World Wind has recently developed a Java SDK[142] that would allow its visualization functionality to be combined with analytical tools from other sources. The ESRI data viewers, including ArcGIS Explorer and ArcReader, provide data viewing, data integration, simple analyses such as distance and, in ArcGIS Explorer, more advanced analyses such as viewshed calculations.

Discipline specific tools, which may blur the distinction between GIS and visualization tools, include Vis5D, MIKE, Interactive Visualization System's Fledermaus, and the Interactive Volume Modeling tool (IVM). Fledermaus is a tool for marine surveying and seafloor mapping that is the commercial offshoot of tools developed at the Ocean Mapping Group at the University of New Brunswick. It is optimized for marine mapping and charting. GIS related tools in Fledermaus include creating points and lines in a 3-D scene, draping images over a 2.5-dimensional surface and surface analyses.[143]

IVM, developed by Dynamic Graphics, was used to create one of the first examples of the use of multi-dimensional GIS in oceanography. Three-dimensional temperature data for Fram Strait, expendable bathythermograph data (XBT) data from the CEAREX expedition and the output of Corps of Engineers model runs for circulation in Chesapeake Bay were gridded in three-dimensions and a variety of three-dimensional volumes were rendered (Manley and Tallet, 1990). IVM is a part of a

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[142] http://worldwind.arc.nasa.gov/java/index.html

[143] See http://www.ivs3d.com/products/technology/gis.html

series of tools developed by Dynamic Graphics for spatial analysis in geology and petroleum exploration. Their first tools were for the gridding of two-dimensional data and led to a 1974 release of the Surface Gridding Library and the Surface Display Library. In the late 1980's the availability of three-dimensional data led them to expand these tools to three dimensions and create IVM. While IVM was a general three-dimensional package, their more recent developments have concentrated on geological applications and the management of borehole data (www.dgi.com/corporate/index.html). Their most recent package is Earth Vision, which uses a minimum tension gridding technique to create voxels. These voxels can then be converted to isosurfaces for display. While these tools do not support traditional GIS analyses, they are optimized for portraying geological features such as faults and other discontinuities.

Vid5D is an open-source visualization tool developed for the display of 5-D (3 spatial dimensions, one temporal dimension and another dimension of measured or derived properties) gridded data sets. It was originally designed to display the output of weather models. It was developed by the Visualization project of the Space Science and Engineering Center at the University of Wisconsin-Madison. Analysis tools include the creation of isosurfaces, making slices though the data, rendering of volumes, the creation of SkewT and other plots, the ability to create new variables based upon existing variables and the ability to integrate external analysis tools to act upon the internal variables. (http://vis5d.sourceforge.net/doc/) While not a true-GIS, Vis5D does have powerful tools for visual display of data. It has been used for the visualization of oceanographic data created in a GIS, e.g. Su and Sheng (1999).

Hydrodynamic modeling applications in GIS include the ArcHydro toolkit (http://www.crwr.utexas.edu/giswr/hydro/ArcHOSS/index.cfm) from the University of Texas and TauDEM from Utah State (http://hydrology.neng.usu.edu/taudem/). MIKE 3 (http://www.dhigroup.com/Software/Marine/mike3.aspx) is a tool for 3-D hydrodynamic modeling.

True geographic information systems that support multi-dimensional data include older systems that are no longer available and new systems that are not yet fully functional for volumetric 3-D. System 9 was an early example of a multi-dimensional GIS. Details of its technology are a bit sketchy but it included a data structure that supported fully three-dimensional objects and topology. System 9 was originally developed by Wild Leitz, a photogrammetry company, in 1987 as a way to expand demand for their imaging technology. The software ran on SUN workstations under UNIX systems and later was ported to other operating systems and hardware including Solaris, HP-UX and IBM-AIX.[144] Its functionality included data capture and management, display and plotting of data and raster image processing

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[144] J. van Eck and M. Utter, "A Presentation of SYSTEM 9," In Otto Kolb, Otto. *Photogrammetrie et systemes d'information du territoire = Photogrammetry and land information systems*. (Lausanne, Suisse: Presses polytechniques romandes, 1990): 139 - 178. For more on the photogrammetric aspects of System 9 see W. Burgermeister and T Banziger "La station de travail photogrammetrique Wild S9-AP comme composante d'un SIT" in the same volume. p 241 - 254.

(www.science.uva.nl/~mes/tclFAQ/tcl-commercial/). These tasks were accomplished using three workstations - one for editing, one for digitizing, and an analytical workstation for gathering photogrammetric data. The systems were linked via an Ethernet network to allow for distributed processing and analysis. System 9 used the Empress database system and Rtrees to store 'blobs', enabling it to store three-dimensions directly in a single database structure for efficiency. The database supported complex features with a hierarchy of relationships and feature classes made up of groups of features. Editing of features was done on a working copy of the database while queries were made to a read-only project database. The graphics were based upon the Programmers Hierarchical Interactive Graphics Kernel System (PHIGS), which was an extension of the Graphics Kernel System (GKS). PHIGS was chosen for performance and interactivity.[145] Programmers included graduates of SUNY Buffalo and the Harvard Lab for Computer Graphics. It was launched in 1985 at the Fédération Internationale des Géomètres meeting and was presented as a topologically structured system using a relational database to store three-dimensional coordinates (Fletcher, 1988). In 1989, marketing was taken over by Prime Computer in a joint venture called Prime WILD GIS Ltd. as a part of the company's CAD marketing. System 9 was then sold to Computervision, which saw System 9 as a way to boost hardware sales as they

[145] J. van Eck and M. Utter. p142.

distributed it on proprietary hardware systems.[146] System 9 was then passed from Computervision to Unisys in 1993 and eventually to MapInfo. Computervision sold the program to Unisys, as they were concentrating on CAD/CAM and Unisys was becoming interested in GIS. (Software Industry Report, Nov. 13, 1993). System 9 was used for the NPDES stormwater discharge system for the Los Angeles County Department of Public Works with land use files translated from ArcInfo to Cad to System 9 (Lehman, 1994). It was also used in CADDiN, a CAD/GIS system for the design of electrical systems. By this time, the database had migrated from a relational database to a "topology-structured object-oriented relational database system" (Skrlec et al., 1994). While System 9 no longer exists, MapInfo Professional includes its functionality, minus the connection to the Empress database[147].

Voxel Analyst, now MGE Voxel, is a tool for volume modeling, analysis and display. Pre-existing three-dimensional grids can be loaded or a grid can be interpolated from sparse data. Cross-sections and isosurfaces can be created and viewed. Varma (2000) cited it as the best example of a three-dimensional GIS at the time of their writing. Voxel Analyst seems to have been mainly used as a visualization tool. Applications include a marine GIS for water temperatures around Taiwan (Shuye and Tsai, 1996), visualizing subsurface methylene chloride concentrations at an industrial

[146] Paul Korzeniowski, "GIS Software Getting Business Data on [the] Map," *Software Magazine*, (May 1993). Available at http://findarticles.com/p/articles/mi_m0SMG/is_n7_v13/ai_13761740

[147] Nick Chrisman, pers. comm., June 2003.

plant (www.claytongrp.com/3d_art.html), and four-dimensional visualization of smog in Perth, Australia (Sandison et al., 1998).

INFOCAM was an example of a GIS tied to specific proprietary hardware. It was developed by Kern and required the use of their analytical stereo plotters for 3-D digitizing. The software was installed on DEC Micro VAX workstations and the workstation configuration could be selected and upgraded, based upon the user's needs. Oracle was used to store a topological database and points were stored with X, Y and Z coordinates. The Z values were stored as coordinates, not attributes but were usually treated as secondary information. Output was as plans and maps either as a screen dump or for plotting on Kern flat bed plotters. Digital terrain models could be created, but there were no specifically three-dimensional types of analyses or outputs.[148]

The Geographic Resource Analysis Support System (GRASS) was developed in the late 1980's as a grid-based analysis and display tool. The Army Corps of Engineers and the USDA developed GRASS. A mixture of government agencies and universities has done further development and GRASS is a public domain tool. It was originally written for UNIX workstations and was later ported to X-Windows systems.[149] GRASS

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[148] F. Gaufroid, "Kern Infocam - A Geographical Information System for Computer Aided Management," in Otto Kolb, *Photogrammetrie et systemes d'information du territoire = Photogrammetry and land information systems*. (Lausanne, Suisse: Presses polytechniques romandes, 1990): 127 - 136.

[149] K. Gardels, "GRASS in the X-Windows Environment - Distribution of GIS Data and Technology," In GIS/LIS. *GIS/LIS '88: proceedings: accessing the world : third annual International Conference, Exhibits, and Workshops*, San Antonio, Marriott Rivercenter Hotel, San Antonio, Texas, November 30-December 2, 1988. (Falls Church, VA: American Society for Photogrammetry and Remote Sensing, 1988).

supports three-dimensional vectors, grids, and voxels. Available features include import and export of data to 3-D, map algebra in 3-D, 3-D interpolation 3-D visualization, 4-D visualization via the use of Vis5D and export to VTK (grass.itc.it/grid3d/index.html). The tools have been used for the modeling of soils (Neteler, 2001) and visualizing dissolved inorganic nitrogen in Chesapeake Bay (Mitasova et al., web page).

The ESRI ArcGIS suite is in the process of developing multi-dimensional tools, though their first emphasis has been on the development of tools to display temporal data and 2.5-dimensional spatial data. Development of multi-dimensional tools has been through the path of data models. The ArcHydro Model provides data structures and tools for both surface hydrology and groundwater. Within the groundwater tools, techniques such as the creation of convex hulls from scattered points and calculations of the properties of these hulls have been created.[150] Within the Atmospheric Data Model, support for netCDF files (a multidimensional data structure used for model output and to store 4- and 5-D observational data) is incorporated.[151] The Arc Marine Data Model includes definitions for multi-dimensional data and applications for 3- D interpolation and display (Wright et al., 2007). While a scientific mesh data type, for 3-D finite element and other numerical modeling of currents, has been defined, there are still no

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[150] http://www.cuahsi.org/his/tk-archydro.html

[151] http://support.esri.com/index.cfm?fa=downloads.dataModels.filteredGateway&dmid=36

tools within ArcGIS to make multi-dimensional analyses such as buffering, data selection of the calculation of intersections.

A new pattern in application development, made possible by frameworks such as open-source software, is the idea of decentralized application development. This is a way to address an additional factor that leads to the lack of development of three-dimensional GIS, the fact that these capabilities are not required in documents such as requests for proposals (RFPs) or evaluation checklists when government agencies are seeking GIS packages. This is a situation where there is an identified research need, but not an equivalent bureaucratic identification of the need. As with open source software, this roadblock can be gotten around when the user community defines needs, and then writes tools that are integrated with a commercial system. This is a successful model for the creation of tools for disciplines that may not involve enough commercial users of the package to warrant tools being developed by a software vendor.

Conclusions

When we began creating the OceanGIS prototype described in the following chapter, the needs and technologies were quite well defined but the acceptance was still a challenge. As the history detailed in this chapter has explained, there had been many advances in technology and data collection. Interestingly, these technological advances, and the stated need for multi-dimensional GIS, has not led to a widespread use of either the commercial or open-source multi-dimensional GIS tools available. While researchers wanted to see their research areas in three dimensions and exposure to video games and scientific visualizations had made them familiar with these types of visual representations, there was still not a perception that full multi-dimensionality was an advantage.

Circulation and ecosystem models made fully populated three-dimensional grids of data a standard resource. Oceanographic data from conductivity-temperature-depth (CTD) casts, high-resolution bathymetry from swath mapping, currents from current meter moorings and circulation models, biological samples from tools such as the MOCNESS (a plankton net able to sample discrete layers using a Multiple Opening and Closing Net System), hydroacoustic data on fish distributions, and three-dimensional tracklines from instrumented marine mammals provided a plethora of data for analysis. Data formats such as netCDF were widely used for storing multi-dimensional scientific data. Computer hardware to support these analyses and visualizations were commonly available on the desktop, with access to supercomputers to run large models fairly straightforward. While VRML was still being put forward as a tool for interaction with three-dimensional datasets, newer types of interactions, such as Java3D and Google Earth, were beginning. The rise of open-source software and community application development was forcing the more traditional software vendors to find ways to make their core functions available to external applications. Java was becoming a de facto standard for scientific programming and for linking modules from a variety of sources. All of these resources were a result of the developments, and then interplay between civilian and military activities, detailed in this chapter. In some ways, the greater challenge was getting potential users to recognize the advantages of these new ways of seeing things. As with the Stommel diagram, some of the most enthusiastic users of our new applications have not been those we first expected.

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GEOMODELER: TIGHTLY LINKING SPATIALLY-EXPLICIT MODELS AND DATA WITH A GIS FOR ANALYSIS AND GEOVISUALIZATION

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Proceedings of the 15th ACM International Symposium on Advances in Geographic Information Systems. Seattle, Washington. November 7 – 9, 2007.
The Association for Computing Machinery, New York, New York.

Chapter 6: GeoModeler: Tightly linking spatially-explicit models and data with a GIS for analysis and geovisualization

Abstract

Numerical simulation models provide a way to understand and predict the behavior of natural and human systems. Ideally, spatially-explicit models would be easily linked to a geographic information system (GIS) for data analysis and visualization. In the past, these two have not been well integrated for scientific uses. This lack of true integration hinders the ability of scientists and managers to create interactive, GIS-based models for research and policy planning. However, GIS packages are starting to expose code and objects to allow closer coupling of core GIS functionality and analytical/modeling tools. In creating GeoModeler, we have provided a prototype of how one might integrate a GIS with oceanographic and decision-support models. Through the use of Java-based application programming interfaces and connectors, a GIS is directly linked with the Regional Ocean Modeling System (ROMS) and with the Method of Splitting Tsunami (MOST) model. Scientists and managers are able to use a graphical interface to display datasets, select the data to be used in a scenario, set the weights for factors in the model and run the model. The results are returned to the GIS for display and spatial analysis. Three-dimensional visualizations are created using elements of the Visualization Toolkit (VTK) and OpenGL. The project creates a framework for linking to other types of back-end models written in a variety of programming languages.

Introduction

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

Models can be created within a GIS, created entirely separately using scripting or advanced programming languages, or ideally they might be created using combined techniques yielding the best of both worlds. Models can be implemented within a GIS in a number of ways. They can be loosely coupled, with the GIS used to prepare data for use in a separate computational model. The GIS can be used just to visualize the model output. The model can be implemented using the functionality of the GIS, for example in calculating hillslopes and drainage patterns for an hydrological model. Finally, the model and the GIS can be tightly computationally coupled, with the GIS used both for the input and for visualization of the output.

GIS-centered models include modeling of seafloor habitat (Greene et al, 2005; Monaco et al., 2005), models of three-dimensional oceanographic data (Wright et al., 2007), models of the spread of disease (Cromley, 2003) and models of the aesthetics of landscapes (Hoesterey, 2005). Examples of hydrological models created within a GIS, taking advantage of the native analytical functions of the GIS, include those built for vector data using the ArcHydro Toolset (Arctur and Zeiler, 2004), or for raster data, such as TauDEM (Tarboton, 2005).

Examples of stand-alone models that could then be visualized in a GIS include weather models such as the Community Climate System Model (CCSM), Rapid Update Cycle (RUC) and ECMWF Re-Analysis models (UNIDATA, 2006). Tools such as RAMAS GIS use a GIS to organize data for input into a stand-alone habitat model (Akçakaya et al., 2004). The MODFLOW groundwater flow model can be visualized with the GRASS GIS (Brodie, 1998; Carerra-Hernandez et al., 2006). Use of a GIS for model parameter setup and the display of results is seen in the watershed management modeling of the ArcView nonpoint source pollution modeling (AVNPSM) system (He, 2003).

Application of GIS to oceanographic models has been limited by a number of factors including: an inability to easily handle datasets such as three-dimensional model output and common data formats such as netCDF (http://www.unidata.ucar.edu/software/netcdf), the lack of volumetric three-dimensional analytical capabilities, and a perception that there is a steep learning curve for their use (e.g. Valavanis, 2002; Vance et al., 2005, Wright and Goodchild, 1997). However, there has been a wide acceptance of GIS by emergency managers and others who routinely use GIS-based decision support and crisis response systems, with integrated scenario modeling and spatial analyses capabilities, to support rapid responses in emergency situations. GIS-model linkages are a part of the national research agenda of the University Consortium for Geographic Information Science (Albrecht, 2002; Usery, 2004). In this research agenda, these linkages are seen as a way to introduce dynamic modeling to the GIS community and to integrate computationally intensive applications within a GIS.

Motivation and aims

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

GeoModeler addresses a number of needs that can be met by enhancing a standard GIS and coupling it with spatially-explicit models. These include:

1. The need to analyze and display three-dimensional oceanographic data. In contrast to the regularly spaced output of most models, the data are usually collected along transects and may involve individual samples or measurements taken from the surface to the seafloor. The data are dense along tracklines, sparse between tracklines and very dense with depth. Analysis and visualization requires reading in standard three-dimensional data formats such as netCDF and tools for three-dimensional interpolation. Analyses include calculating parameters such as the depth to which the water column is uniformly mixed (the mixed-layer or thermocline depth) and depth integrated temperature or chlorophyll concentrations. For display, the data and analyses need to be combined with baseline data including bathymetry or coastline data.

2. The need to easily set up the inputs for complicated ocean circulation models and creative tools to display the output from the model. Models have numerous parameters and compiler specifications and the typical technique of creating a parameter file is nonintuituve for new users. The output of the models is voluminous and hard to visualize. Being able to quickly create three-dimensional visualizations of one or more model outputs and to view these visualizations interactively makes understanding the output easier. Rapid visualization makes it easier to see errors in model setup and to compute corrected model runs.

3. The need to combine the output of model runs with socio-economic data, such as census data, to calculate affected populations and other emergency management scenarios. While a model may illustrate a physical process, the process can have direct impacts upon human activities. An emergency manager may be much more interested in the impact of an event on the population than the extent or timing of an event.

4. The need to create visualizations and analyses of the intersection of planes and paths with three- and four-dimensional data. Animals follow linear three-dimensional paths. Intersecting a plane with a volume is a good way to visualize structures. Phenomena in the oceans and the atmosphere are inherently three- and four-dimensional. Models provide output in three spatial dimensions and a fourth temporal dimension. Standard GIS packages do not handle truly three-dimensional

spatial features such as volumes and convex hulls. There are standard data formats, such as netCDF, for storing four-dimensional data and there are now tools for reading netCDF into standard packages such as ArcGIS. While these data can be read in and animations of two-dimensional slices of the data can be created, analyses are limited. For research it would be useful to be able to do analyses such as the intersection of the three-dimensional line with a volume or the intersection of a volume with a volume to create a new volume.

As GeoModeler is a prototype, some of these needs have been met, and other will require further enhancements and developments.

Software components

GIS packages are starting to expose software code and objects to allow closer coupling of core GIS functionality and analytical/modeling tools. The GeoModeler application prototypes the direct integration of a GIS and modeling capabilities in support of research, management, and decision making. Through the use of Java-based application programming interfaces (APIs) and connectors, a GIS front-end is directly linked with models. Scientists and managers are provided with a GIS-based graphical interface to display datasets, select the data to be used in a scenario, set the weights for factors in the model, and run the model. The results are returned to the GIS-based application for display and spatial analysis. The project creates a Java-based framework for back-end models written in a variety of programming languages. The analytical and visualization tools provide more than just a simple coupling of a GIS to a model. GeoModeler provides spatial analytical functions but does not provide temporal functions beyond making animations. It does not provide time series analysis tools such as Fourier analysis or high-pass/low-pass filtering.

The GeoModeler application employs the Java3D API, which is designed as a high-level, platform independent 3-D graphics programming API, and is amenable to very high performance implementations across a range of platforms. To optimize rendering, Java3D implementations are layered to take advantage of the native, low-level graphics API available on a given system. In particular, Java3D API implementations are available that utilize OpenGL, Direct3D, and QuickDraw3D. This means that Java3D rendering will be accelerated across the same wide range of systems that are supported by these low-level APIs.

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

ArcGIS Engine and implementations of ArcObjects (http://esri.com/software/arcgic/arcgisengine) are used in a GeoModeler component creating a tsunami inundation decision support tool with communication to an ArcGIS-based front-end. The front-end provides for both setup - allowing the user to specify the datasets to be used, the weights for elements of the model and the outputs desired, and for display - showing the results of the model run in a map or other spatial output. ArcGIS Engine allows for a Java API while ArcObjects, written in C++, are used for analysis. With the use of the Java connector to ArcIMS, the results may also be displayed in an ArcIMS or other map server. Analyses include intersections, unions, and buffering.

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

Results and case studies

GeoModeler provides a prototype of an integrated system implementing GIS-based analysis, compute intensive scientific models, and geovisualization. The system illustrates the strength of using Java as a linking mechanism and the integration of a number of open-source utilities and analysis tools. It takes advantage of advances in GIS software including APIs to ArcObjects and direct reading of netCDF files. A number of test cases have been created to illustrate the tools available in GeoModeler. These include applications in physical oceanography, tsunami inundation and propagation, and marine mammal studies.

Displaying and analyzing oceanographic data

Analyzing oceanographic data requires the ability to ingest and manipulate three-dimensional data. A standard GIS can read three-dimensional data, but cannot go beyond displaying two-dimensional slices through the data or 2.5 –dimensional surfaces. In GeoModeler we have created tools to read netCDF files of model output and shapefiles of oceanographic sample data (x and y with multiple z values). GeoModeler is not limited to simply displaying visualizations. We are also developing analytical tools for oceanographic data and integrating them with the GUI. The tools are intended to be familiar both to GIS users and to users of scientific graphics packages.

GeoModeler builds upon an earlier tool called OceanGIS (Vance et al., 2005). OceanGIS was initially designed to allow 3-D oceanographic calculations on *in situ* data, and to overlay the results of the calculations on base data such as bathymetry. Tools were developed to perform oceanographic analyses such as calculating basic water properties given by conductivity-temperature-depth (CTD) measurements, such as mixed-layer depth, geostrophic velocity and dynamic height. These tools are integrated into GeoModeler. The GeoModeler interface and display use graphical objects to provide functionality related to the type of data being displayed. As a data layer is added, the relevant tools for analyses are exposed for use. In the example shown in Figure 14, the addition of a layer of CTD data causes tools for calculating mixed layer depth and other appropriate oceanographic parameters to become available. Data can be

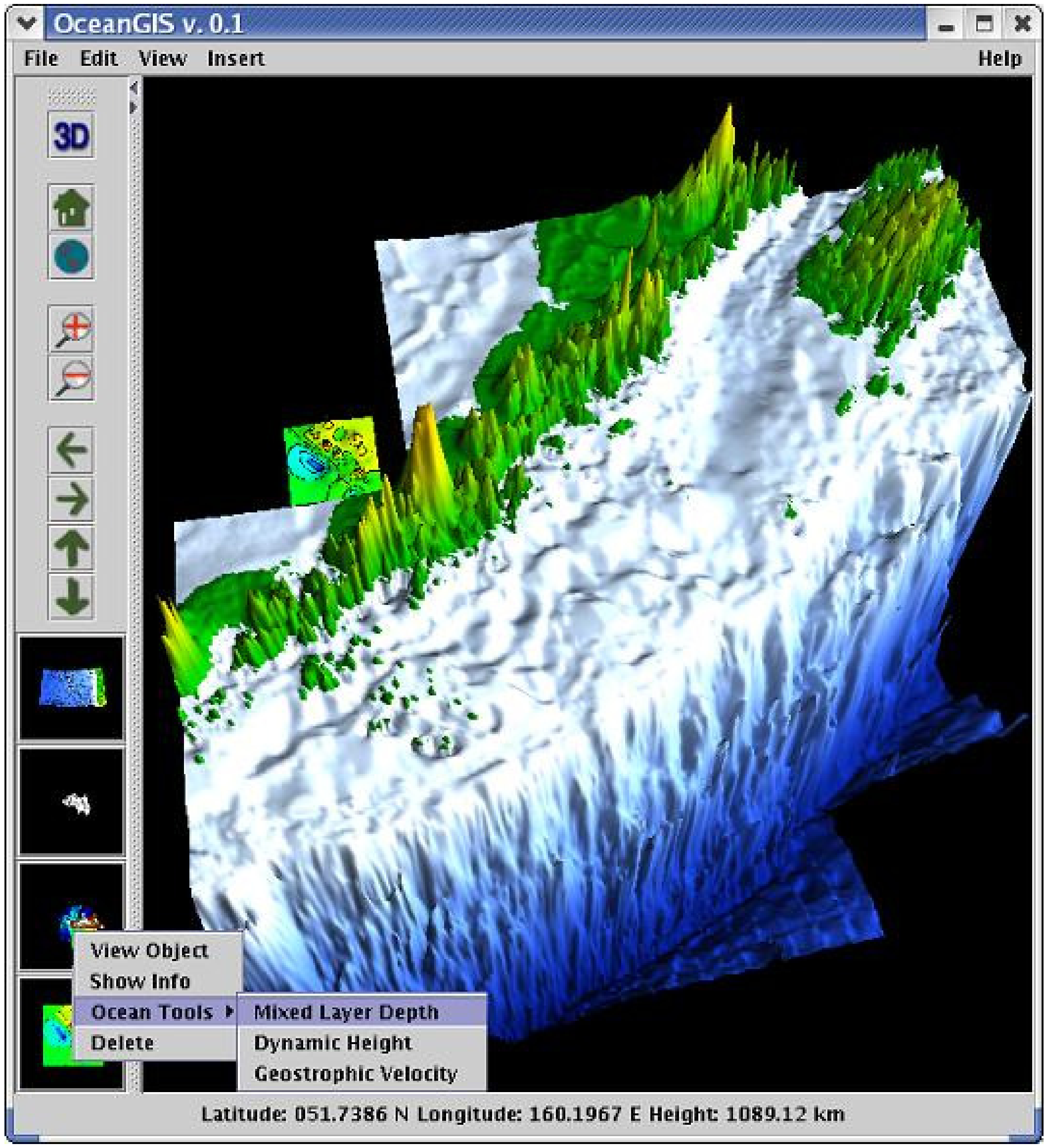

Figure 14 GeoModeler screen shot showing tools for analyzing conductivity-temperature-depth data from the Bering Sea, Alaska. Tools include calculation of mixed layer depth and other oceanographic variables.

read directly from an OPeNDAP server by the Java code in GeoModeler. Data can also be read from shapefiles and directly from netCDF files. GeoModeler has met the challenge of making analytical calculations on three-dimensional data. It can read in standard data formats and can integrate multiple formats in a single display. Open-source and proprietary tools have been used for data ingestion. As these types of data are typical of model outputs, GeoModeler has made it easier to see and understand these types of complicated and extensive datasets. Further work is needed to integrate algorithms for three-dimensional interpolation and to expand the types of calculations that can be made, e.g. depth integrated temperature. Other needed enhancements are the inclusion of a variety of surface interpolators.

Setting up the parameters for complicated ocean models

While models are powerful tools, they are also hard to set up and run. Changing parameters and rerunning a model can be a tedious and non-intuitive process. For a new user of a model, the process is especially daunting and can be a barrier to non-modelers using models. A graphical interface for setting parameters and displaying results can make using a model much easier. The Visualization Toolkit (VTK) provides a way to create a visual interface. The initial implementation of GeoModeler creates a VTK interface to the Regional Ocean Modeling System (ROMS) (http://ourocean.jpl.nasa.gov). ROMS is a widely used ocean circulation model. It is a free-surface, terrain-following, primitive equations ocean model that includes accurate and efficient physical and numerical algorithms. It has been expanded for a diverse range of applications (e.g. Haidvogel et al., 2000) and adapted to several coupled models for biogeochemical, bio-optical, sediment, and sea ice applications.

The test application, written in Java, uses an interface that allows the user to modify any of the C-preprocessor directives that ROMS uses in its build-script to enable various physical and numerical options (Figure 15). The initialization file can also be

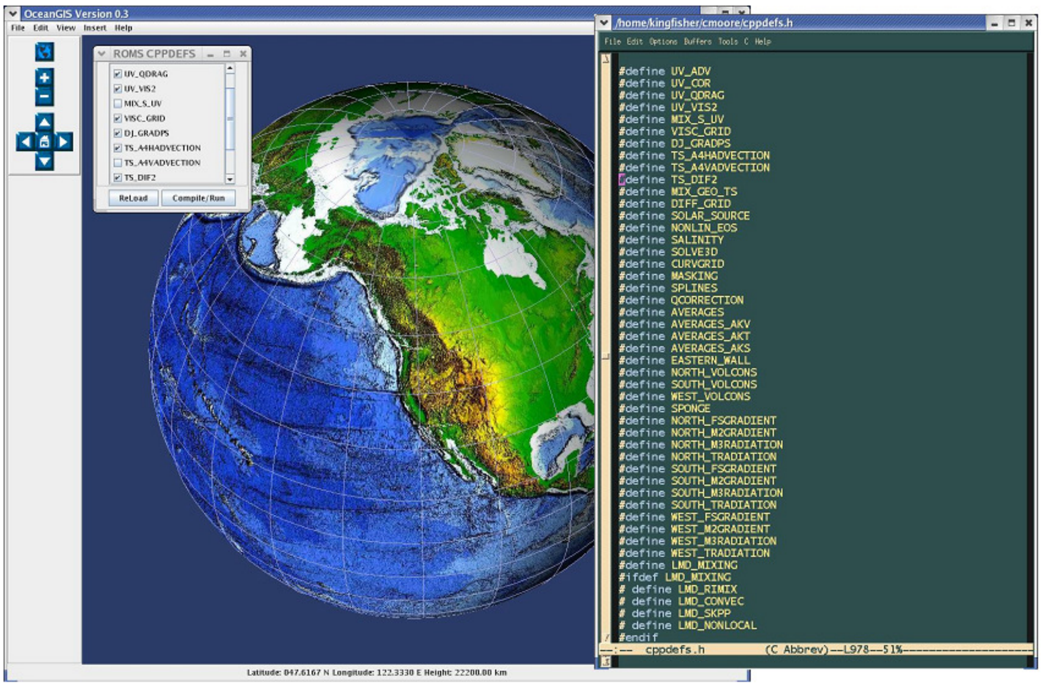

Figure 15 GeoModeler interface to set up preprocessor directives for running the ROMS model.

modified to reflect changes in timestep, tiling, and initial conditions. The model is configured, compiled and launched through the GeoModeler interface, and model results are output to an OPeNDAP ((Open-source Project for a Network Data Access Protocol) (www.opendap.org) server directory, allowing either viewing in GeoModeler or sharing results with remote colleagues.

The GeoModeler ROMS Data Reader is a GUI class that reads netCDF output of ROMS model data, and allows 3-D renderings to be created and animated in a georeferenced framework. Since GeoModeler utilizes the GeoTools (www.geotools.org) library, shapefiles of data using standard projections can be rendered simultaneously (as opposed to simply overlaying). ROMS model output is then loaded through the ROMS Data Reader, and the user selects the variable of interest, contour levels, color maps, etc. and can animate the resulting rendering (Figure 16).

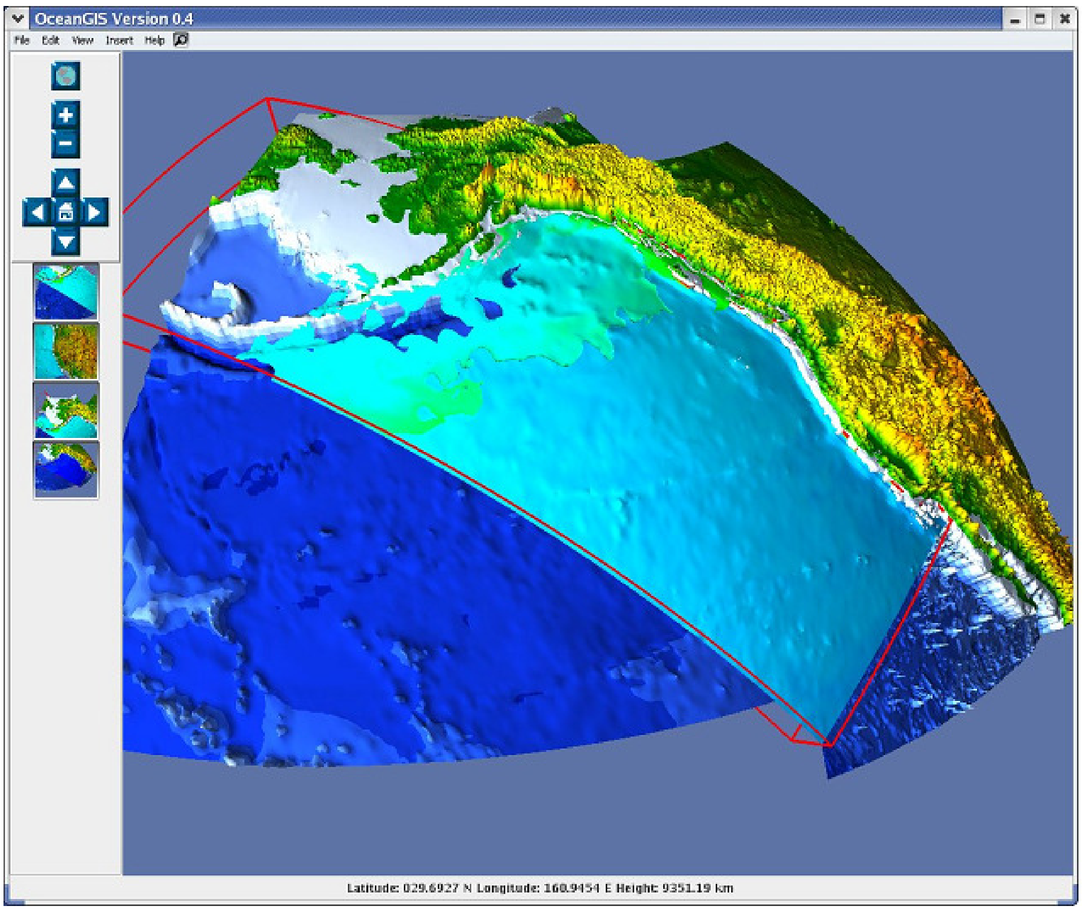

Figure 16 ROMS model output for salinity in the North Pacific. Red lines show extent of the three-dimensional model domain.

Ocean circulation models are not the only type of model used in marine research. Models of the propagation and height of runup of tsunamis are used both by researchers and by emergency managers. As with the ROMS model, integrating a graphical, GIS-based interface with the model makes use of the model easier.

A second test model for GeoModeler is the implementation of an interface to launch tsunami models and allow the integration of results into a GIS framework. The initial results for this implementation are shown in Figure 17. The model output

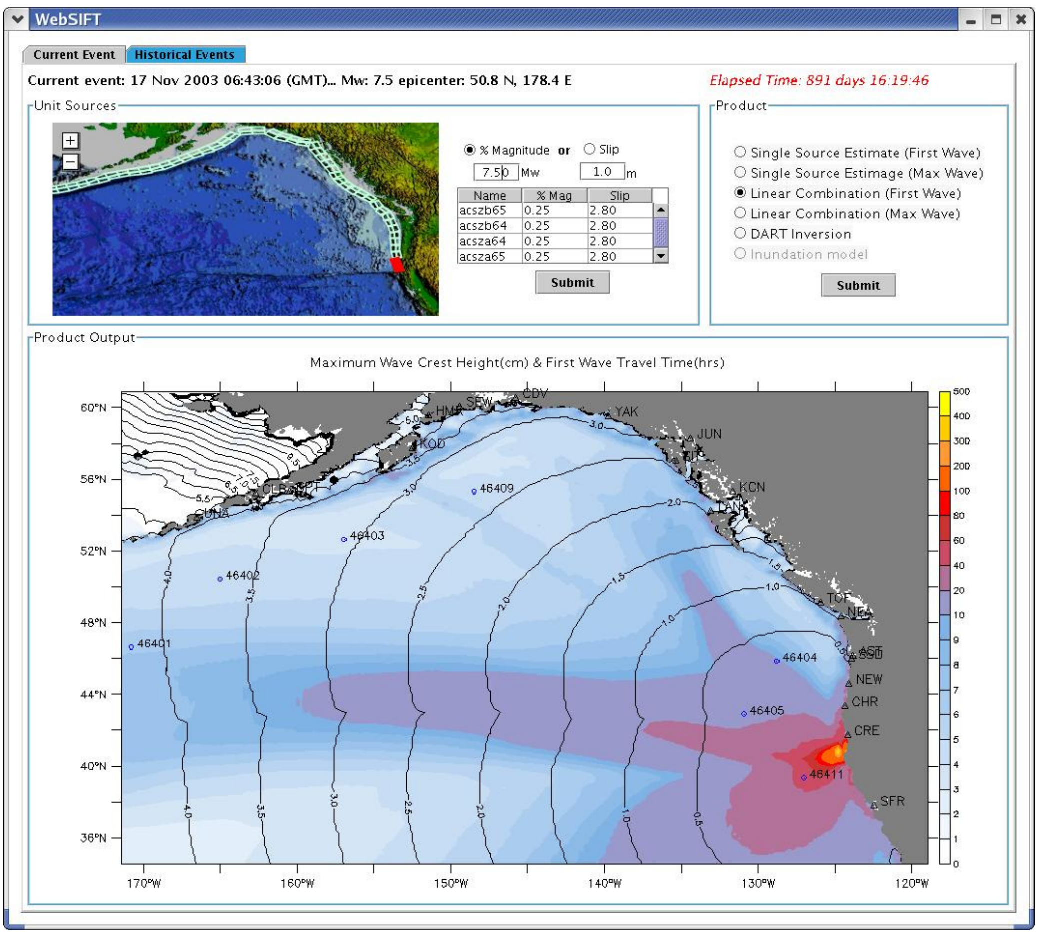

Figure 17 Output from the MOST tsunami propagation model

renderer/animator reads results of the Method of Splitting Tsunami (MOST) model, and surface height is rendered at each of 1440 timesteps. This model run includes “runup”, or the adjusting of the model boundary condition to simulate inundation (Titov and Gonzalez, 1997). Rendering this surface over high-resolution topography, overlaid with an aerial photograph produces a fairly realistic view of the event. A complete description of this event can be found in Titov and Synolakis (1997).

The MOST model parameters include a series of uniform-sized seismic faults, called “unit sources”, shown in Figure 18. The user loads a shapefile of seismic fault data, shown as yellow rectangles, along the coastal trenches. These sources are initially set using an interface that allows the user to set the magnitude for each source, as well as the vertical distance the fault moves (the slip). An initial condition for running the inundation model is built up from a linear combination of model runs for each unit source. This initial condition is passed to the inundation model, with default parameters pre-set to give a rapid estimate of inundation in time for emergency managers to view results well before the approaching wave strikes populated areas.

GeoModeler has shown that it is possible to use a GIS-based interface to set up model parameters. The resulting application has used VTK and Java3D to create a powerful tool for visualizing model output. Future work includes getting all the parameters for MOST model runs into the interface so the GeoModeler tool can be used

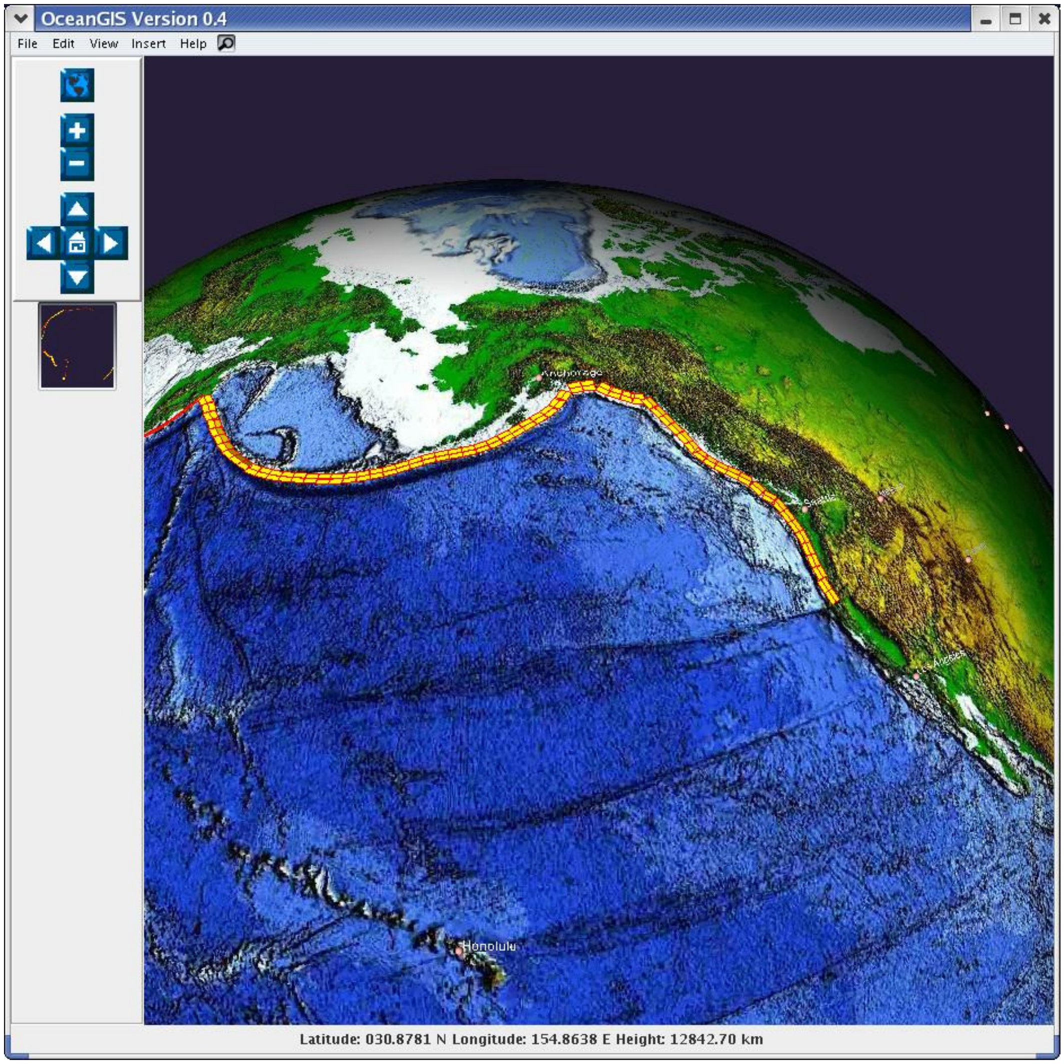

Figure 18 Source regions for earthquakes used in the MOST model calculations

for research. GeoModeler will also be used as an interface to other ROMS models and will also be used to display particle tracking models tied to ROMS and other ocean circulation models. Linking models directly with a GIS has improved the ability of modelers to visualize their results and the ability of non-modelers to use these types of models.

Combining the output of model runs with socio-economic data

For model output to be fully useful for emergency managers, it needs to be integrated with related socio-economic and infrastructure data. These types of data are easily available in GIS formats. The GeoModeler framework has proven useful for tsunami modeling, in both the propagation phase and the inundation phase. The MOST model described above is an example of a model of the propagation phase, demonstrating that we can deliver estimates to emergency managers rapidly. However, emergency managers still require tools integrating critical infrastructure, evacuation routings and at risk populations and hazards for decision support system applications. A prototype application was developed using ArcEngine to integrate inundation model output scenarios with critical GIS layers. It is a way of visualizing results and performing common analysis functions that can be found in a GIS, but are difficult to run in standard modeling software packages.

The Tsunami GIS application allows users to create inundation scenarios for pre-calculated near-shore and off-shore sources for a tsunami event in a selected region. The final product is a map of inundated areas and estimates of the affected population in the inundation zone. The tsunami height modeling application shown in Figure 19 is an example of modeling the inundation phase for the city of Seaside, Oregon.

The ArcObjects development environment lets us build a stand-alone GIS application that has the look and feel of a standard ArcGIS desktop, but with tsunami-specific menus added to the standard ArcGIS functionality and editing capabilities. The geoprocessing API operates in the back-end to merge the gridded inundation result with the census information for the area of study to create a new polygon of affected

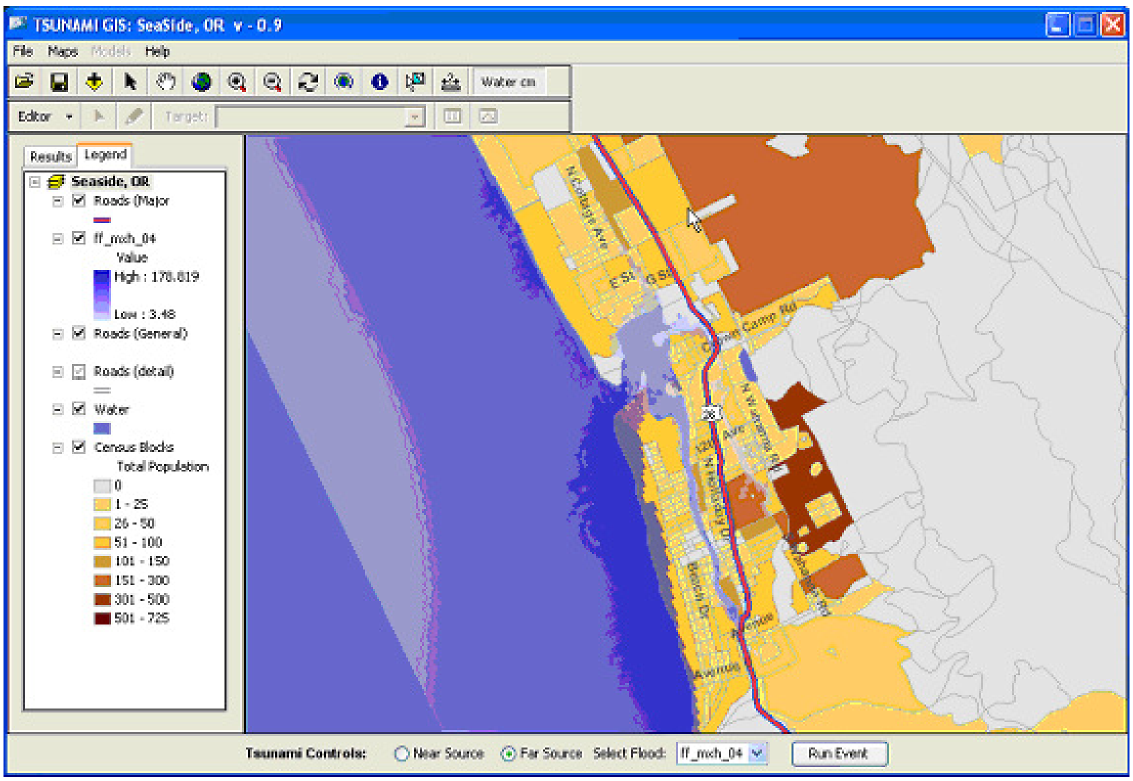

Figure 19 Tsunami GIS application showing a near-shore source inundating Seaside, Oregon. Affected areas are highlighted by census block.

areas. Census data are used to calculate estimates of populations at risk including the elderly or handicapped. Critical infrastructure – hospitals, schools, bridges and emergency centers within the inundation zone can be highlighted and standard geoprocessing functions such proximity analysis can be run to determine mitigation strategies. Users are able to print maps and reports and export map images to be used in operation manuals and reports.

ArcEngine's framework allows users to add their own data sets (e.g. inundation grids; evacuation routes; infrastructure) as well as links to live data feeds and servers to add current and derived data products on the fly. The ability to customize the application using the ArcObjects modules will allow developers to implement additional models and algorithms as they are developed. These will include adding elevation data and distance from the shoreline to the calculation of populations at risk.

GeoModeler has made it easier to combine the results of models with related socio-economic data to support emergency managers. Use of the ArcObjects exposed through ArcEngine has added GIS analysis functions such as buffering and merging of data layers. Further work is needed to implement other types of GIS analyses. Linking models with socio-economic considerations provides a tool to plan for impacts and mitigation during emergencies. The ability to run the tool and change parameters such as the height of the tsunami supports scenario testing.

Visualizations and analyses of the intersection of planes and paths with three- and four-dimensional data

With the inherent three-dimensional nature of oceanographic or atmospheric model data, GIS spatial analysis tools fall short. Simple calculations such as buffering have a natural extension in three dimensions, and calculating volumes enclosed by isosurfaces and fluxes of properties through an area is common for the geo-scientist. There is a pressing need to extend the standard statistical and spatial analysis tools to three dimensions. The Visualization Toolkit (VTK) has some functionality for determining whether a point in three-space falls inside or outside a closed region, and its data representation allowing for rapid topology traversal makes these calculations efficient. We are extending this functionality to include calculating the intersection of a line and a volume, a plane and a volume, as well as the intersection of two volumes. Figure 20 shows the intersection of the path followed by a diving marine mammal with a volume defined by the sea surface and a mixed-layer depth surface as described above. The illustration shows the technique simply as an example, but applications of this technology to marine mammal studies include determining the sensitivity of foraging depth to water temperature and the response of animals to physical and biological oceanographic parameters.

Allowing GIS applications to spatially analyze enclosed volumes is of particular importance in the field of marine hydrothermal vent studies. Hydrothermal vent effluent forms a buoyant plume with a sub-surface maximum chemical concentration that rises from the vent caldera. Isosurfaces of this neutrally buoyant plume then form completely enclosed volumes that can be probed by intersecting this volume with a plane and contouring concentration at the intersection (Figure 21). User interaction allows the plane to be rotated and translated about all 3 spatial axes, with intersection

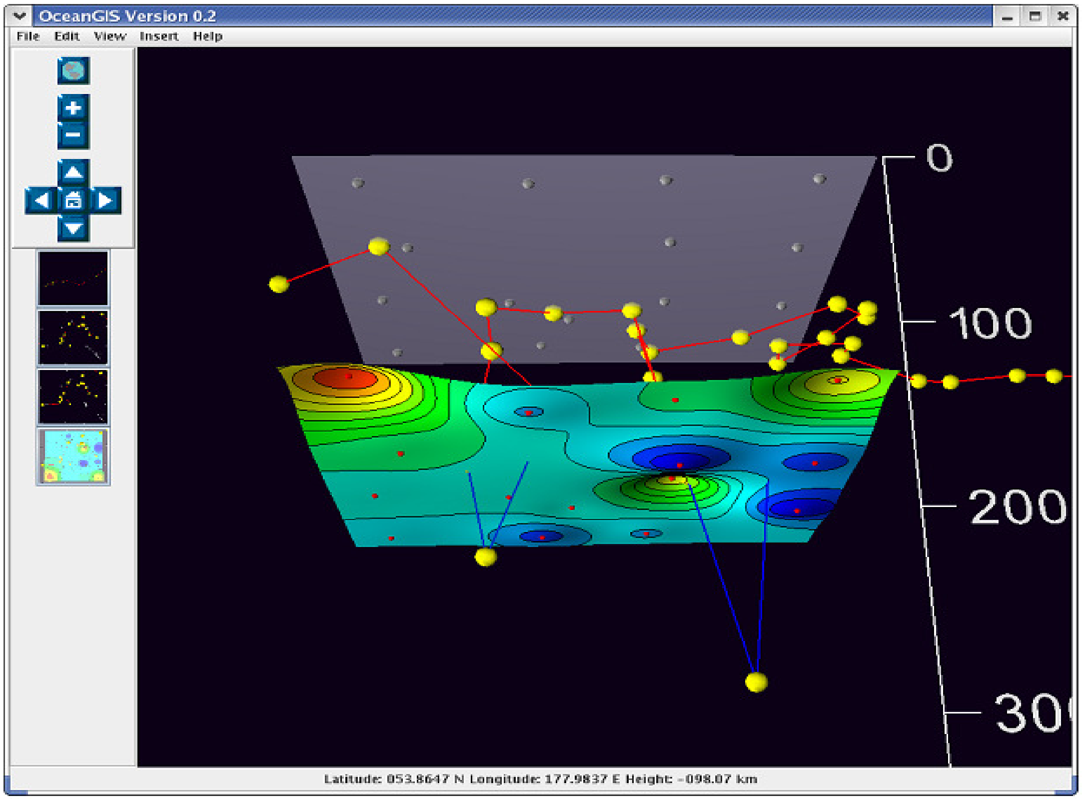

Figure 20 Path of a hypothetical marine mammal through the water and intersection with an isosurface of the mixed layer depth.

contours updating in real time. This probing technique can be quite powerful, and can be accomplished as the vent plume evolves in time, providing both an animation of the isosurface, as well as an animation of the probed concentration.

GeoModeler has met the challenge of visualizing arbitrary slices through three-dimensional data through the use of VTK functions. Tools for calculating the intersection of a path in three-dimensions with a volume and volume on volume intersections are being created. Linking models directly with a GIS has improved the ability of a scientist to visually interrogate model results and to create animations to

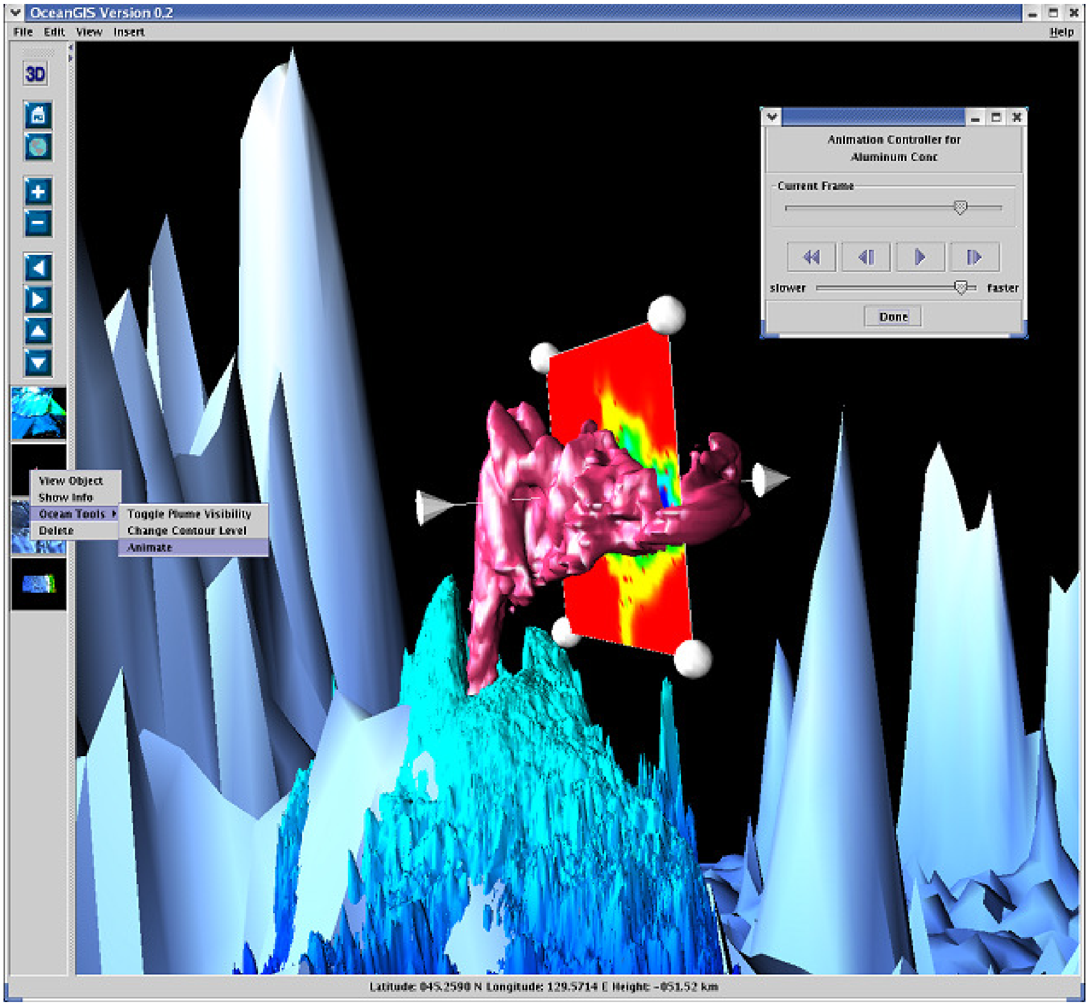

Figure 21 Hydrothermal vent plume isosurface (red) Data are a three-dimensional grid of particle densities for hydrothermal vent effluent.

highlight temporal features in the output form a model. All of these tools have made it easier to comprehend and explain the complicated spatio-temporal features seen in both data collected by instruments and data created by models.

Conclusions

GeoModeler provides a fully functional prototype of closely linking scientific models and a GIS. GeoModeler provides more than simple coupling tools to these models. It provides analytical tools specifically adapted to the type of model, and type of model output, being analysed. Future improvements to GeoModeler will integrate model outputs by storing them in a database within the GIS. With this integration, the models will become simply another analysis tool available within GeoModeler. At the same time, the analytical functions available will be expanded and enhanced. While our current emphasis is on spatial analysis tools, future developments may include temporal analyses.

The features of GeoModeler have been applied to a variety of models. The ease with which these test models have been implemented suggests that the integration of further models should be straightforward. The ease with which modelers have been able to use new GIS-based functionality has made them more open to implementing GeoModeler. The enhanced visualization capabilities and the ability to easily include other datasets such as GIS-based socioeconomic data will enhance the results of the existing scientific models.

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Chapter 7: Is there a there? Analysis and volumetric visualization of environmental factors affecting otolith daily increments in *Theragra chalcogramma*

Abstract

Presentation of data for fisheries, and many other disciplines, tends to reduce the data to the simplest dimension that will still convey a message. With the development of sophisticated multi-dimensional visualization and analysis tools, this simplification may no longer be necessary. This paper explores the ways in which the biological data, and contemporaneous physical oceanographic data, can be visualized to support exploration of the environmental factors that could affect the observed strength and clarity of daily otolith increments. Anecdotal evidence suggests that daily increments seen in otoliths of *Theragra chalcogramma* collected in Shelikof Strait, Alaska have shown a qualitative decrease in the clarity of the individual increments over the past 10 years. An investigation of the temperature patterns in the environment of these larvae provides information on the temperature history of the larvae. These patterns are visualized using a variety of techniques from geographic information systems (GIS) and scientific visualization applications. The aim of creating the visualization techniques is to provide qualitative explorations of the data while the GIS tools provide quantitative analyses of the data. Both provide ways to understand the complex four-dimensional environment experiences by the larvae.

Introduction

Presentation of data for fisheries, and many other disciplines, tends to reduce the data to the simplest dimension that will still convey a message. The results of a plankton net tow through the water column are presented as a single depth integrated value assigned to an arbitrary point on the path of the net. Water temperatures collected at a grid of stations are presented as a two-dimensional surface either vertically along a transect or as a horizontal surface at an arbitrary depth thought to have biological importance. However, as techniques for visualization become more easily applied, it has become possible to present the data in displays that are closer to the original dimensionality of the data collection. The path of a towed net can be calculated from navigational data and portrayed as a path rather than as a point. Temperature data can be presented as a three-dimensional grid of data displayed with bathymetry and other ancillary data.

This paper explores the ways in which the biological data, and contemporaneous physical oceanographic data, can be visualized to support exploration of the environmental factors that could affect the observed strength and clarity of daily otolith increments. Analysis of the daily increments seen in otoliths of *Theragra chalcogramma* collected in Shelikof Strait, Alaska have shown anecdotal evidence of a qualitative decrease in the clarity of the individual increments over the past 10 years (Dougherty, pers. comm.). One hypothesis to explain this is that the fish are experiencing less variability in temperature during their early weeks. Laboratory research has shown that larvae grown at uniform temperatures show less distinct daily otolith increments than those grown under varying temperatures (Neilsen and Geen, 1985). An investigation of the temperature patterns in the environment of these larvae provides information on the temperature history of the larvae. These visualizations help us determine whether the decrease in increment intensity observed in the Shelikof Strait pollock larvae reflects differences in the variability of water temperatures experienced by the larvae. Given an assumed path for the larvae from hatching to the end of their first summer, the temperature data can be combined with the results of circulation models for the region to create a full temperature history for the larvae.

During sampling on cruises, temperature data are collected at the same time that the larvae are collected. Data are collected using a SeaCat temperature sensor mounted just above the bongo net used to collect the larvae. This temperature dataset provides a unique three-dimensional snapshot of the temperatures of the water column coincident with biological samples taken over a standard sampling grid. The temperature data are analyzed for changes in the overall temperature structure and the variability within the structure using a multi-dimensional geographic information system (GIS) and integrated analysis and visualization tools. Specific challenges include displaying and visualizing three-dimensional data, making analytical calculations upon these data and visualizing the results, defining subsets of the dataset for further analysis, integrating the visualization of the physical data with that of the biological data, and providing meaningful summary plots and statistics for the data. The purpose of the project is to see if using and GIS and visualizations: a) provides a better qualitative understanding of the environmental conditions, b) makes it possible to detect subtle interannual differences in the temperature patterns, c) provides tools to calculate useful statistical measures on the data and d) makes apparent new analysis or visualization tools that are needed to support this kind of research.

Scientific background

Walleye pollock, *Theragra chalcogramma*, became the focus of a large commercial fishery in Alaska in the 1970's and 1980's. For the pollock fishery to be successfully and sustainably managed, it is necessary to predict the strength of year classes to be able to set appropriate fishing quotas. The strength of the year class is set early in the life history of the species. While the early life history of this population is predictable in its timing, location, and mechanics, there is considerable inter-annual variation in recruitment to the fishery. This is the result of variability in the biological and physical environment experienced by young pollock. The Fisheries Oceanography Combined Investigations (FOCI) program of NOAA was created, in part, to understand the recruitment processes of the pollock population in the Gulf of Alaska, and more specifically in Shelikof Strait. The results provide input to management decisions. The program started in 1984 and repeat sampling of grids of stations continues to this day. While not as long a time series as the CalCOFI program, the FOCI data still provide a long time series of environmental and biological data in an environment that is undergoing major changes.

The early life history of pollock starts with the return migration of spawning adults from the Pacific to the southern entrance of Shelikof Strait (Figure 22). The adults spawn in late March and early April in a small part of the Strait, producing a large patch of eggs. Spawning occurs at depths of 150 - 250 m. The free floating eggs hatch while at depth and rise to the upper 50 m of the water column soon after hatching. The patch of larvae then drifts to the southwest in prevailing currents during late April and May. The path of the drift bifurcates near Sutwick Island and the Semidi Islands, with one fork staying close to the Alaska Peninsula in slowly moving coastal waters and the other path taking the larvae out into the faster moving Alaska Coastal Current (ACC). The larvae in the ACC are either carried offshore into the Gulf of Alaska or return onshore west of Chirikof Island.

While the larvae are in a patch they stay below the turbulence of the mixed layer and migrate vertically on a daily basis between 15 and 50 m depth. They are deepest during the day and shallowest in the evening. The growth and survival of pollock larvae are affected by variations in prey production and distribution. Water temperature, currents, food availability, and predation affect prey availability. The larvae are also affected by the weather; with larvae that reach their first feeding stage during calm weather having a higher survival than those reaching the stage during stormy weather. A number of environmental factors can affect the intensity and width of the daily increments. The differences are pronounced enough that manipulating the environment

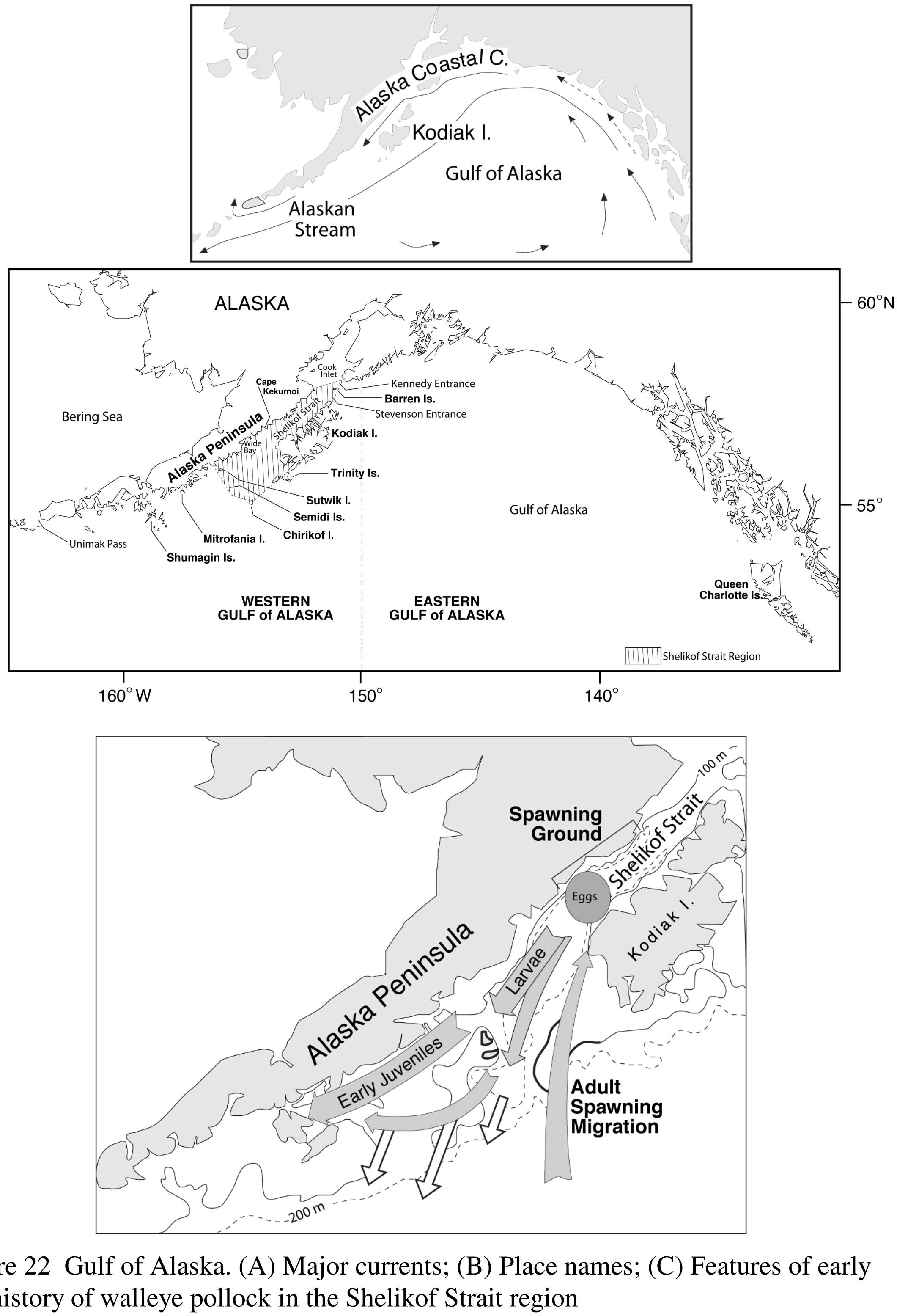

Figure 22 Gulf of Alaska. (A) Major currents; (B) Place names; (C) Features of early life history of walleye pollock in the Shelikof Strait region

of hatchery raised fish can be used as a way to tag them for later identification after they are released to the wild. Daily increments on otoliths have been used to determine larval growth rates and hatch dates. These rates and dates can be used to calculate mortality rates (Yoklavich and Bailey, 1990) and to study the effect of environmental factors on larval survival. Bailey and Macklin (1994) report that larvae reaching first feeding stage during calm weather, as determined by comparing meteorological records with hatch date information, have a higher survival rate than those who reached that stage during a storm. The elements deposited in the otoliths have been used as a record of the environment experienced by the larvae and as a technique to determine the geographic origin of the larvae (Fitzgerald et al., 2004).

Methods

Since 1985, cruises have repeatedly occupied a grid of stations from Shelikof Strait to the Shumagin Islands (Figure 23). The stations are spaced 10 km apart and are sampled to the shallower of 10 m off the bottom or 100 m depth. The stations are sampled once a year in May to gather information on the distribution and size of larval pollock. A bongo net is towed at each station (Stabeno et al. 1996) and a SEABIRD SeaCat SBE 16 temperature and conductivity sensor is deployed just above the net. The SeaCat data provide concurrent environmental data to accompany the samples gathered in the bongo net. Conductivity-temperature-depth (CTD) casts are conducted a number of times during a cruise as a check of the accuracy and calibration of the SeaCat.

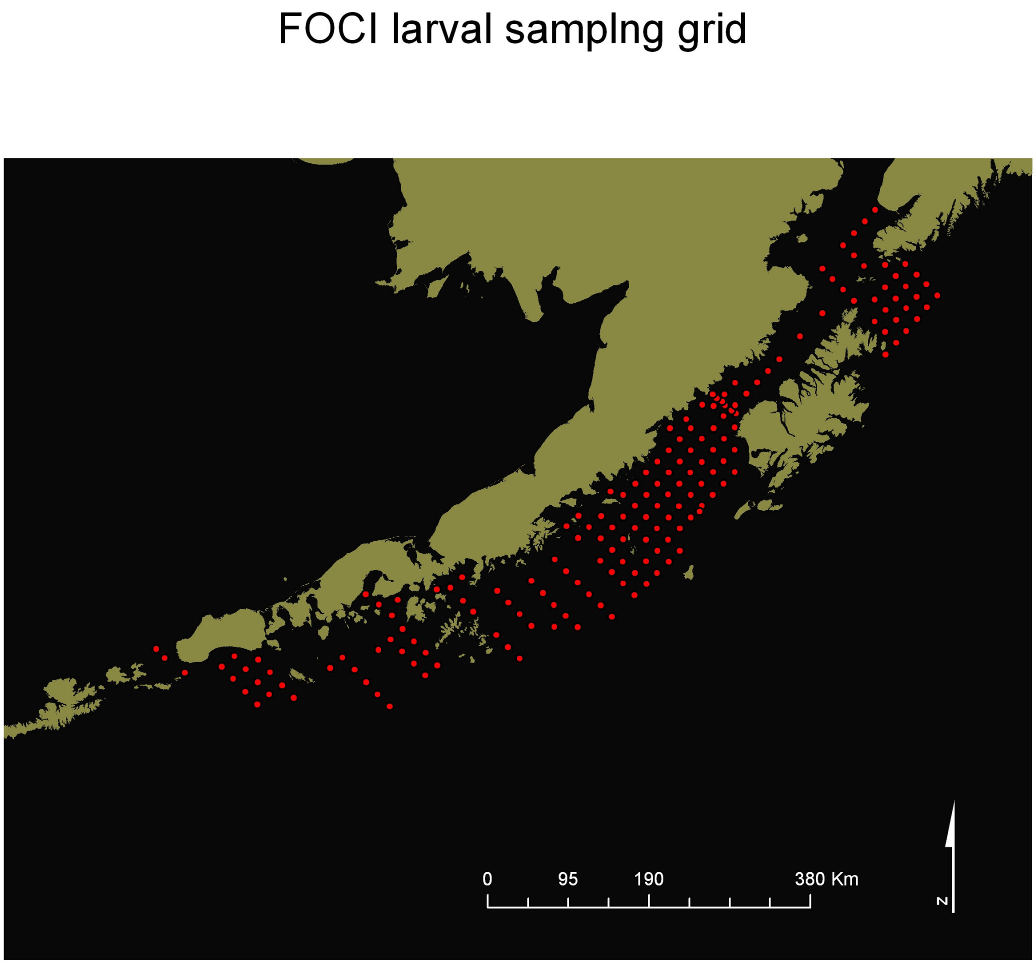

Figure 23 Stations for the FOCI larval sampling grid.

The data from the upcast are recorded, filtered, binned to 1-m bins and stored in files along with header data about the weather conditions at the time the cast was conducted. At a number of stations, conductivity-temperature-depth (CTD) casts were taken using a SeaBird 911-Plus sensor. These are used as a check the calibration of the SeaCat sensors. Since our goal is to look at macroscopic trends in temperature data, rather than using the data for mass-balance calculations, we feel the SeaCat data provide the level of accuracy needed. For a more complete discussion of SeaCat accuracy and

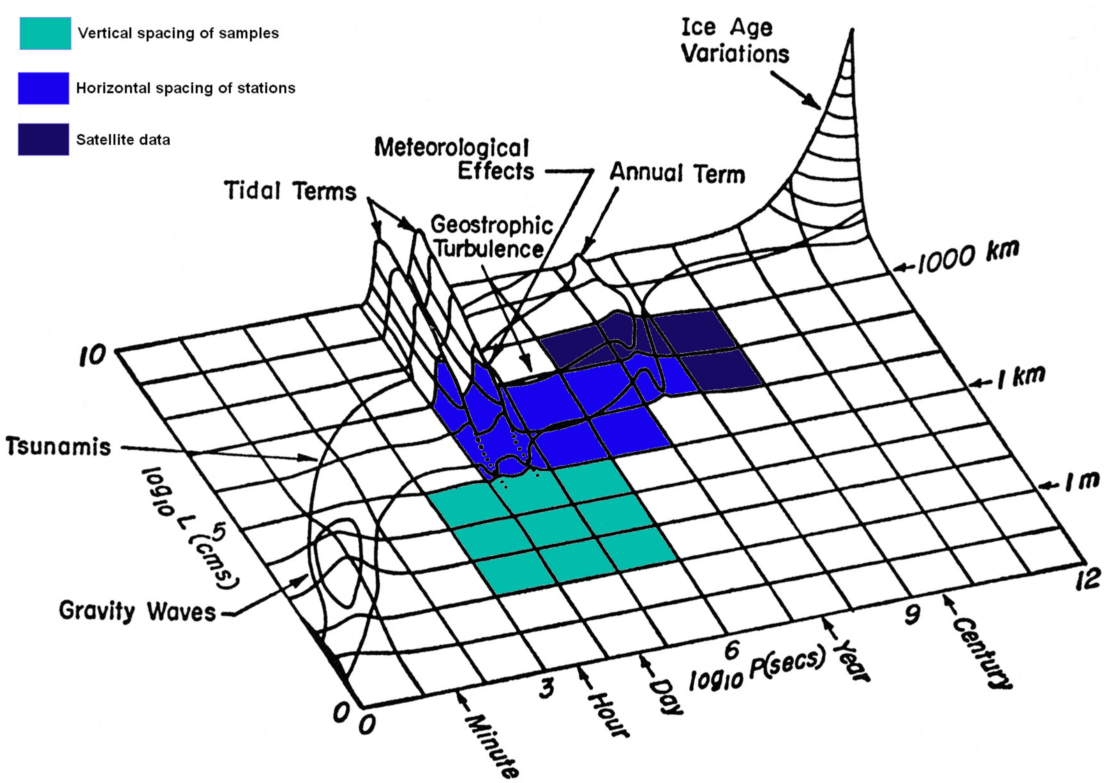

Figure 24 Stommel diagram showing the time and space scales of the data collection in studies of larval pollock and the associated oceanographic phenomena. CTD casts sample at a 1m vertical spacing. Stations are spaced 10 km apart and the entire sampling grid is 100km x 500km

measurements see Freitag et al. (1999). Data were processed for cruises in 1999 - 2001 and 2005 - 2007. While the specific cruise dates varied between years, the cruises used are from a time series of late larval cruises that have been conducted since 1984. The cruise is timed to sample the larvae once they have migrated to the surface waters and started feeding. For the purposes of this work, the stations occupied during a cruise are assumed to provide a quasi-synoptic view of the temperature conditions over the sampling grid. While it takes about 10 days to sample the entire grid, we are assuming that the features affecting the daily increments are fairly long-lasting and are not of such a short time scale that they would be missed in this sampling regime. Figure 24 shows a Stommel diagram of the time and space scales of the various sampling methods used and the associated phenomena that can be detected with these sampling regimes.

For analysis and display, an awk program is used to reformat the data and the files are read into GeoModeler (Vance et al., 2007), Java Ocean Atlas [http://odf.ucsd.edu/joa/jsindex.html] and ESRI's ArcGIS for analysis and display. GeoModeler is used for calculations of mixed-layer depth and for visualizations in three-dimensions. Java Ocean Atlas is used for other oceanographic calculations and for the creation of vertical section plots of the data. ArcGIS is used for the calculation of horizontal sections, for the calculation of two-dimensional statistical measures and for additional visualizations in 2.5- and three-dimensions. Three-dimensional visualizations are used as a way to check for outliers, to gain a general feel for the large-scale patterns within a year and for visual comparison of these patterns between years. Unfortunately, we have not been able to locate analytical tools that would allow us to calculate statistical measures in three-dimensions of the spatial patterns in the data or how the scales of these patterns change between years. Of necessity, we have used two-dimensional slices, both vertical and horizontal, to look more closely at these patterns. Simple statistical measures, the mean and standard deviation of the temperatures at each station and the mean and standard deviation over the whole grid, have been used for intra-annual and inter-annual comparisons. Plots for 2000 and 2006 are shown in this paper. These were chosen as typical years for the date range studied. 1999 and 2007 are anomalously cold years and bear more resemblance to each other than to the rest of the years studied.

Results

Qualitative exploration of temperature data

Making a qualitative exploration of the temperature data collected by the SeaCat allows scientists to gain a general understanding of the temperature data, to make a visual comparison of the data in various years, and to do a final quality check on the data. Differences in overall temperatures and in the three-dimensional patterns in the temperature can be seen. To do this, it is necessary to display the data in a three-dimensional view, to code the data points by the temperature or salinity measures at the point, to add bathymetry and topography to place the data in context, and to be able to rotate the view to see the data from all sides.

To create this visualization (Figure 25) the temperature data were loaded into

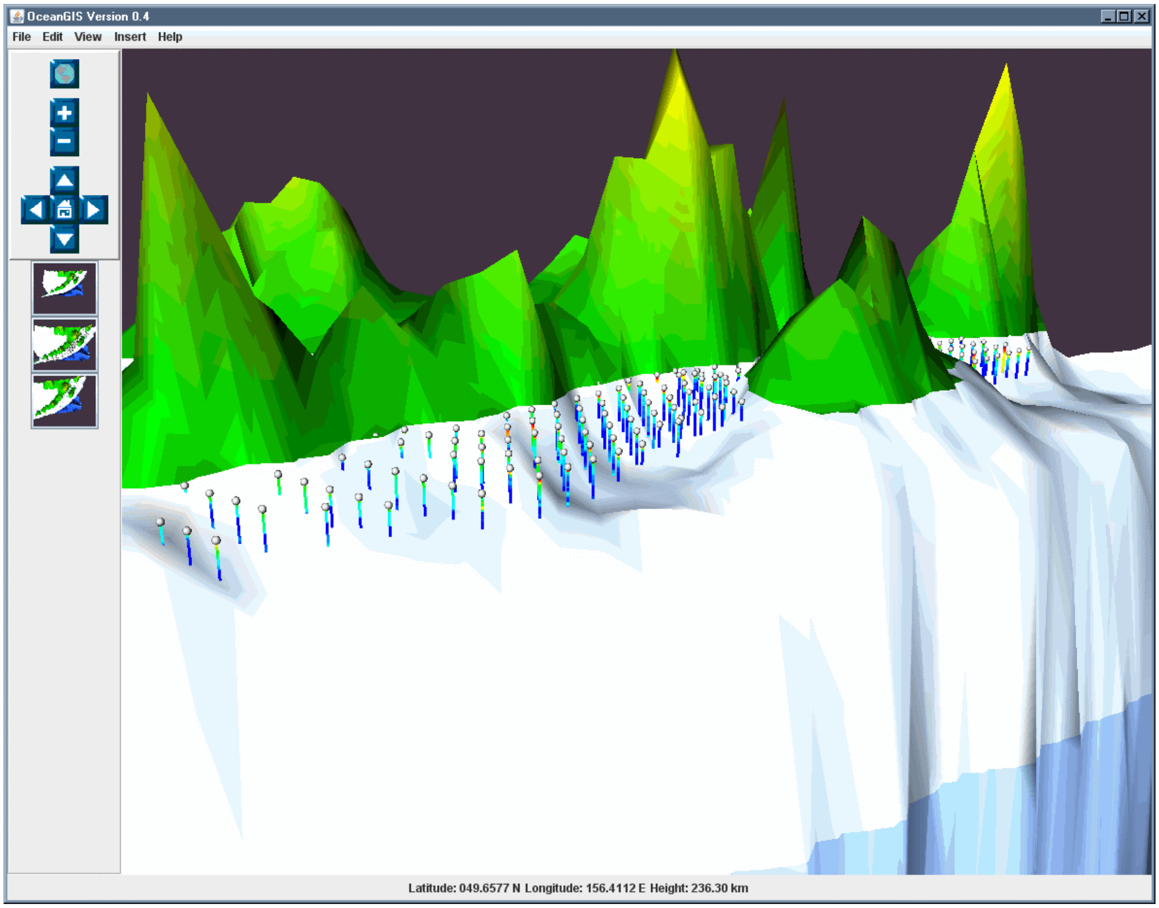

Figure 25 GeoModeler temperature profiles for 2006. View looking to the northeast between the Alaska Peninsula and Kodiak Island. Temperature data show as vertical columns with darker blues indicating cooler temperatures, lighter blues and yellows indicating warmer temperatures. Temperatures range from 3.4 to 10.4 °C. View is from the southeast looking towards the Alaska Peninsula. Topography is shown in shades of green while bathymetry is represented in shades of white and blue. Vertical exaggeration is 200x

shapefiles, read into GeoModeler, and the points were coded by temperature. The salinity data can also be viewed in a similar manner. The size of the sphere marking the location of the new tow can be changed and the vertical exaggeration of the entire scene can be adjusted. Bathymetric data from the ETOPO5 dataset was added for context. The view can be rotated on the screen using the typical mouse button actions found in tools such as GoogleEarth and ESRI's ArcScene. A screenshot can be created and printed for reference and to share with colleagues.

Determining the characteristics of the environment occupied by the larvae

While temperature data are collected from the surface to the shallower of either 10 m off of the bottom or a depth of 100 m, the larvae do not occupy this whole volume. There are a number of descriptions of the vertical environment of the larvae in the literature. Kendall et al. (1994) describe the larvae as staying below the turbulence of just below surface and above or within a thermocline if such a feature it present. They observed a measured mean depth of feeding larvae of 40 m. Brodeur and Wilson (1996) say the larvae migrate between 15 and 50 m depth in late May and stay in water temperatures of 5 to 8°C. The construction of a mean temperature profile from a collection of stations is a common technique to identify the depth profile of temperatures in a study region. The danger of this technique is the fact that significant spatial patterns can be lost in the averaging process. Ideally, it would be possible to calculate the mixed layer depth or the thermocline depth over the entire area and to create plots of all of the depth-temperature profiles. In this way, it is possible to define a temperature environment for the larvae at a specific place and time.

Scientists can create a number of analyses and visualizations to show the volumetric extent of the larval environment. Once the data are loaded into ArcGIS, the attribute selection tools can be used to create data subsets over a depth range, e.g., 15 to 40 m, or over a temperature range, e.g. 5 to 8°C. From this subset of the data, one can calculate statistics such as the mean and standard deviation of the temperature for each cast, and the overall mean and standard deviation of the temperature in the volume. These statistics can be displayed as a two-dimensional map of the mean temperature and standard deviation (Figure 26). The maps of the standard deviation show similar patterns of low variance for all of the years. However, without a calculation of the depth of the thermocline, it is impossible to determine whether these statistical measures might be describing the distribution of temperatures above and below the thermocline. For this reason, very different temperature profiles might produce similar values of the mean and standard deviation.

Two tools are used to calculate the mixed-layer depth - GeoModeler, and Java Ocean Atlas paired with ArcGIS. GeoModeler is much easier to use for the calculation but the surface interpolation tools in GeoModeler are not as flexible as those in ArcGIS. GeoModeler adds the mixed layer depth as a point on the visualization of the cast (Figure 27). Java Ocean Atlas can calculate the mixed layer depth using a number of algorithms for salinity and temperature profiles and outputs the calculations to a database file. The file can then be joined with the spatial information stored in ArcGIS

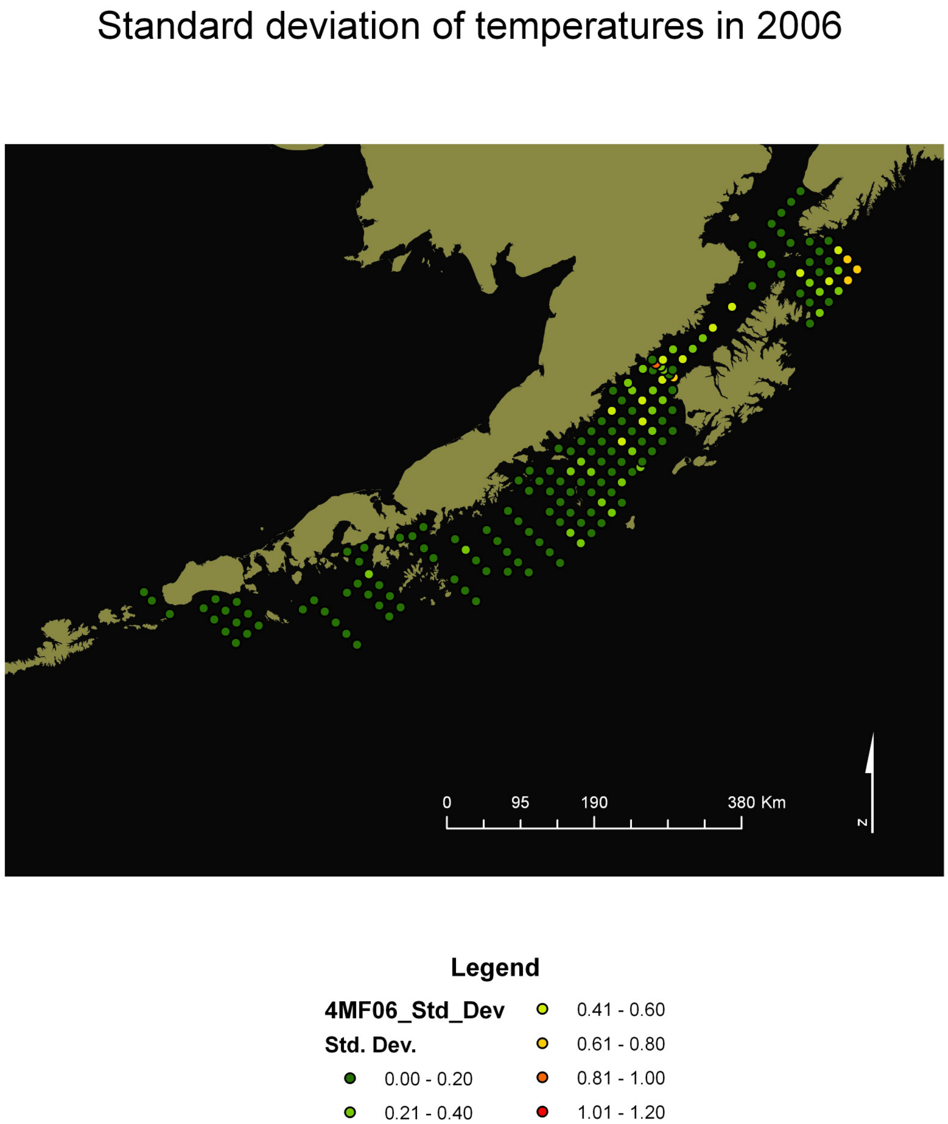

Figure 26 Standard deviation of temperature for each cast taken in 2006. The range of the legend is scaled for all years studied to highlight the small range of variation in 2006

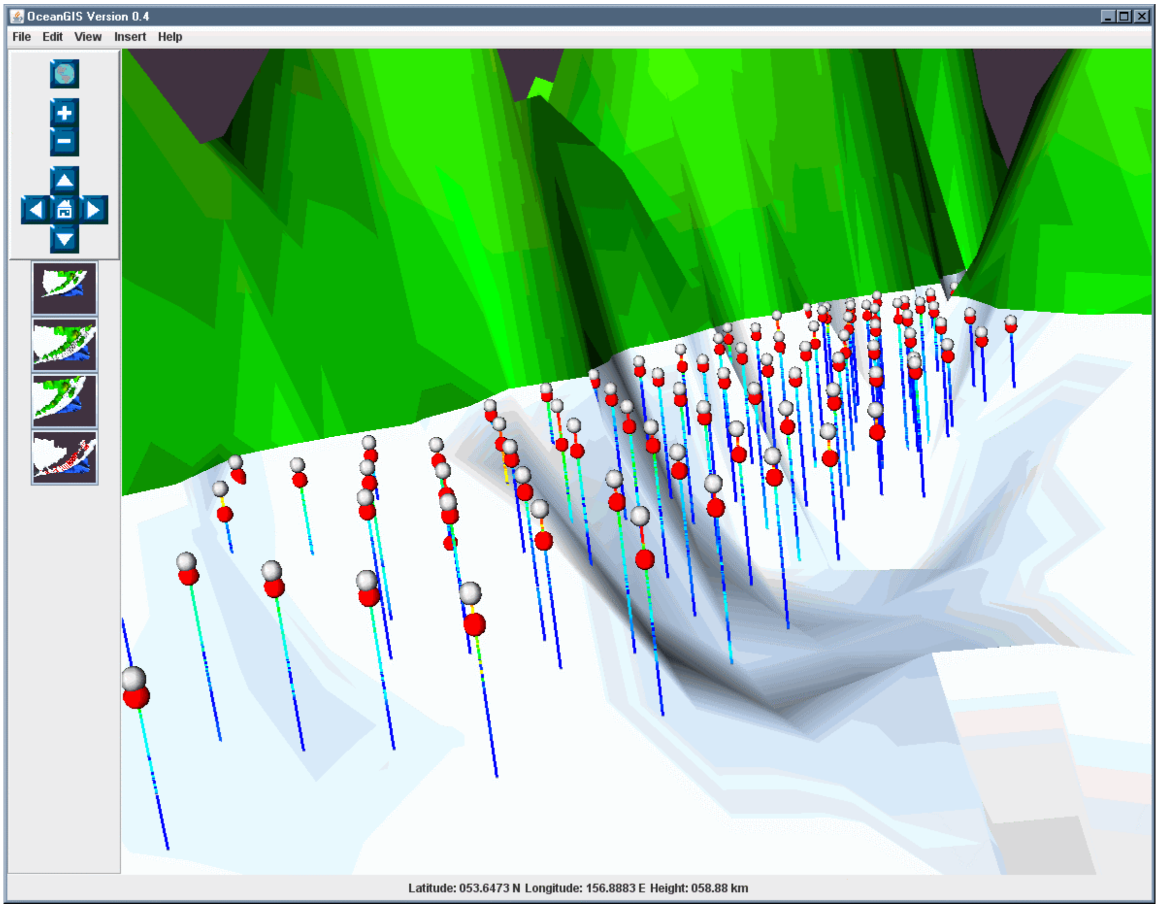

Figure 27 Mixed layer depth calculated in GeoModeler. The white spheres are the surface and the red spheres are the mixed layer depth for each cast. Darker blues indicate cooler temperatures, lighter blues and yellows indicate warmer temperatures. Temperatures range from 3.4 to 10.4 °C. View is from the southeast looking towards the Alaska Peninsula. Topography is shown in shades of green while bathymetry is represented in shades of blue. Vertical exaggeration is 200x

shapefiles and a variety of surface interpolation tools used to visualize the data (Figure 28). The plots for 2000 and 2006 show some differences. The mixed layer depth was deeper and more variable in 2000 than in 2006. Mixed layer depths of 20 m were more common and there were areas where the layer was as deep as 30 – 40 m. This kind of visualization could be used to examine the intra-annual patterns in the mixed layer

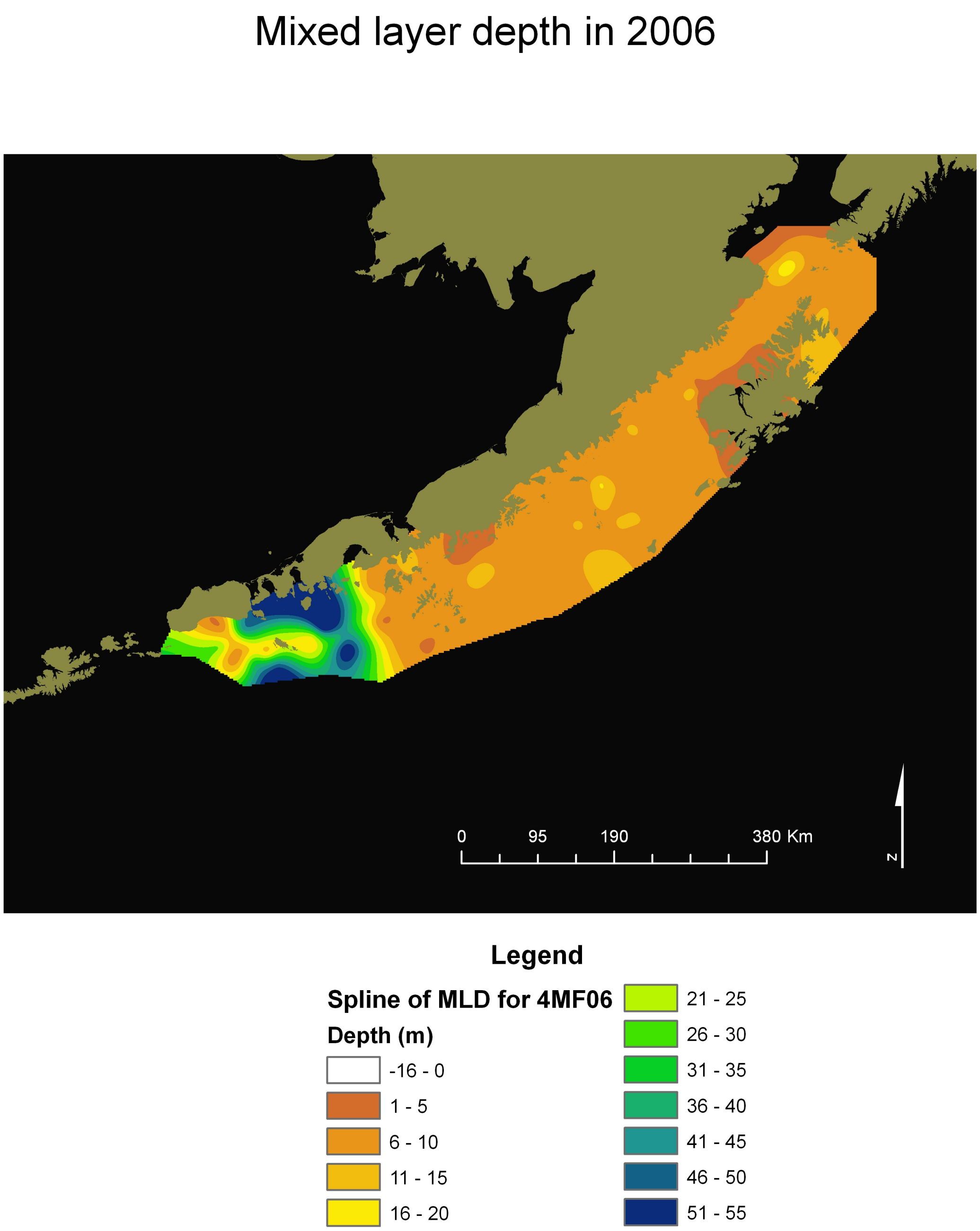

Figure 28 Surface showing the mixed layer depth in 2006 as calculated by Java Ocean Atlas. Data are for cruise 4MF06.

depth and inter-annual variations in the depths. The mixed layer depth could also be used to subset the data into a layer of varying thickness. Researchers could then calculate statistics on this more uniform layer.

The ability to select by attribute in a GIS database can also be used to explore the temperature patterns at arbitrary depths. For example, a slice of the data at the 40-meter depth identified as the mean feeding depth can be taken and a temperature surface created in ArcGIS (Figure 29). The surface shown is a interpolated using a tension spline as other interpolation schemes, such as inverse distance weighting, do not handle the anisotropy in station spacing well. A two-dimensional view of the surface, rather than a surface viewed in a three-dimensional view, was used as it is more familiar to the scientists interpreting the data. Since the graphic is representing a horizontal slice through the data, the planar view is more intuitive. These slices can be used to compare visually between years and one can calculate spatial statistics such as patchiness indices. For 2000 and 2006, the slices are visually similar, with most of the temperatures in the range of 3 to 6 °C. In contrast, temperatures in 2007 are mostly below 3.5 °C and are as cold as 2 °C. The overall pattern of temperatures, with a band of warmer water across the southern entrance of Shelikof Strait and progressively cooler water to the southwest is evident in both 2000 and 2006.

Drift of larvae down Shelikof Strait

Pollock larvae drift to the southwest down the Strait in the prevailing currents

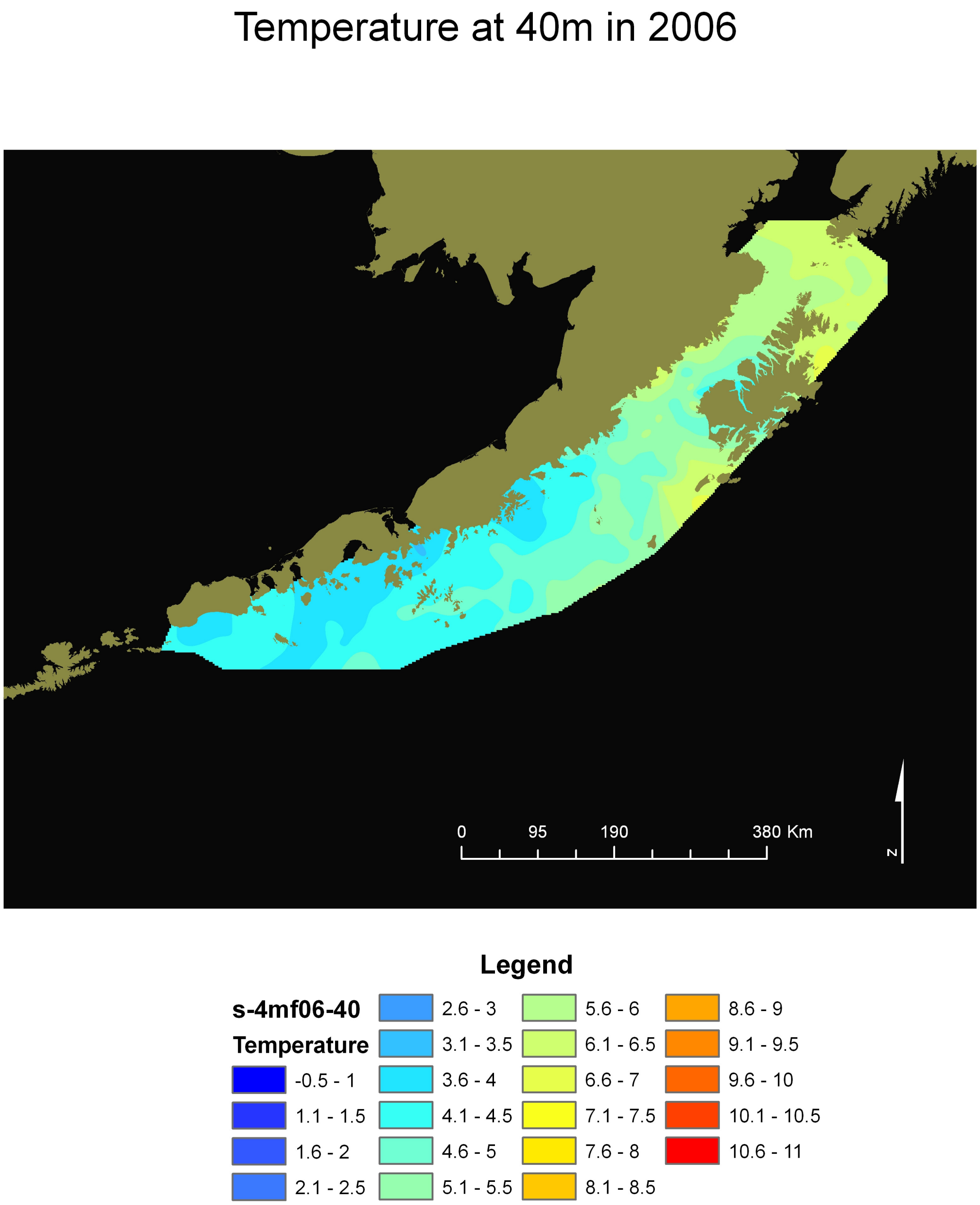

Figure 29 Tension spline surface of temperature at 40 m in 2006.

and by late May they are in the vicinity of Sutwick Island (Kendall et al., 1996). The currents through Shelikof Strait bifurcate as shown in Figure 22 and larvae may either be swept off of the shelf or may stay closer to shore and end up around the islands. These two possible drift paths for the larvae are shown by inter-annual variations in the numbers and location of larvae by late May (Incze et al., 1989, Kendall and Picquelle, 1990). Larvae that stay closer to shore have a higher survival rate and grow faster. Knowing the path of the currents in a given year gives information about conditions and possible larval survival and growth. Drifters are released each year both before and after the cruises described here. The drifters are drogued at 40 m and are tracked via satellite. They are assumed to follow the path that a patch of larvae might take. The tracks of the drifters can be added to GeoModeler and displayed with the temperature data. The drifter data are reformatted from text files and represented as tracklines on the plot (Figure 30). The path of the drifter is currently represented by a trackline on the surface; it would more properly be represented by a path at a depth of 40 m or the drogue depth if another depth was used. One or more drifter tracks can be displayed. Ideally these data would be combined with satellite data, such as sea surface temperature, which shows features such as eddies. Unfortunately the cloudy conditions frequently found in Alaska limit the usefulness of satellite data.

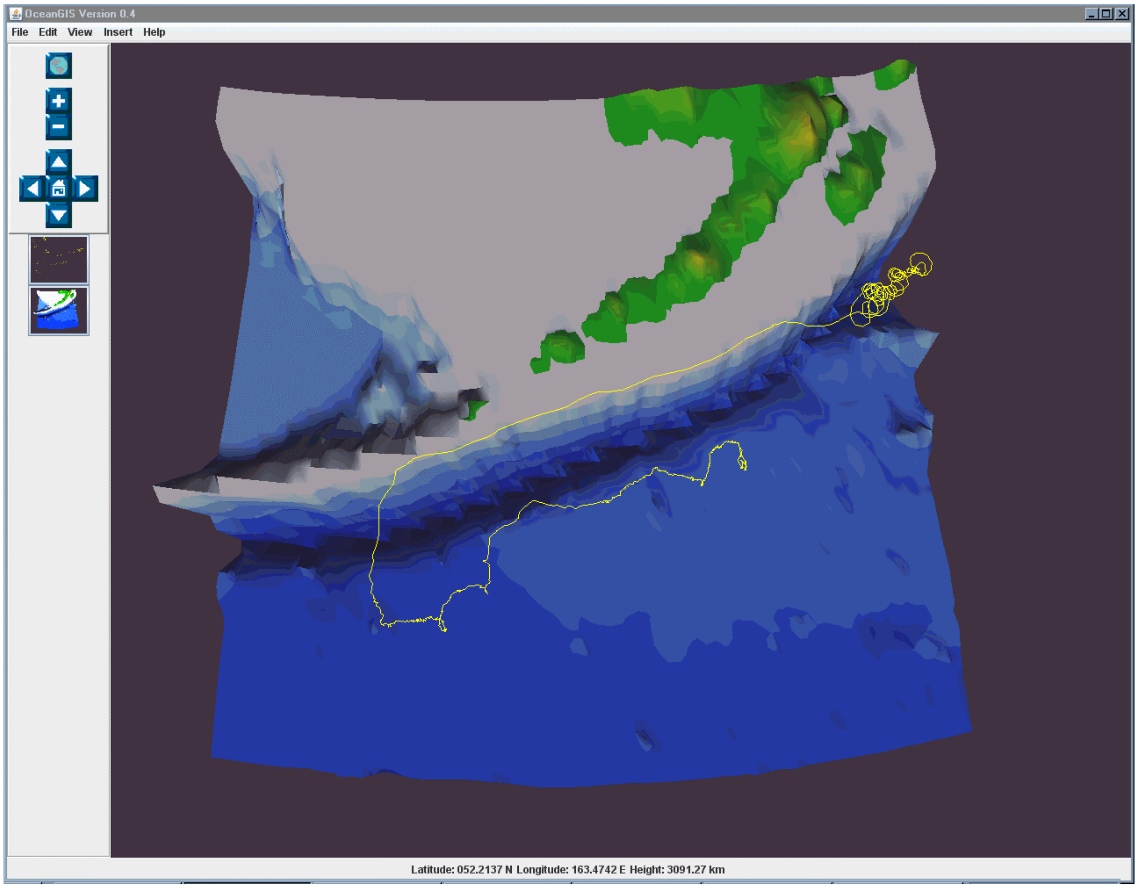

Figure 30 Track (in yellow) of a drifter drogued at 40 m. The drifter started just to the southeast of Kodiak Island, spent time in a eddy and then moved to the southwest in the Alaska Coastal Current. It turned offshore and was caught in a counter flowing current. Bathymetry data are smoothed ETOPO5 data shown with a 100x vertical exaggeration. Depths range from 0 to 6900 m. Topography ranges from 0 to 980 m.

3-D path of larvae/temperature history from model runs

Ideally, one would like to be able to recreate the temperature history of larvae. The temperatures experienced by the larvae have effects beyond the strength of the otolith increments and, in models, individuals with early birthdate and/or 'warm' history are longer (Hermann et al., 1996). Circulation model runs allow for the calculation of the path taken by the larvae and have been used to calculate the time integrated temperature experienced by the larvae. To look at the relation of the temperature path and otolith increments, one would want to calculate the actual path of the larvae and the water temperatures encountered along the path. To visualize this one would create a path similar to that of the hypothetical marine mammal in Figure 20 in chapter 6. The path would be coded by temperature and statistics would be calculated for the temperatures on the path. With the use of a particle tracking model run on top of the circulation model in would be possible to create three-dimensional “spaghetti tracks” for a cohort of larvae.

Variability in time and space

The visualizations did not show a clear trend in temperature patterns over the eight-year period processed. One reason for this is that the inter-annual variability may be greater than the change seen over this relatively short time period. For example, 2006 and 2007 are visually much more different than 1999 and 2007. Figure 31 shows a Stommel diagram of the variability in temperature at the various time and space scales present in the data. The diagram is based on temperature data for the past decade. The temperature is measured every meter from the surface to a depth of 100 meters and the stations are spaced about 10 kilometers apart. We sample each station on the grid once a year. So the possible data points are:

1 station - the mean and variance of temperature for the day the cast is taken

- the mean and variance of the means and variances for the 10 years of samples at that station (though many stations have not been sampled every year).

10 stations (assuming it takes about a day to sample these 10 stations)

- mean and variance of the stations for the day they are sampled
- mean and variance of the means and variances for the 10 years

100 stations (assuming it takes us about two weeks to sample all the stations)

- mean and variance of the stations over two weeks
- mean and variance of the means and variances for 10 years

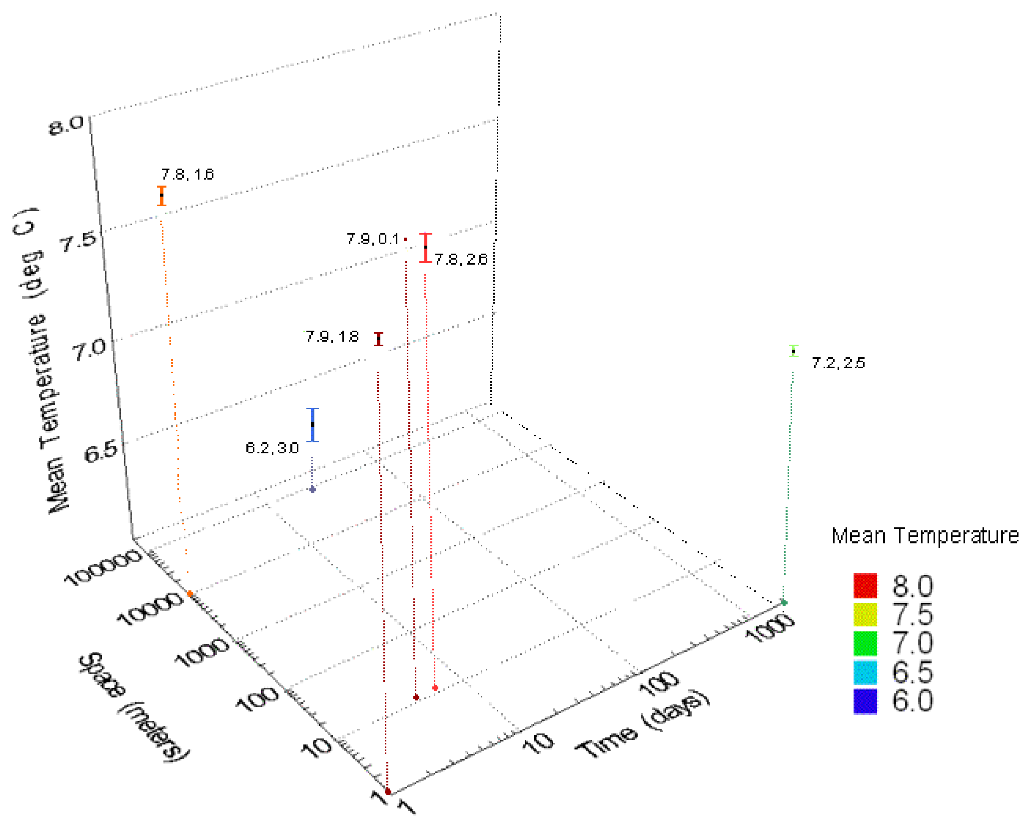

Figure 31 Stommel diagram of the variability in temperatures over a variety of time and space scales. Each data point shows the mean and variability of the temperatures at stations sampled over the indicated time and space scales.

The variance within a single cast (1 station/about 20 minutes) can be as large or larger than the variance at a single station over the full 10 years or the variance over all of the stations for an entire cruise (2 weeks). The largest and smallest variances occurred within single stations that were 10 km apart and were sampled less than 24 hours apart. The system is so physically dynamic, with eddies and currents in the horizontal and upwelling and mixing in the vertical, that variability is occurring at myriad scales and in various directions. Simple statistical summaries are seemingly useless and diagrams of the space and time variability may be the only way to identify these patterns.

Discussion

Scientists who have seen the visuals we created found them helpful and have asked us to create further tools and visualizations. While we have not conducted rigorous use studies of the visualizations, we have presented them to a variety of audiences. Fisheries biologists (at ICES 2007), atmospheric scientists (at meetings of the American Meteorological Society in 2006 and 2007), geographers (at meetings of the Association of American Geographers in 2007), computer scientists (at the Association of Computing Machinery/GIS meeting in 2007), and GI scientists (at the ESRI User Conference in 2007) have all viewed the tools and made suggestions for their expansion and further development. The requested new diagrams include visualizations and analyses of larvae, particle and drifter tracks in three-dimensions and the identification of three-dimensional barriers to the dispersion of larval fish.

Creating a new Stommel diagram for these types of fisheries data would be useful for analyzing data where we have more than one sample a year. For example, measurements taken at a mooring, which yield 1 sample per minute over weeks to years at a spacing of 1 meter vertically and 10's of kilometers horizontally. This is exactly the type of data that the original Stommel diagram used and represented. Including remotely sensed data would represent other time and space scales. It would give you multiple samples in time at a single depth, but a small spacing horizontally. The challenge in the Gulf of Alaska is getting clear images. We have sampled years where there was a single clear sea surface temperature image for the entire region over the duration of a three-month field season. The output of circulation models, such as the ROMS model, would give temperatures at 5km spacing in the horizontal and 1m in the vertical. A dense dataset such as this would allow calculation of a full Stommel diagram. For the data we do have – which is dense in Z, much less dense in X and Y and quite sparse in time, it will be necessary to resort to developing 3-D analogs to the various landscape metrics used by terrestrial ecologists.

Plans for further development on this project include expanding the data set to include the full time series since 1984. For further statistical modeling, we need to quantify, or at least categorize, otolith increment clarity to expand from our anecdotal information. To avoid the problems that occur when we make a statistical calculation across the thermocline, we plan to better define the variable thickness layer that the larvae inhabit. In the meantime, the use of GIS visualizations can highlight places where this variability in the thickness of the mixed layer depth might be biologically important and where statistical calculations might be biased. We plan to explore the use of 3-D statistics to quantify patchiness, variability, and the duration of patches. To determine whether the SeaCat casts accurately represent the temperature environment of the larvae, we plan to create a parallel temperature history for the larvae using circulation modeling. We will run a particle-tracking model based upon the ROMS model to track the temperature history of larvae. The larval temperature histories determined by the two methods will be compared. We will also use analysis tools developed for groundwater applications to calculate and visualize the volumes of water temperatures conducive to larvae found in the Strait and south towards the islands. We encountered a lack of 3-D analogs for standard statistics such as standard deviation, patch statistics and other measures of variability. Usability problems we encountered included the fact that a 3-D display works well when the user can interact with it but is much harder to understand as a static 2-D picture. This suggests that these tools serve better as exploration tool than as presentation tool.

We approached analysis with the challenge of how visualization techniques might contribute to understanding of multi-dimensional patterns in temperature that in turn affect otolith daily increment strength. Since larvae experience a four-dimensional world, displaying and visualizing three-dimensional data, making analytical calculations upon these data, and visualizing the results is crucial. ArcGIS, Java Ocean Atlas and GeoModeler provided the tools needed for defining subsets of the dataset for further analysis, integrating the visualization of the physical data with that of the biological data, and providing meaningful summary plots and statistics for the data. We were able to create 2-5- and 3-D representations, subset data, calculate statistics, and create arbitrary 2-D slices through the data. Scientists who have seen the visuals we created found them helpful and have asked us to create further tools and visualizations.

Using GIS and visualizations allowed us to provide a better qualitative understanding of the environmental conditions by providing a visual representation of the three-dimensional environment. It made it possible to detect subtle interannual differences in the temperature patterns by visual inspection. GeoModeler and ArcGIS provided tools to calculate useful basic statistical measures on the data and the visualizations made it apparent that these calculations are biased by variations on the mixed layer depth. Unfortunately, we were unable to locate and implement truly three-dimensional statistical tools to account for variability in both the horizontal and vertical directions. Most importantly, using the prototype made it apparent that new analysis or visualization tools are needed to support this kind of research. These tools include: quantification of the relative strengths of the otolith increments and statistics to summarize three-dimensional data; the incorporation of better visual clues to make two-dimensional static views of three-dimensional visualizations more easily understood; greater flexibility in the symbolization used in GeoModeler and surface interpolation tools for GeoModeler; and linking the temperature patterns shown in the SeaCat data with the use of model output to create “temperature histories” for individual larvae.

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Chapter 8: Conclusions

This dissertation started with the premise that the creation of a new technology or technique may not lead directly to adoption. Instead, there are three possibilities - something is built and users come, something is built and users don’t come, and, finally, potential users gather but the technology has not yet been built. Whether the development is a new tool for gathering data, or a new graphical technique for analyzing the data—if it doesn't meet a perceived need users may not come. Even if it *is* accepted and used, the need that a technology meets may not be that which the original developer intended. In turn, a need may be widely described while the technology to meet it remains undeveloped or unused. In this case, a theoretical need may not translate into a *practical* need.

In each scenario there is a combination of three factors at work. The first is a scientific *need* for a type of data or analysis; the second is a *technology or technique* developed to meet the need. The third is a *perception* that using the technology is somehow "better" that the existing tools and that the tool is easy to use. The technology can be both cause and effect; in some cases, the result of a new technology can drive the need for a second technological development.

Exploring the history of three-dimensional plotting illuminates how research needs can lead to new technology. In turn, these new technologies needed, and could create, intuitive three-dimensional maps and diagrams. Chapter 2 presented the history of multi-dimensional plotting and mapping to 1960 to set the scene for the development of the Stommel diagram: a three-dimensional graphic depicting the time and space scales of phenomena in the oceans and the tools used to sample them. The maps and charts described were all a product of the data available for their creation, the goals of their creators and the graphical fashions of the time. Each reflected a need to portray a phenomenon, the technology available both to collect the needed data (as well as to create the graphical depiction), and the abilities of the viewer to understand the new chart or map. The needs included seeking ways to represent both space and time, the need to represent data from three spatial dimensions, military needs to represent terrain in a way that could be quickly created (and equally quickly comprehended) and the need to represent the "invisible" data collected in the atmosphere and in the deep ocean. Data-gathering technologies included tools such as improved surveying equipment, drilling equipment for geological sampling, airplanes for taking air photos, and sensors for both the ocean and the atmosphere resulting from WWII. Display technologies included artistic techniques for portraying perspective, mechanical methods of creating terrain models, and graphical techniques to both present and hide classified data. With each new graphical development, viewers became familiar with seeing the world simplified in new ways. Once detailed two-dimensional maps became familiar, creating perspective maps also became possible. Increasingly, three-dimensional representations became commonplace, familiar, with more attributes and increased detail appearing in these representations.

How the Stommel diagram emerged thus illustrated a case where a technology led to a need. Improved technologies for data collection led to an unexpected result: the ability to gather too much data, or the wrong types of data. It became possible to collect large amounts of data simply for the sake of collecting data. To avoid this wasted effort, it was necessary to visualize patterns to see if data were showing the phenomenon of interest – and it was increasingly possible to do this qualitatively. Chapter 3 presented the historical development and diffusion of the Stommel diagram. While Stommel created his diagram to meet a pedagogical need – Stommel felt that the rise of big oceanography was leading to cruises designed by leaders who gave too little thought to whether the sampling strategy used was actually correct for the phenomena being studied - it ended up meeting other unexpected needs and gaining acceptance by a much wider audience.

While the Stommel diagram described oceanic phenomena, it was not widely used in physical oceanography. Several factors may account for this. By publishing his pioneering 1963 paper in *Science*, Stommel succeeded in placing it before a wide audience, but not in a journal central to physical oceanographers at the time. Moreover, the article itself was primarily qualitative, and thinly sourced. Stommel may well have hoped the diagram would serve primarily to buttress his arguments about the need to carefully design large-scale oceanographic experiments, rather than to convince oceanographers about the need to adopt graphical representations. Moreover, the arguments Stommel made in *Science* were already made in his “Dream-like” paper of 1954, which contained many more quantitative arguments and thus may have been perceived as more useful by physical oceanographers.

The situation in the biological and ecological sciences was markedly different. With the collection of long time series such as the CalCOFI dataset, which started in 1949 and continues to the present, and terrestrial datasets such as those collected at Hubbard Brook, which started in 1963 and also continues to the present, and other Long-Term Ecological Research (LTER) sites it became not only possible, but necessary, to use graphical summaries to understand the data. Certain researchers in the more biological and ecological sciences perceived that the Stommel diagram filled the need for this type of graphical summary. However, the technique was not static. While some researchers used the fully three-dimensional version of the diagram (and made an attempt to quantify the relative magnitudes of the various phenomena), others limited themselves to a qualitative description of intensity and used the two-dimensional version of the diagram.

A more quantitative exploration of the spread of Stommel diagram between scientific disciplines described the role of perception in the adoption of a new technique. The diagram was a technique to summarize data perceived as useful by some, but as not enough of an improvement or an oversimplification for others. Chapter 4 explored the spread of the Stommel diagram using techniques from literature research, the sociology of science, the history of science, and innovation diffusion. The use of traditional techniques of geographic diffusion of the diagram was complicated by the fact that the spatial diffusion of the paper is not purely geographic. The strength of professional interactions outweighs the geographic distance between researchers. By the same token, the role of research schools and invisible colleges was less easily determined without more research into the intellectual setting in oceanography. What is apparent is that the Stommel diagram became a part of the standard part of the body of knowledge to the point that it was used with citation to the original paper. Use of the Stommel diagram does not seem to be leveling off as might be expected from innovation diffusion theory and epidemic models for the spread of ideas. This is due to the expansion of the disciplines using it and also the publication of a second article (Haury et al., 1978), which made use of a new version of the diagram, and introduced Stommel's original work to a new generation of scientists.

What conclusions emerge from looking carefully at these developments? One can make a number of observations from studying the articles using Stommel diagrams. The first is the fact that almost all of the articles use a two dimensional diagram. So while Stommel took four-dimensional phenomena and represented them in three dimensions, those who followed him took these four dimensions and reduced them to two dimensions. Only within the climate studies and Haury et al. (1978) was the original three-dimensional diagram retained. Some of this is related to the way that the data used for research are gathered. Physical oceanographers frequently use time series at a point, leading to a time series analysis, not to a spectral space-time analysis. Another factor is what can be visualized from analogy in the physical world versus concepts that are basically abstract. For example, a climatologist can see cloud patterns and can draw analogies with plumes of smoke. An ecologist may be able to see at least surface representations of plankton patches, or can study growth in laboratory experiments. An urban historian can look at the current geographic layout of a city and mentally extrapolate back to an earlier city form. Oceanographers cannot truly see deep ocean circulation.

Looking ahead: how might the Stommel diagram be used in future applications? Chapter 4 also included ideas for new Stommel diagrams - including one for the relationship between spreading rate at mid-ocean ridges and biological diversity, an animated Stommel diagram to show how the importance of spatial and temporal factors might change with climate change, and quantitative versions of the Haury et al. Stommel diagram based upon data collected using new types of plankton samplers. A challenge to the idea of creating a new Stommel diagram is the fact that visualizations have become so good that summaries like the Stommel diagram may no longer be needed.

The need for better visualization leading to new technologies was explored in looking at the development of multi-dimensional techniques after the Stommel diagram. What is lagging is analysis tools, especially statistical tools to describe three and four-dimensional data. Attempts at multi-dimensional GIS build on the analysis power of original GIS and make use of available multi-dimensional data structures. But there is not a wide enough perception of need for multi-dimensional GIS to drive either widespread commercial or open-source development. More energy is devoted to visualization.

What developments in multi-dimensional plotting have occurred since Stommel developed his diagram? This was the focus of Chapter 5: the needs and technologies are quite well defined but the acceptance is still a challenge. Researchers want to see their results presented in three dimensions, and their exposure to video games and scientific visualizations has made them familiar with these types of visual representations. Circulation and ecosystem models make fully populated three-dimensional grids of data a standard resource. Oceanographic data gathered with a variety of sensors provide a plethora of data for analysis. Data formats such as netCDF are widely used for storing multi-dimensional scientific data. Computer hardware to support these analyses and visualizations are commonly available on the desktop, with access to supercomputers to run large models fairly straightforward. Newer types of interactions, such as Java3D and Google Earth, are expanding. The rise of open-source software and community application development is forcing the more traditional software vendors to find ways to make their core functions available to external applications. Data selection is so fast and easy (and time series analysis so rapid) that can one can easily analyze fully dimensioned datasets. These developments made it possible to create a variety of analytical and display tools for the massive multi-dimensional datasets being collected.

In some ways, the greater challenge is getting potential users to recognize the advantages of these new ways of seeing things. Some users are still more comfortable with reduction of dimensions seen in maps and diagrams such as the Stommel diagram.

No less important for this story is the development of a number of multi-dimensional GIS packages. Chapter 5 also examines the emergence of System 9, Voxel Analyst and GRASS, as well as GIS-related visualization tools such as EVS, IVS and Vis5D. While each of these technologies met a need, acceptance and use has varied. Of the active GIS, GRASS has the best developed multi-dimensional capabilities but its acceptance is hampered by the perception that it is hard to use and less well supported because it is an open source tool. System 9 and Voxel Analyst both represented advanced multi-dimensional tools but they have become a part of larger packages that do not emphasize their functionality. The visualization tools meet the need for visual representations but do not meet the need for analysis tools.

Chapter 6 described the creation of GeoModeler, a prototype for a multidimensional GIS tuned for oceanographic and fisheries data. GeoModeler provides an example of technological developments leading to the creation of new technologies. These developments include methods for linking modules and the opening up of commercial functionality to open-source development. GeoModeler provides a fully functional prototype of closely linking scientific models and a GIS, but it provides more than simple coupling of tools to these models. It provides analytical tools specifically adapted to the type of data or model output being analyzed. The visualization created is a three-dimensional, interactive, view of the data and the results of the analyses. GeoModeler can be used to analyze and display the results of both field data and model output. Linking models directly with a GIS has improved the ability of a scientist to visually interrogate model results and to create animations to highlight temporal features in the output from a model. All of these tools have made it easier to comprehend and explain the complicated spatio-temporal features seen in both data collected by instruments and data created by models.

New technologies can also meet a need even while still being perceived in mixed ways by members of research communities. Chapter 7 described the application of GeoModeler and other GIS and visualization tools to understanding the environmental factors affecting the strength of daily increments in pollock otoliths. We approached the analysis looking at the challenge of how visualization techniques might contribute to understanding of multi-dimensional patterns in temperature, that in turn affect daily increment strength. Since larvae experience a four-dimensional world, displaying and visualizing three-dimensional data, making analytical calculations upon these data and visualizing the results, is crucial. ArcGIS, Java Ocean Atlas and GeoModeler provided the tools needed for defining subsets of the dataset for further analysis, integrating the visualization of the physical data with that of the biological data, and providing meaningful summary plots and statistics for the data. It then become possible to create 2-5- and 3-D representations, subset data, calculate statistics, and create arbitrary 2-D slices through the data.

The creation of Stommel diagrams research on walleye pollock, showing the time and space scales of both the important phenomena and of the data collected, argues for improvements in data collection. The phenomenological diagram clearly shows that there are important phenomena that may be missed under the current sampling regime. The plot of the variability of temperature over time and space scales shows the extent to which dynamic processes produce complicated patterns of variability. While there are limitations to the amount of ship time and researcher effort that can be put towards sampling, these diagrams may show ways in which these efforts could be refocused and expanded. As with the intent of the original Stommel diagram, these diagrams provide a practical guide to improved data collection and analysis.

What has slowed the acceptance of new tools such as GeoModeler? One negative perception is that a 3-D display works well when the user can interact with it, but is much harder to understand as a static 2-D picture. This suggests that these tools work better for exploration rather than for publication. A lack of 3-D analogs for standard statistics such as standard deviation, patch statistics and other measures of variability was also problematic.

Improved technologies for data collection after World War II created a need for better analysis tools. Stommel perceived that the ability to collect data might be outstripping the ability to collect data, and he wisely created the Stommel diagram. Continued development of technology produced large datasets in yet another field, ecology, and yet another need/opportunity to analyze and display these data. Stommel believed his diagram was a tool useful in summarizing the data and understanding the processes being measured. At the same time, improved technology was contributing to a computational revolution: it led to the development of GIS, and to improved visualization tools and experiments with multi-dimensional GIS.

Many of these same large multi-dimensional datasets that Stommel considered could be visualized and analyzed with these new tools. But these new tools are not necessarily perceived as an improvement. User response is mixed. Though widely accepted, some fisheries scientists find them useful and others are still more comfortable with two-dimensional plots and maps. In the end, the lesson of the Stommel diagram is: “let those who want to use what is built come.” Describe a new technique as clearly and widely as possible, and accept that the strongest users may be from a very different discipline than originally targeted.

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