Title
Multiple Roles for GIS in US Global Change Research (NCGIA Research Initiative 15): Report of the First Specialist Meeting (95-10)

Authors
Goodchild, Michael F.
Estes, John E.
Beard, Kate M.
et al.

Publication Date
1995-03-01

RESEARCH INITIATIVE 15:

Multiple Roles for GIS in US Global Change Research

REPORT OF THE FIRST SPECIALIST MEETING

Santa Barbara, California

March 9-11, 1995

Michael F. Goodchild, UC Santa Barbara
John E. Estes, UC Santa Barbara
Kate Beard, University of Maine
Tim Foresman, University of Maryland Baltimore County
Jenny Robinson, SUNY Buffalo

Technical Report 95-10

We acknowledge with thanks financial support for this meeting from the National Science Foundation and the U.S. Geological Survey. Ashton Shortridge developed a background bibliography for the meeting and helped in numerous other ways to make the meeting a success. Finally, we thank the staff of NCGIA, particularly LaNell Lucius and Sandi Glendinning, for their assistance with the conference.

TABLE OF CONTENTS

NCGIA Research Initiative 15: Multiple Roles for GIS in US Global Change Research

REPORT OF THE FIRST SPECIALIST MEETING

held in Santa Barbara, California, March 9-11, 1995

INTRODUCTION

Background

The National Center for Geographic Information and Analysis was announced by the National Science Foundation on August 19, 1988, and awarded to a consortium of the University of California, Santa Barbara; the State University of New York at Buffalo; and the University of Maine, for an initial period of five years. Funding began December 1, 1988 under a five year cooperative agreement with the Regents of the University of California. The cooperative agreement was extended in 1994 for an additional three years, to December 31, 1996. The Center's mission reflects the desires of the NSF, as expressed in the solicitation document: to advance the theory, methods and techniques of geographic analysis based on geographic information systems (GIS) in the many disciplines involved in GIS-based research; to augment the nation's supply of experts in GIS and geographic analysis in participating disciplines; to promote the diffusion of analysis based on GIS throughout the scientific community, including the social sciences; and to provide a central clearing house and conduit for disseminating information regarding research, teaching and applications.

The primary vehicle for managing NCGIA research is the Research Initiative, designed to focus research on a well-defined topic for a period of two to three years. Research initiatives are defined through a process of broad solicitation and authorized by the NCGIA Board of Directors. One or more leaders are identified and a steering committee is formed. The specialist meeting brings together 20 to 50 specialists to discuss the topic of the initiative, map out a research agenda, and identify specific topics that offer a reasonable chance of yielding to intensive research in a two or three year period. Another purpose of the specialist meeting is to stimulate collaborative research in the national and international community. The report of the specialist meeting is published in the NCGIA Technical Reports series. During the initiative's period of active research following the specialist meeting, work proceeds at the NCGIA institutions and elsewhere, and may take advantage of small workshops or sessions at national and international meetings. The end of the active research period is marked by a conference or series of sessions at which the results are presented to the broader community. The initiative ends with the acceptance of its closing report by the NCGIA Board of Directors.

In its seven years of operation, NCGIA has completed 9 research initiatives and begun a further six. A total of 16 have been approved by the Board. Complete details on each initiative are available in the Technical Reports series, the Closing Reports, the NCGIA newsletter *Update*, and the NCGIA WWW home pages at each site (the Santa Barbara URL is http://www.ncgia.ucsb.edu/). Many reports are available via ftp from ncgia.ucsb.edu.

Research Initiative 15

The idea of an NCGIA research initiative on the role of GIS in global change research originated with John E. Estes in 1991, and was included in the renewal proposal submitted to NSF in November of that year. In August 1992 NCGIA adopted new procedures for identifying new initiatives designed to include a broadly based solicitation of topics from the national research community; external peer review; and formal approval by the Board of Directors, initially in principle and subsequently in detail. Initiative 15 was one of two recently identified initiatives used as guinea pigs for the new process. A request for approval in principle was submitted to the Board of Directors at its December, 1992 meetings; final approval of a detailed proposal was given at the June 1993 meetings.

Unfortunately, progress on the initiative was delayed through mid-1994 because of the illness of one of the initiative leaders. After several changes, the group of initiative leaders was finally identified as Michael F. Goodchild (UC Santa Barbara, NCGIA Director), John E. Estes (UC Santa Barbara, visiting the US Geological Survey through September, 1995), Kate M. Beard (University of Maine), and Tim Foresman (University of Maryland, Baltimore County). A steering committee was formed in August 1994 of the following:

John E. Estes, US Geological Survey and UC Santa Barbara, coleader
Michael Goodchild, UC Santa Barbara, coleader
Kate M. Beard, University of Maine, coleader
Tim Foresman, University of Maryland, Baltimore County, coleader
Roberta Miller, CIESIN
Peter Thacher, World Resources Institute
Jerry Garegnani, NASA
David Kirtland, US Geological Survey
Francis Bretherton, University of Wisconsin
Bob Corell, NSF
Jeff Dozier, UC Santa Barbara
Catherine Gautier, UC Santa Barbara
Berrien Moore, University of New Hampshire
Jenny Robinson, SUNY Buffalo
John Townshend, University of Maryland, College Park
Cort Willmott, University of Delaware
Dorsey Worthy, NOAA

and held its first meeting in Reston, VA on September 26. Plans were developed for two specialist meetings, the first to be held in Santa Barbara in March 1995.

Objectives of the initiative

The general context for the initiative is provided by the widely held perception that GIS and related technologies will play an important role in global change research. Remote sensing will clearly be the most important source of data for global change research, at least within its physical dimensions, because of remote sensing's potential for high spectral resolution and uniform coverage of the surface of the Earth. GPS is clearly important to all kinds of field observation. The importance of GIS, on the other hand, can only increase as global change research becomes more data- and computation-intensive, as it moves from studies of single processes to integrated modeling, as it struggles to link human and physical processes, and as it places more emphasis on policy formulation and decision-making. Four major areas of application are seen as currently driving interest in GIS among the global change research community:

- storing, manipulating, and preprocessing of data for models, including resampling, aggregation, and generalization;

- integration of data from disparate sources with potentially different data models, spatial and temporal resolutions, and definitions;

- monitoring global change at a range of scales; and

- visual presentation and use of the results of modeling and GIS-based analysis in a policy-supportive, decision-making environment.

While these four areas of application may explain current interest in GIS, they are neither expressions of the longer term potential of GIS in global change research, nor a basis for a sustainable research program. Instead, the following were proposed as the scientific objectives of the initiative:

- to identify *technical impediments* and problems that obstruct our use of GIS in global change research, and our understanding of interactions between human systems and regional and global environmental systems;

- to assess critically the quality of existing *global data* in terms of spatially varying accuracy and access, sampling methodologies, and completeness of coverage, and to develop improved methods of analysis and visualization of such data;

- within the context of global change, to develop theoretical/computational structures capable of *building up* from knowledge at smaller spatial scales and lower levels of aggregation;

- to develop methods of *dynamically linking* human and physical databases within a GIS and for exploring the regional impacts of global change; and

- to develop methods for detecting, characterizing, and modeling change in *transition zones* where assumptions of spatial homogeneity are untenable.

These objectives form the scientific core of the initiative. Taken together, they represent a massive challenge, and it is clear that only limited progress will be possible within the constraints of the initiative.

The five objectives imply a broad interpretation of the term "GIS" that is much wider than the narrowly defined capabilities of current GIS software. This follows current practice in the research community, which tends to identify "GIS research" with a broad set of scientific issues surrounding the use of computers to process, store, analyze, and visualize geographic information. Goodchild (1992) has suggested that the research community decode "GIS" as *geographic information science*, a subset of information science dealing with information tied to specific locations on the surface of the Earth. Thus while the degree of interest in GIS as software varies markedly across the global change community for reasons discussed in detail below, the issues of GIS as a research focus are much more general and fundamental.

The I15 specialist meetings

Although every previous initiative has used a single specialist meeting to identify and prioritize its research agenda, the coleaders felt that the subject matter of I15 was best addressed with dual meetings. The first would bring together active researchers from the global change research community to discuss the actual and potential roles played by GIS in their work, and impediments that currently make GIS less than ideal as a research tool. The results would be synthesized, and discussed at a second specialist meeting of experts in GIS technology and research. With this dual approach it would be possible to separate needs from capabilities, allowing global change researchers to focus on what they actually need to do their research, and GIS researchers to focus on how those needs might best be met.

At its September meeting the steering committee developed a framework for organizing the first specialist meeting. The wide range of topics addressed by global change research was narrowed to eight areas:

Atmospheric science and climate
Oceans, ocean-atmosphere coupling, and coasts
Biogeochemical dynamics, including soils
Hydrology and water
Ecology, including biodiversity
Demography, population, and migration
Production and consumption, including land use
Policy and decision-making

A target of four participants was established for each area, and efforts were initiated to identify suitable participants who satisfied two loosely defined criteria: active research in the field, and an interest in the issues to be addressed by the initiative.

In addition, and following standard NCGIA practice, an open call for participation was issued, disseminated through a variety of electronic lists, and published in assorted newsletters. Respondents were asked to submit a two page position paper addressing the subject matter of the initiative. The responses were circulated among the steering committee, and a total of nine participants selected in this manner.

Invited participants were also asked to prepare a two page position paper prior to the meeting. The results were compiled and circulated, so that every participant arrived having read something about the range of concerns and expertise of the group.

The first specialist meeting was held at the Upham Hotel in Santa Barbara, California, March 9-11, 1995. A tutorial on GIS was provided on the previous evening by Michael Goodchild to give participants who felt unfamiliar with the current state of GIS software and GIS research an opportunity to obtain a minimal understanding. The meeting opened with a welcome from Jeff Dozier, recently named Dean of the School of Environmental Science and Management at UC Santa Barbara and previously chief scientist of the NASA EOS program. Michael Goodchild described the background to the initiative and its objectives. This was followed by introductions of each of the participants and short statements from other members of the steering committee. The group then broke into three small discussion sections, and the remainder of the meeting was occupied with a mix of group discussions and plenary summaries. The close of the meeting on March 11th was disrupted by a major rainstorm which hit the Santa Barbara area late on March 10th and provided much excitement and diversion.

This report presents the findings of the first specialist meeting. At time of writing, plans are being developed for the second specialist meeting in early 1996. The report is in four sections. Following this introduction, the second section presents a synthesis of findings. This is followed by more specific reports from each of the three working groups formed at the meeting. A list of participants and the position papers written prior to the meeting by the participants form the appendices.

SYNTHESIS OF CONCLUSIONS

By definition, Initiative 15 covers a wide range of topics, and many views of the roles of GIS in global change research were presented at the first specialist meeting, so it is inevitably difficult to synthesize conclusions. For this reason, this section should be read in conjunction with the position papers in Appendix 2, which represent the views of the individual participants as expressed prior to the meeting, and with the three sections that follow, which focus on the three areas of Data Issues, Representation and Analysis, and Integration and Communication.

That said, it is possible to distill some useful overall conclusions in addition to the more detailed ones presented later. First, the term "GIS" means different things to different people, particularly in the context of global change research, and this point is explored in detail below. Second, the meeting reached a useful consensus on the complex nature of the global change community, and the second subsection below expands on this. The third subsection presents the meeting's rationale for dividing its discussions into three sections, and for using this tripartite division to organize its thoughts on a research agenda. The fourth and final section brings the results of the three separate discussions together, and describes NCGIA's plans for the second specialist meeting, and for specific research activities within the overall agenda established by the first specialist meeting.

Perspectives on "GIS"

Most published definitions of "geographic information system" refer to both data and operations, as in "a system for input, storage, manipulation, analysis, and output of geographically referenced information". In turn, geographically referenced information can be defined fairly robustly as information linked to specific locations on the Earth's surface. This definition suggests two tests that can be applied to a software package to determine whether it is a GIS: the integration of a broad enough range of functions, and the existence of geographic references in the data. Clearly the first is less robust than the second, and there have been many arguments about whether computer-assisted design (CAD) or automated mapping functions are sufficiently broad to qualify packages for the title "GIS".

At this time, several hundred commercial and public-domain packages meet these qualifications, and the GIS software industry is enjoying high rates of growth in annual sales which now amount to perhaps $500 million per year. However, the majority of these sales are in applications like parcel delivery, infrastructure facilities management, and local government, rather than science. Moreover, the term "GIS" has come to mean much more than is implied by this narrow definition and test. At its broadest, "GIS" is now used to refer to any and all computer-based activities that focus on geographic information; "GIS data" is often used as shorthand for digital geographic information; and the redundant "GIS system" is becoming the preferred term for the software itself. One can now "do GIS", specialize in GIS in graduate programs, and subscribe to the magazine *GIS World*.

A further and largely academic perspective is important to understanding all of the ramifications of current usage. In many areas of computer application, such as corporate payroll or airline reservations, the objects of processing are discrete and well-defined. On the other hand many geographically distributed phenomena are infinitely complex, particularly those that are naturally occurring as distinct from constructed by humans. Their digital representations are thus necessarily approximations, and will often embed subjective as well as objective aspects. The use of digital computers to analyze such phenomena thus raises a series of fundamental and generic scientific issues, in areas ranging from spatial statistics to cognitive science. The GIS research community has begun to describe its focus as "geographic information science", emphasizing the distinction between the development of software tools on the one hand, and basic scientific research into the issues raised by the tool on the other.

In summary, three distinct perspectives are identifiable in current use of the term "GIS", and reflections of all three can be found in the position papers in Appendix 2:

1) GIS as geographic information system, a class of software characterized by a high level of integration of those functions needed to handle a specific type of information.

2) GIS as an umbrella term for all aspects of computer handling of geographic data, including software, data, the software development industry, and the research community.

3) GIS as geographic information science, a set of research issues raised by GIS activities.

From the first perspective, the position papers and discussions at the specialist meeting helped to identify a range of advantages and disadvantages of GIS as a software tool for global change research. Some of these can be seen as technical impediments, implying that further research and development of the software may remove them. Others are more fundamental, dealing with the problems of large-scale software integration and the adoption of such solutions within the research community. In this area, it may be possible to draw parallels between GIS and other software toolkits, such as the statistical packages, or database management systems, or visualization packages. In each of these cases, the average researcher faces a simple make-or-buy decision - is it preferable to write one's own code, or to obtain it? The answer can be very different depending on the discipline of the researcher, the cost of the software, and its ease of use. In the specific case of GIS, the following issues seem important:

- *Ease of use*: How much learning is needed to make use of the software? Will it be quicker to learn the package or to write code, or to find code written for this exact problem by some colleague? Many GIS are reputed to be difficult to use, and GIS courses require a heavy investment of time. On the other hand it may be preferable to rely on a GIS than to write code in an area unfamiliar to the researcher, such as map projections.

- *Cost*: Many researchers are averse to purchasing application software, although they expect to pay for more generic packages such as operating systems and compilers. Many commercial GIS have a high price-tag. A GIS will be considered worth the investment if it is perceived as needed by a large enough proportion of the research community, like a statistical package.

- *Software integration*: Is the level of software integration in a GIS viable? A researcher needing to solve a problem in map projections might prefer a public-domain map projection package to a GIS that offers the same functionality bundled into a much more costly package; the same argument could be made in the context of spatial interpolation techniques. Any generic, integrated tool imposes a cost on its users because it cannot achieve the same performance as a tool designed for a specific purpose, so this cost must be compared to the benefits of integration.

- *Terminology*: Does the GIS use terms familiar to the researcher, or does use of GIS require the researcher to embrace an entirely unfamiliar culture very different from his or her own? Researchers see time as a fixed resource, and fear that adoption of any new technology will be at the expense of other areas of expertise.

If we adopt the second meaning of GIS above, the world of GIS seems very different. Other geographic information technologies, such as remote sensing and GPS, now fall under the GIS umbrella, and the use of GIS is no longer an issue: global change research has no choice but to use computers and digital data; and the vast majority of the types of data needed for global change research are geographically referenced. From this viewpoint, the discussions at the I15 specialist meeting addressed a much broader set of issues, including:

- Requirements for computer-based tools in support of global change research, focusing in particular on the need to model dynamic processes in a variety of media, together with relevant boundary conditions and interfaces.

- The need for interoperability between tools, to allow users of one collection of tools to share data and methods of analysis with users of another collection - and associated standards of format, content description, and terminology to promote interoperability.

- The need to harmonize approaches to data modeling, defined as the entities and relationships used to create digital representations of real geographic phenomena. The current variation in data modeling practice between software developers, the various geographic information technologies, and the different disciplines of global change research is a major impediment to effective use of GIS.

- The accessibility of data, including measurements shared between scientists; and data assembled by governments for general purposes and useful in establishing geographic reference frameworks and boundary conditions for modeling.

- The role of visualization and other methods for communicating results between global change researchers and the broader communities of decision-makers and the general public.

The third perspective above defines GIS as a science, with its own subject matter formed from the intersection of a number of established disciplines. From this perspective global change research is an application area with an interesting set of issues and priorities, many of which fall within the domain of geographic information science. These include the modeling of uncertainty and error in geographic data; the particular problems of sampling, modeling, and visualizing information on the globe; and the development of abstract models of geographic data.

Of the three, the second meaning of GIS is perhaps the most appropriate to the first specialist meeting of I15, as it provides a more constructive perspective than the first, and a greater sensitivity to context than the third. All three are necessary, however, in order to understand the viewpoints expressed by the participants before and during the meeting, and the research activities that will emerge under I15 in the next two to three years.

Global change research communities

"What is this GIS anyway?" may have been the question uppermost in the minds of many participants as they arrived at the meeting, but it was quickly supplanted as participants realized that the multiple roles of GIS in US global change research extend well beyond the immediate needs of scientists for computerized tools. First, global change is a phenomenon of both physical and human systems. Many of the changes occurring in the Earth's physical environment have human origins, and thus mechanisms for their prediction and control are more likely to fall within the domain of the social sciences. Moreover, many would argue that when measured in terms of their impacts on human society, the most important changes to the globe are not those currently occurring in its physical environment, but are economic and political in nature. The issues raised by computerized tools are very different in the social sciences.

Second, the need to integrate physical and social science in order to understand global change creates its own set of priorities and issues. Not only are the characteristics of data different, but the differences in the scientific cultures and paradigms of physical and social science create enormous barriers to communication that are exacerbated by the formalisms inherent in GIS.

A recurring theme in global change research is the need to build effective connections between science and policy. Complaints about the lack of connections surface whenever Congress is asked to approve another major investment in global data collection, such as NASA's Mission to Planet Earth. Several obvious factors are to blame: scientists are not trained to present their results in forms that can be readily understood by policy-makers; decisions must be made quickly, but science marches to its own timetable; the scientific culture does not provide adequate reward for communicating with policy-makers. GIS as broadly understood is widely believed to have a role to play in this arena. It is visual, providing an effective means of communicating large amounts of information; it is already widely used as a common tool by both the scientific and policy communities; and it supports the integration of information of various sources and types. Participants at the first I15 specialist meeting identified "policy-makers" as the second major community after "scientists" whose needs should be considered in any discussion of the roles of GIS in global change research.

Finally, participants argued that the meeting had to consider the needs of the general public. One of the biggest impediments to progress in global change research, perhaps the biggest of all, is the general public's reluctance to accept global environmental change as a major problem requiring the commitment of massive research effort and the development of effective policy. As GIS becomes more widely available, through the Internet, World Wide Web, home computers, and other innovations in digital technology that impact the mass market, the same arguments made above about the roles of policy-makers will become applicable to the general public. In summary, the group agreed that three major communities should be considered in examining the roles of GIS in global change research: scientists, policy-makers, and the general public. They agreed that major issues could be discussed in the context of each of these groups.

Another recurring theme in global change research is the potential role of the general public in collecting data. The GLOBE project (Global Learning and Observations for a Better Environment) is conceived along these lines as a network of school children around the world who will collect data on their own local environment, learning about it in the process, and then contribute those data to a central agency responsible for interpretation and synthesis. In turn, the central agency will return a global synthesis to the primary sources. In a sense, this concept promises to return us to the earliest days of environmental data collection, before the organization of official climate measurement stations, and offers to give back to the general public the role then played by the amateur scientist. Although there are substantial concerns about quality control, this concept offers perhaps the only feasible solution to the current dilemma faced by national governments who can no longer support dense networks for primary field data collection in the face of rising costs and steadily decreasing budgets.

The issues

Each participant was asked to identify major issues in the position papers they prepared prior to the meeting. A first round of breakout sessions was used to find clusters among them that could be used to structure subsequent discussions. These were brought to a plenary discussion, and a lengthy debate arrived at the following conclusion: that the subject matter of the meeting and I15 could be organized into a matrix of three rows and three columns, the three rows being the three communities discussed above, and the three columns being Data Access; Representation and Analysis; and Communication and Integration. This scheme opened the possibility of dividing the group either by the rows or by the columns, but subsequently the columns prevailed. Thus the following three major sections are the reports of the groups formed to discuss each column's subject matter.

The Data Access group's report, titled Data Issues, identifies four major themes. First, all of the global change communities are affected by issues of data quality. In any multidisciplinary enterprise it is common for the data used by a scientist to have been collected, processed, manipulated, or interpreted by someone else prior to use, creating a demand for new mechanisms to assure quality that have not been part of traditional science. Tools are needed to model and describe quality; to compare data with independent sources of higher accuracy such as ground truth; to verify the output of models of global environmental change; and to support updating. Much of the necessary theory to support such tools has been developed in the past decade, and needs to be brought to the attention of the global change research community, implemented in readily available tools, and disseminated in education programs.

Second, remote access to data must be supported by effective methods of data description, now commonly termed "metadata". Search for suitable data can be seen as a matching process between the needs of the user and the available supply, both represented by metadata descriptions; and both user and supplier must share a common understanding of the terms of description. The advent of technology to support remote access, including the World Wide Web, has put enormous pressure on the community to develop appropriate methods of description and cataloging.

Third, the group addressed issues of access and archiving, touching on the institutional arrangements necessary to support free access to global change research data, and the concerns for copyright, cost recovery, and legal liability that are beginning to impact the use of communications technology. While much data for global change research is unquestionably for scientific purposes, other data is also useful for commercial and administrative purposes, and in many cases these tend to dictate access policies. Techniques need to be improved to support content-based search for specific features, and there are many other technical issues to be addressed in this rapidly developing area of spatial database technology.

Fourth, the group identified a number of issues under the rubric of facilitating input, output, and conversion. These include interoperability, the lack of which is currently a major contributor to GIS's difficulty of use and a major impediment to data sharing among scientists. Interoperability can be defined by the effort and information required to make use of data and systems; in an interoperable world, much of what we now learn in order to make use of GIS will be unnecessary or hidden from the user. The group discussed possible relationships with the Open Geodata Interoperability Specification initiative.

The Representation and Analysis group's report focuses initially on data models, their definition, and their relationship to alternative world views. The group developed a summary list of the technical roles of GIS, and the broader issues raised by its use in analysis. Recommended research topics and action items are grouped into three categories. Research on data models is seen as holding the key to effective harmonization between different global change research communities, through the development of common languages of data model description, and translators between alternative data modeling schema. The implementation of many of these ideas is presented under the heading of interoperability, which is seen from this perspective as a user view of the outcome of a reconciliation of data models. Finally, the group identified a number of areas where enhanced analysis tools are needed to support global change research, notably in support of visualization, the analysis of uncertainty, analysis on the curved surface of the planet, and in support of aggregation and disaggregation across scales.

The third group's report on Integration and Communication is divided into a discussion of communication within the global change research community on the one hand (inreach), and with the outside world on the other (outreach). Communication within a research community can build on a common base of terminology and shared techniques and formalisms, and the discussion in this area identifies a number of needed enhancements to the analytical methods currently embedded in GIS. The problems of outreach are less technical but perhaps more challenging, because there is no such shared base of knowledge and experience. The group recommends a two-part approach, first assessing needs through a series of requirements studies, and then providing a series of "best-practice" studies that aid communication by providing illustrations and exemplars. It imagined a feedback process in which views from the user community on GIS impediments would drive research and development, the results of which would be incorporated into new "best practice" demonstrations disseminated on the Internet and through similarly effective mechanisms.

Needless to say, the three reports present a collection of ideas and recommendations for research that is extensive and challenging, and well beyond the capabilities of the research community in the timeframe of this research initiative. Nevertheless, many of these topics are well within the bounds of available time and resources, and the three reports form a useful set of priorities both for NCGIA and for the GIS research community generally.

NCGIA plans for the initiative

Any NCGIA specialist meeting identifies far more problems and issues than can possibly be addressed either by the center itself or by others within the timeframe of a single initiative. Many others are topics that are covered in one way or another by other NCGIA research initiatives, or by other individuals or groups in the research community. In this section, we identify preliminary plans for research activities at NCGIA during the active research phase of the initiative. They have been carefully selected from the research agenda constructed at the first specialist meeting, taking into account such factors as: research interests of NCGIA faculty, staff, and visitors; likelihood of progress within the timeframe and resource constraints of the initiative; and likelihood that results can be communicated and disseminated in ways that will have a valuable impact on the field. In addition, the section addresses NCGIA's thoughts on the timing, format, and objectives of the planned second specialist meeting.

Data models

The group returned again and again to the issue of data models, identifying them as holding the key to better integration between social and physical aspects of global change, between the disciplines, between software packages, and between scientists and other communities. In essence, a data model captures the choices made by scientists and others in creating digital representations of phenomena, and thus constrains later analysis, modeling, and interpretation. For example, once a remote sensing satellite has collected information in discrete rectangular pixels, using them as the basis entities of its measurements, it is difficult to extract any useful information about the distribution of radiance within pixels, or to create other representations that do not reveal their origins in one way or another.

It is important to understand the distinction between data models and data structures. The physical arrangement of bits and bytes in a digital store is described by a data structure, and by rearranging it is possible to convert one data structure into another. On the other hand a data model is conceptual rather than physical, and concerned with the meaning of the bits and bytes. In general, it is not possible to convert one data model into another without reference to the reality that the data model represents. In a geographic context, the differences attributable to generalization and aggregation, sampling, and more technical issues such as planar enforcement are data model issues; the distinction between raster and vector is often one of data structure.

Within the general arena of spatial data handling, there is much confusion over differences in data models. Some is terminological: the terms "raster" and "TIN" commonly used in GIS have rough correspondence respectively to the "finite difference" and "finite element" of numerical analysis and environmental process modeling. The term "flow" has different interpretations in surficial hydrology, atmospheric science, transportation, and migration. Each GIS embeds one or more possible data models in its world view, and uses terms to describe them whose meaning often conflicts with meaning in other systems - for example, "polygon overlay" has very different meanings in ARC/INFO and System/9, and there is abundant confusion over the precise meaning of the broadly synonymous terms "layer", "coverage", and "theme" in different systems.

A more consistent approach to data models in GIS would offer some immediate advantages: easier conversions between systems, a shorter learning curve, and more consistent terminology and command languages. Such issues lie at the heart of current efforts to define standards for GIS data, and the OGIS activity noted earlier. In general, the problem can be tackled in one of two ways: by building pairwise translations between systems; and by building a single, overarching schema with translations to each system. The main disadvantage of the first option, besides its conceptual and operational complexity, is that it would require the user of each system to learn the schemas of every other system likely to provide or use data. The second option, on the other hand, might be embedded in a more powerful theory of geographic information.

In addition to these general concerns, data models have a number of specific implications for global change research. In this area of application there is a need for data models that go well beyond those devised for more traditional GIS, to embrace time, the third spatial dimension, scale, interaction, and the curved surface of the planet. All of these are challenging issues. For example, it is unlikely that the dimension of time can be accommodated by a simple extension of GIS data structures, since to do so in a modeling environment would likely be hugely inefficient, a fact that has not escaped the designers of such dynamic modeling frameworks as cellular automata. A more comprehensive perspective is needed, and one that is again firmly grounded in theory.

With these considerations in mind, NCGIA proposes to devote the second specialist meeting to a discussion of advanced geographic data models for global change research. We feel the time is ripe, in that there has been an increasing focus on data models in the GIS research community in recent years, and much of the necessary underlying theory is already in place. We propose to organize a meeting of about 20 participants, including those who have published extensively on fundamental geographic data modeling; global change researchers who have thought deeply about data models; and the GIS vendors. We propose to hold the meeting in Santa Fe, NM in late January 1996, in conjunction with the Third International Conference/Workshop on Integrating GIS and Environmental Modeling, which is also being organized by NCGIA. This will provide the opportunity for cross-fertilization between the two meetings, and for a series of presentations on I15. The proceedings of this meeting will be published, probably as a book, and the meeting will discuss specific follow-on activities.

Interoperability

A second strong theme that emerged from the first specialist meeting was that of interoperability. Interest in this area stems largely from the widespread acceptance of the notion that despite its abundant functionality, GIS is hard to use, particularly in exploiting its potential for integrating data from a variety of sources. Even though we now have a range of format standards to help us in exchanging data, and every GIS now supports a range of alternative import and export formats, the fact remains that transfer of data from one system to another is far more time-consuming and complex than it need be. Moreover, every system has its own approach to user interface design, the language of commands, and numerous other aspects of "look and feel" that help to create a steep learning curve for new users.

To take one example, suppose two data sets are available. One is a map of land cover, stored in IDRISI as a raster with each cell classified by dominant land cover class. The other is a map of county boundaries, stored in ARC/INFO as a polygon coverage (vector) with an associated attribute table of county names. A user wishes to answer the question "how much of the area of each county is covered by each land cover class?" Conceptually, the question is well-enough defined for analysis. Certain parameters are unspecified, such as the pixel size in IDRISI, but these would only be of interest if we also wish to have an estimate of the confidence limits on each area, and are not central to the main question.

In the reality of current GIS, this simple task will spawn a long series of additional questions, complex series of operations involving transfer of data, raster/vector conversion, and overlay. While all of these will require user intervention, none serve the clarify the original request in any way; in principle, they can all be hidden from the user. Moreover, the spurious specification of transformations required by current GIS obfuscates issues of accuracy and the clarity of decision-making based on GIS analysis. We spend far too much time with current GIS learning about and dealing with issues that are artifacts of the design of the system. Thus one possible test of how well we have achieved interoperability in the future could be based on what we no longer need to know, or what no longer needs to be taught in our courses. In examples like this, the distinction between raster and vector is in principle no more fundamental than the distinction between real and integer, which was important in the early days of Fortran but is now largely hidden from the user.

Interoperability is a major issue of many dimensions, and will not be achieved within the timeframe or resources of I15. The most significant effort in the area is currently occurring under the auspices of the OGIS Foundation, which involves participants from the GIS industry, government agencies, academic research, and other users. NCGIA recently organized a small workshop on interoperability in connection with the Symposium on Spatial Databases (SSD 95) in Portland, ME, and received approval in principle from the Board of Directors for a ful-fledged initiative on interoperability to begin in 1996. The specific issues of interoperability for global change research will be handled through collaboration between the two initiatives. We also plan to build a small demonstration package using global data, and it is likely that several of the topics studied under the new initiative will also have direct relevance to I15. In addition, NCGIA is currently being funded by CERL to research ways to include data quality in the basic OGIS specification, and to implement previous research on error modeling in a series of modules for GRASS.

Spatial analysis

The first specialist meeting identified several areas where current techniques of spatial analysis are inadequate for global change research. One is the availability of techniques for analysis of phenomena on a spherical surface. A survey of existing techniques was compiled for NCGIA by Robert Raskin in 1994 as a preliminary to the initiative and published as a technical report (Raskin, 1994). In August 1995 Raskin will continue this work, and extend it in several new directions.

Another issue identified by the specialist meeting is the lack of attention to methods of sampling the spherical surface. For the past two years NCGIA has been collaborating with a project being directed by Jon Kimerling at Oregon State University to review methods available for achieving a uniform sampling density on a spherical surface, and to extend these to hierarchically nested methods capable of sampling over a range of densities. This is closely tied to earlier NCGIA work on hierarchical data structures for global GIS, in which we developed a schema based on triangular decomposition of an octahedron (Goodchild and Yang, 1992), using an idea first developed by Geoffrey Dutton and described by him as a Quaternary Triangular Mesh.

In August 1995 NCGIA will begin a six month project to develop improved methods for spatial interpolation, including methods for the sphere, that incorporate various kinds of geographic intelligence. These "smart" interpolators will go beyond the traditional generic types such as kriging and thin plate splines by attempting to model processes known to affect geographic distributions of specific phenomena, and to take advantage of known correlations. This work will be led by Cort Willmott, University of Delaware and participant in the I15 specialist meeting.

Global population database

With funding from ESRI and CIESIN, NCGIA has constructed the first consistent global database of population based on a regular grid. The database was completed in 1995, and is being distributed for use in studies which integrate human and physical processes of global change, and thus need demographic data on a basis compatible with most physical data sets. The work has been led by Waldo Tobler, with assistance from Uwe Deichmann and Jonathan Gottsegen. It uses a range of techniques of spatial analysis for disaggregating and reaggregating census population counts from arbitrary regions to grid cells.

During I15, we will continue to develop this approach, with new techniques that incorporate new types of evidence about population distribution, such as high-resolution images and images captured at night. With funding from ESRI, we are currently building a series of instruction modules aimed at K-12 classes and building on the ArcView package, to illustrate the principles involved in this effort.

Global spatial data policy

Another issue that arose repeatedly during I15 was the need to understand the influence of national government policy and other dimensions of the policy context on the availability of spatial data. This issue has recently come to the fore in arguments about access to climate records, under the auspices of the WMO. Other debates are occurring in the context of the Internet, and its implications for intellectual property rights and the international market for data. John Felkner is currently researching the WMO debate as a case study and likely precursor of other similar debates in other fields. John Estes has been actively following other debates in the general area of global spatial data policy, and efforts such as the U.S. Department of State-led Earthmap (http://www.gnet.org/earthmap) , the Japanese Millionth Map, and the international community's Core Data, to coordinate base mapping around the world and achieve a higher level of availability for digital framework data in the interests of global change research (Estes, Lawless, and Mooneyhan, 1995).

Digital library research

The Alexandria digital library (ADL) project is one of six being funded by NSF, ARPA, and NASA to conduct basic research in digital library technology and to develop basic capabilities in this area. ADL is a collaboration between the UCSB map and imagery laboratory, the departments of computer science and electrical and computer engineering, and the three sites of NCGIA, to develop a digital library for spatially referenced materials, particularly maps and images. Funding began in October 1994.

By August 1995 ADL had developed a Rapid Prototype, based on commercial off-the-shelf software (ArcView, Sybase, and Tkl/Tk) as a stand-alone system consisting of a store of maps, images, photographs, text and video objects; a catalog compatible with the Federal Geographic Data Committee (FGDC) metadata standard and the library catalog standard US MARC; and a user interface allowing the user to specify an area of query and other query parameters by interacting with a base map. The next phase of development, due in November 1995, will be a similar capability on WWW, including the ability to define an area of interest by interacting with a digital gazetteer based on the GNIS database from USGS.

NCGIA will use its links with ADL to pursue several of the issues raised during the first I15 specialist meeting, including metadata, and the impact of assorted issues of intellectual property, pricing, and privacy on access to global data. A one-day workshop is being organized by ADL in November 1995 in conjunction with the semiannual meeting of the six digital library projects to discuss broad issues of metadata, including the question of whether discussion of spatial metadata can be usefully brought under a broader umbrella, or whether it is inherently separable. Another area of importance in which I15 and ADL have a common interest is the development of metrics to compare requests formulated by users with descriptions of data available. ADL is also actively researching questions of content-based search, and the blurring of the distinction between metadata and data, a point raised during the I15 specialist meeting. We anticipate that there will be many such areas of common interest between ADL and I15 during the next two years.

Education linkages

Through an ongoing relationship with UNITAR (United Nations Institute for Training and Research), an opportunity exists to establish a direct linkage between NCGIA activities conducted under this initiative and education and policy implementation on a global scale. Under a recent agreement, UNITAR will be conducting a training program entitled "Spatial Information Systems for Global Change". The objective of this activity is to train national teams who will become the leaders in using spatial tools and methodologies to inform national decision-makers on climate change-related issues and to assist them in preparing and ultimately implementing national implementation strategies under the UN Framework Convention on Climate Change. This program will contribute to and complement other related UNDP (United Nations Development Program) enabling activities.

The challenge in UNITAR's proposed training program is to link science and policy in a manner that allows local decision-makers to have access to and to understand how to make use of the specialized tools and resulting output from climate change analysis. Specific areas of need include:

- assessing agricultural impacts of climate change;
- assessing impacts of sea-level rise;
- monitoring and predicting regional climatic anomalies;

- monitoring greenhouse gas sources and sinks;
- establishing a clearinghouse of spatial information;
- establishing a mechanism for environmental and climatic data exchange.

While UNITAR has extensive experience in providing GIS training and encouraging the development of effective GIS capacities in developing countries, this new initiative will require extensive input from global change and GIS scientists and from researchers with expertise in policy sciences. UNITAR plans to offer specially tailored workshops for individual countries who are signatories to the UN convention and eventually to develop a series of training modules, based on their current "Explorations in GIS Technology" workbooks, to bring together the experience gained through the development and presentation of these workshops. NCGIA has been invited to participate both in the development of training materials and in contributing to the substantive materials on which they will be based.

References

Estes, J.E., J. Lawless, and D.W. Mooneyhan, editors (1995) *Proceedings of the International Symposium on Core Data Needs for Environmental Assessment and Sustainable Development Strategies, Bangkok, Thailand, Nov. 15-18, 1994.* Sponsored by UNDP, UNEP, NASA, USGS, EPA, and USRA, Vol. I 59p., Vol. II 130p.

Goodchild, M.F. (1992) Geographical information science. *International Journal of Geographical Information Systems* 6(1): 31-46.

Goodchild, M.F., and Yang Shiren (1992) A hierarchical spatial data structure for global geographic information systems. *Computer Vision, Graphics and Image Processing: Graphical Models and Image Processing* 54(1): 31-44.

Raskin, R. (1994) Spatial Analysis on the Sphere. Technical Report 94-7. Santa Barbara, CA: National Center for Geographic Information and Analysis.

DATA ISSUES

Tim Foresman and Ken McGwire

Many perspectives on the issues of data were available when considering an appropriate or effective list of research issues under the NCGIA Initiative 15 charter. Data are the foundation of understanding and advancement for the domain of global change research. Global change provides a challenging context for examining the current impediments to spatial data handling and the conversion of data to information. These challenges are concerned with issues of data volume, multiple scales of data, access to widely disparate data resources, and long-term storage of data. Other issues attendant to this topic, but not necessarily unique to global change research, are concerned with quality of data, documentation of data fitness (metadata), facilitation of data exchange, and handling of temporally sensitive data or time-series data. The issues identified by the I15 data working group provide a collection of possible research areas associated with the evaluation, collection, processing, and storing of data. The primary focus of this working group was on conceptual and procedural requirements for improved data sources with respect to global change research objectives.

Issues identified by the working group were organized into six major categories, each containing a spectrum of overlapping interest to global change researchers and GIS specialists alike. It was thought by the assembled group of experts that this arrangement of topics represented a reasonable approach to defining research issues, but does not represent any ranking or priorities related to these topics. Data issues were originally organized under the titles of:

- data quality
- metadata
- access and archiving
- facilitating input, output, and conversion
- product quality enhancement, and
- temporal update requirements.

A description of the major highlights for these categories is provided with the goal of furthering our understanding of current impediments to the use of data by global change researchers within a GIS context. This will provide a focus for efforts in GIS research community to address global change research requirements. A great deal of overlap was identified between and within the six categories listed above during the I15 meetings. Much of this redundancy has been addressed in the following discussions, including the collapsing of product quality enhancement and temporal update requirements into the data quality discussion.

Data quality

In this context data quality refers to the quantitative characterization of data and establishment of criteria to assess its fitness for use. Common concern with respect to this topic was evident when discussing the unknown quality of potential data resources. The following issues were highlighted by the I15 data issues subgroup:

1. *Quality assessment criteria.* What methods exist for characterizing the statistical uncertainty of continuous fields in multiple dimensions? What efficient methods exist for communicating the expected precision and biases of a multi-dimensional dataset to a potential user?

In discussion, the two dimensional, time invariant approach of traditional GIS development was often seen as a limitation to the effective use of GIS by global change researchers and this area is not an exception. Measures of cartographic accuracy are typically defined with respect to well-defined, fixed targets. This approach is ineffective for three dimensional, time varying fields characterizing the transfer of mass and energy. Methods need to be developed, or if existing then made available, for characterizing statistical uncertainty of continuous fields.

Participants with some familiarity with the previous work of NCGIA suggested that findings associated with NCGIA Initiative 1, "Accuracy of Spatial Databases," be reviewed in the context of needs outlined by the I15 group to identify whether any methods would seem reasonable candidates for extension beyond two dimensions.

The theme of interdisciplinary communication was brought up several times in open session, especially with respect to integrating environmental and socio-economic data. Thus, methods of characterizing data products should be developed which are meaningful across disciplines.

Clearly the data quality issue pervades the entire spatial data processing flow, and the characterization of data quality should encompass efforts of end-users by providing useful supplements to recent federal and vendor quality assurance standards or criteria. These efforts should take into consideration how scientists, policy-makers, and the public account for uncertainty in spatial data, if at all. What forms of documentation and visualization are most useful to maintain awareness of uncertainty in the basic data sources?

2. *Certification of data for various applications.* As mentioned, there was open discussion of the needs for development and use of data sets in ways that cut across traditional disciplinary boundaries. In doing so, how can discipline-specific knowledge be passed on to new users so that the potentials and limitations of data sets are better understood? Can the data quality issues described above be put in a taxonomy or codified with respect to different applications?

A suite of data products derived from satellite measurements are to be made available from the Earth Observing System Data and Information System (EOS/DIS). However, the official adoption of algorithms poses a question as to which methods are best? Adoption of an algorithm is generally driven by some degree of community consensus. Have there been any lessons learned in this process of scientific consensus, and are there opportunities for representing this consensus opinion in such a way that less experienced users can use the data intelligently?

3. *Data vs. model output.* Most physical parameters cannot be directly measured in a thoroughly systematic manner over the globe. Thus, global fields must be estimated using statistical or physically-based models. Subsequent analyses which use these estimates as inputs should be able to consider the potential variability of estimated values. An example of this capability can be implemented in the statistical domain with geostatistical methods or in the physical domain with Monte Carlo simulations. In order to characterize such products in a GIS for global change applications we must determine the appropriate methods for given types of parameters and models.

Because of the aforementioned inability to validate many parameters or because of the uncertainty in future states, currently global scale models are being validated through comparison with other models. The assessment of a model's possible accuracy and subsequent utility is then based on the ways in which it agrees or deviates from a set of existing models. Such measures of relative agreement may be useful characterizations, though not based on absolute accuracy. Is there a need to establish a systematic method for performing or documenting such agreement in modeled data products?

4. *Improving the quality of spatial data.* Many data production systems include consistency checks to help ensure that erroneous measures are screened out. Can we go beyond this and actually improve the accuracy of spatial data by taking advantage of the correlations which exist between data sets? How would such procedures be described with respect to subsequent use and accuracy assessments?

5. *Temporal data.* Adequate handling of time series and time dependent variables will be of critical importance in the further migration of GIS into the global change research arena. What GIS techniques should be developed to allow the interpolation of multi-temporal spatial data to common time steps? Are variations of the current GIS paradigm of static map layers appropriate, or should analysis functions generally allow for temporal resampling on the fly?

Are there optimal methods for characterizing the time dependence of data? For example, satellite data may be created for a large area by mosaicing multiple orbital passes. The derived product now has a spatial pattern of temporal discontinuities. These inconsistencies may create a biased representation of phenomena such as vegetation productivity if rates of change are high. Current methods implemented by the EROS Data Center store information on the acquisition characteristics of each pixel in their AVHRR mosaics, but is such information being used effectively in the quality assessment process?

In recognizing the inherent degradation of data over periods of time (data rot), can we design methods for reasonable life cycle management of data and can these methods be assigned to a data set? What are the best techniques for characterizing the potential effects of continuous or discrete, sporadic landscape changes such that these uncertainties may be assessed during analysis? How can we enhance our investment in data through periodic updates of subsets or all of the database?

Metadata

Requisite to advancing any research agenda is the establishment of common understanding by the participants of a problem's definition. While metadata (loosely defined as data about data) has been recently well publicized in federal and academic information management circles, there remains a wide gulf in the fundamental understanding of what metadata precisely entails. This divergence in conceptual definitions will need to be addressed before more detailed research can remove technical or theoretical barriers to improved documentation of global data resources. The following highlights were identified as appropriate research needs for metadata:

1. *Uncertainty of spatial data*. Whereas the previous section discussed the concept of ideal characterizations of data quality for global change data sets, this issue asks how this information on data quality will be associated with the dataset and how should it be condensed for rapid communication? How should uncertainty estimates of attribute and location best be defined in documentation files? Are metadata models flexible and thorough enough to handle the various distinctions outlined in the data quality section above, such as temporal series or performance relative to other models? How can this information about the dataset be effectively used and communicated in automated database searches?

2. *Knowledge of existing standards.* It can be quickly demonstrated that most global scientists are not fully aware of many existing data quality standards developed from federal agencies, vendor consortia, and professional associations. What steps can be taken to encourage the use of such standards, while lowering the burden on users to be immediately cognizant of all possible standards? For example, is there a site on the Internet which serves as a clearinghouse for such documentation?

3. *Support of high-level constructs*. What methods can be applied to define abstract ways of describing data flow from collection, through processing, and up to decision making? It was pointed out in discussion that the language used by the GIS and modeling communities is sometimes inconsistent (e.g. the term "vector"). What mechanisms can be developed in terms of metadata definition and query handling that will facilitate the identification of appropriate data by users who are not closely involved with a given instrument or dataset?

This concept may also include the issue of data versus information. In searching for data, a researcher may want to identify whether a particular phenomenon exists within a dataset. This could be quite time consuming. Is it practical that metadata regarding such data contents could be generated by automated feature recognition techniques? Could current metadata constructs support a query such as "find all the sea surface temperature data sets for the South Pacific which have anomalously high values for two consecutive years."

Access and archiving

Barriers to the use of global databases will be reduced as capabilities for accessing and archiving large volumes of data through the electronic communication networks become essentially transparent to the user community. Most of these efforts are being addressed by various research teams in computer science and electronic library research. However, the specifics for spatial data handling remain significant research areas. The major items discussed during the I15 specialist meeting are described below.

1. *Recoverable archives.* By definition, archives are for storage of data. However, there are instances where data exist in an archive, but cannot be restored. How can data be maintained and recovered over long periods of time, that is, decades to half centuries or longer? As the period of storage increases so does the volume of data. How should trade-offs be made relative to designing and protecting data deemed critical for long-term analysis of the planet's processes? Will the archive status of global change datasets be handled in an ad hoc manner by players in the various disciplines, or should there be an ongoing effort to define key parameters which must receive priority for the long term investment involved in data archiving?

2. *Maintaining primitives.* What approach should be taken to ensure that data remains in its original primitive state as opposed to processed or reformatted formats? It has been pointed out that a few interesting advances in global research have been brought about by locating and analyzing data that was overlooked in the past. This was demonstrated by the late of the Antarctic ozone hole in satellite-based ozone data for the Antarctic which had originally been rejected as flawed by automated data screening methods. What are the most efficient methods to maintain access to both raw and manipulated data types, given the massive data volumes which are expected in the coming decades?

3. *What level of processing?* Can protocols be established to justify the levels of processing applied to various global databases? What are the most efficient methods for determining whether to process on demand versus storing precomputed values? One approach to addressing this that was mentioned is to determine how current users develop and distribute multiple products. The prototype capability being tested for accessing AVHRR data from the NASA Goddard Distributed Active Archive Center at multiple resolutions was described as an example. In performing such flexible data access, what techniques can be applied which account for data loss and generalization resulting from compression and resolution adjustment?

4. *Support of high-level constructs and selection by feature.* How can high-level constructs be represented in queries to large, distributed databases? What techniques are available and what research agenda should be pursued to provide the capability to search and retrieve data by features, relationships, or time-critical events in a database? What advances in object-oriented database design and automated feature recognition should be examined for searches of specific phenomena over a distributed network of databases?

5. *Public access.* What institutions will provide for public access to global data and what capabilities must be developed to communicate such data and information to the layperson or decision maker? What are the appropriate roles, and hardware and software requirements for groups such as libraries and schools to effectively make this information available? What interdisciplinary connections would be required to facilitate the use of global data by policy makers and their staffs?

Facilitating input, output, and conversion

A variety of advances are being made among vendors and among federal agencies in defining standards for the integration of different data formats. Data conversion advances have progressed as a result of both broader representational requirements and the advocacy of open data standards. Federal agencies have been working in concert to develop, promote, and mandate data exchange standards to open opportunities for data interoperability at the national level. Items of concern in this area which remain for GIS in global change research include:

1. *Interoperability.* What role can the research community play in improving data exchange, both institutionally and technologically? Can the research community further encourage open data access to proprietary data sources and formats? What data format translators are required to facilitate the sharing of data across traditional disciplinary boundaries and who will develop these tools? Such efforts would require a review of the current arrangements that exist for distribution of data within the various disciplines conducting global change research.

2. *Reducing burden on data providers.* What can be done to make it less discouraging to provide data to the global research community? How can the burden of multiple page documentation be streamlined or automated to free up data producer's finite resources?

Further issues

Some other items of concern that did not appear to fit within the constructs of the above data issues were discussed amongst the workshop participants relative to the data issue topic. These are included as they may provide additional context for defining specific research items for advancements in spatial data systems for global research.

1. *Lack of global multidisciplinary data sets.* It appears that most global data sets are constrained to specific research disciplines. Oceanographic data sets are not easily understood or applicable to

terrestrial ecosystems modelers and Landsat data are not easily applied to atmospheric models. What would multidisciplinary data sets look like? How can interdisciplinary teams approach the construction of integrated Earth systems modeling without a fundamental understanding and exchange of multidisciplinary data?

2. *What are target spatial and temporal resolutions for mesoscale modeling?* General circulation models provide estimates which are often too coarse to interpret meaningfully at the scale of many terrestrial processes or regional decision making. Mesoscale modeling techniques are being explored which take GCM outputs as boundary conditions and use much more detailed spatial data to calculate processes at finer scales. What are the ultimate spatial and temporal resolutions which may be reasonable for such efforts? What sources of data msut be developed to support such detailed modeling efforts around the world in a consistent manner? What are the sensitivities of these mesoscale models to error in the various spatial data inputs?

3. *System design to bring these ideas to a coherent implementation.* A comment which was made near the end of the meeting for the data issues group was that a comprehensive analysis of the aforementioned research issues within a broader systems context would likely provide greater benefit to the research community. Such an effort would require a better understanding of the priorities, interdependence, and required levels of effort for the aforementioned data issues.

Other discussions

Other topics relevant to the data issues group were discussed among meeting participants, and some of these comments are identified here. It was pointed out that to look at data issues as a subject in and of itself would likely result in continuing barriers to an effectively integrated analytical system. As an introduction to the I15 meeting, a vision of an end-to-end system integrated within an object oriented paradigm was presented by Jeff Dozier. Such a capability would require a rethinking of the topics presented here in a cross-cutting manner from acquisition through decision making.

During the meeting Francis Bretherton made a presentation on the topic of metadata which is clearly relevant to the data issues group. This presentation described a reference model to begin the task of developing consistent implementation of metadata across disciplines. This material was originally presented at the 7th Conference on Scientific and Statistical Data Bases in Charlottesville, Virginia on September 29, 1994.

The role of socio-economic data and methods to better integrate it with environmental data was raised several times in discussion. One of the key aspects of this discussion with respect to the data issues group had to do with methods to deal with the irregular spatial framework of socio-economic reporting units (i.e. countries, states, counties, etc.) The work by Waldo Tobler to create a population dataset on a regular, fine latitude/longitude grid using pycnophylactic interpolation was identified as an example of progress in this area.

A final data issue that was addressed by the group was a concern for the recent change in WMO data policy associated with cost recovery efforts. The sharing of meteorological data through this network has enabled a vast amount of research and the group indicated that the potential risks in reducing the uniformity and accessibility of this global data collection network may have serious implications for global change research.

Concluding comments

A few items deserve mention, although most are considered commonsense to experienced scientists. These include the reality that data will always be imperfect. The degree of imperfection and its causes will always be of interest to the research community. Each discipline will soon be, if it is not already, overwhelmed by the data volumes associated with intensive global scale studies. Lastly, the life cycle of data from the collection of each datum, to science user, to long-term archives needs to be viewed as a system. An understanding the life cycle of massive, disparate databases will be paramount for managing these resources within the context of global change research.

REPRESENTATION AND ANALYSIS

Kate Beard

Discussion

One of the key impediments to GIS identified by this group was the range of different data models used by various constituents of the global change research community. A large part of the discussion focused on data models and people's understanding of data models. Several people offered their view of data models and it became clear that lack of a common understanding of the term "data model" is in itself an impediment. Thus a goal of the subsequent discussion was to articulate various views of data models as a foundation for reconciling or understanding different viewpoints.

Every domain has its own worldview which is often reflected in its models. In initial discussion of data models, Bretherton identified a data model as a set of data structures, but stressed that it also incorporated higher level abstract concepts that include metadata. Beard suggested that a data model must formalize the abstract concepts behind data structures. Brand described a data model as the high-level conceptualization of the problem that defines the way data is captured and stored. Bliss used the relational data model used for the STATSGO soils database as an example of his understanding of a data model. Maidment offered the "General Control Volume Equation" from fluid dynamics as an example of a data model and described how he translated this into the vector model of a GIS. He described this model as including some representation of space and a description of flows into, across, and out of a unit space. Willmott pointed out that the general control volume equation based on differential equations was a good example of a model with relevance across many domains. This provided a good example of the possibilities for finding commonalties among data models used in different disciplines.

In summary of the discussion, a data model was identified as a conceptual model of how a system works, what the flows are and how time and space are handled. A three part structure was identified, as follows:

a) *the conceptual level*: organizes what is observed; it is the abstract concepts in the universe of discourse and their relationships; the concepts of objects and relationships which includes assumptions about dimensionality, continuity, and uncertainty.

b) *the representational level (data structures)*: identifies how objects of the conceptual level are represented; identifies data structures such as the layer-based or object-based approaches in GIS. One data model can be represented by a set of possible data structures, such as points, pixels, or TINs.

c) *the implementation level*: the bits and bytes.

One identified task was to document the different data models in use by the global change community. Cornillon suggested a three part agenda to explore identification and reconciliation of data models:

1) characterization of existing different models;

2) development of new models based on existing needs;

3) interfaces between models.

Bretherton suggested that the actual problem is how to interface such models with GIS. A number of suggestions followed on approaches to reconciling different models. Maidment suggested one goal could be to measure the representational efficiency of a data model. Bliss indicated there must be a common underlying idea of time and space for all models.

Some of the discussion focused on different fundamental assumptions of models. Band pointed out that the California GAP Analysis uses a data model based on individuals. Bretherton indicated that the main difference between fluid dynamics modeling and the discrete GAP model is that in the latter the attributes travel with the individual. In modeling parlance this is described as the difference between the Lagrangian and the Eulerian approaches.

Berk suggested another research issue would be data model evaluation. What are the costs of making a mistake? What are the metrics for measuring user satisfaction with a data model? He also suggested that another possible characterization of data models would be by number of parameters and whether they are linear or non-linear. Chen raised the question of how time series could be included in a GIS-compliant data model. Maidment redirected the discussion to the focus of global change in which the concept of change is the key word. In the context of data models the model must support some representation of change.

Following the discussion of models the group returned to the fundamental question "What is the role of GIS in Global Change Research?". The following topics were identified as important:

- Integrating GIS with user-based or user-defined models;
- Inclusion of temporal analysis and links to spatial statistics;
- Uncertainty representation as an issue that needs to be more forcefully addressed by the GIS community;
- Abandoning the myth of the local decision maker as less sophisticated;

- Identifying a wide range of use issues which are relevant to the success of GIS within the global change research community.

- Focus on how to describe change and how to describe movement through a landscape;

- Focus on reconciling or finding mappings between different descriptions of space;

- User interface issues and the interoperability of analysis functions among systems;

- Research on aggregation and generalization of data;

- Development of distributed systems, in which both data and analysis tools will be distributed;

- Integration of data from different sources and scales;

- GIS is strong in pattern analysis. This capability should be applied to the modeling techniques of global change research.

- GIS should accommodate more (useful) data models. The map layer model is inappropriate for global change research. Current GIS do not allow the integration of domain knowledge, rather they are data-driven.

Most of these issues can be traced to a need for more sophisticated data models than are now in use in GIS.

Summary of representation and analysis impediments and action items

Research topics were organized under three sections: data model issues, interoperability issues. and analysis issues.

1. *Data models*: The goal of the research agenda under this section would be to define and improve data models and to develop more flexible methods for mapping between the concepts in different domains. This was seen as a more basic reserch task involving interaction among differnt domain scientists. A workshop was also suggested as a possible approach to clarify and itemizing model differences. Itemized tasks under this section included:

a. Development of a language for data model description;

b. Documentation of models from each domain;

c. Abstraction and identification of shared elements;

d. Construction of translators between models at the conceptual level.

2. *Interoperability (user view)*: The research goal under this section was to overcome impediments to interoperability at several levels. This section was seen as having an implementation focus in contrast to a more basic research approach to reconciliation of conceptual issues covered under Section 1. Research tasks were to investigate issues of interoperability:

a. among disciplinary domains;

b. among GIS analysis tools and models;

c. between scales (time and space);

d. between data structures (for example between raster and vector data structures);

e. among distributed systems (interoperability should provide support for processing between dissimilar systems as well as exchange of data between dissimilar systems);

f. among user communities (scientist, policy makers, public; the focus here would be to investigate institutional and educational structures to promote interdisciplinary or cross cultural exchange);

g. across space-time referencing systems;

h. representation of uncertainty and error propagation (this was identified as a cross cutting theme in which the research focus here would be on uncertainty or errors associated with interoperability, e.g. the loss of information in the transformation between data structures or the potential loss of information in reconciling concepts from different domains).

3. *Analysis issues*: The research agenda under this section was intended to enhance or develop new spatial analytical functionality. This section was seen to have both a basic research component as well as an implementation component for cooperative development with industry.

a. Development of analytical tools to aid in developing sampling strategies and variable selection;

b. Development of tools to support spatial aggregation and disaggregation considering spatial distribution of variables being aggregated and disaggregated (there are obvious reliability or uncertainty issues associated with this topic);

c. Enhancement of space/time statistics and estimation methods such as interpolation;

d. Uncertainty; the emphasis under this section would be investigation of uncertainty associated with analytical processes as well as an analytical tools to better describe and visualize uncertainty;

e. Enhancement of pattern recognition tools (there is a need for analytical tools to quantify pattern and differences in pattern across space time scales);

f. Development of visual analytical tools (this topic has some relation to the pattern recognition topic above in that there can be effective visual tools to extract or highlight patterns);

g. Development or enhancement of tools for model simulation;

h. Development of higher dimensional systems (this included the development of tools for handling three, four, and potentially n dimensional spaces);

i. Development of spherical analysis tools (for example this could include development of GIS operations for the sphere).

INTEGRATION AND COMMUNICATION

Jenny Robinson

Preface

In preliminary discussions on the first day, integration and communication were recognized by the participants as the third of three major areas of concern. It was felt that GIS had much to offer as a tool for integration of data and analysis between the various disciplines involved in global change research, particularly between the physical and social sciences. Its data models accommodate the integration of multiple layers of data and their simultaneous linkage for modeling and analysis, while the software's functions provide comprehensive support for associated tasks of projection change, resampling, or format conversion. In addition, GIS was perceived as an important tool for communication of the results of scientific research, their transformation into policy, and communication of the importance of global change science to society as a whole. GIS is a visual technology, opening the opportunity to influence people more effectively than through more conventional means. The working group on integration and communication provided an opportunity for the discussion of some of these issues and their implications, and identification of suitable associated items of a research agenda.

The group met three times. 26 people participated in one or more session. Eighteen people attended only one session, five people attended two sessions, and three people attended all three sessions. The "one session" attendees were in many cases the most vocal people in the group, hence there was considerable variation of group focus, tone, and dynamics from one session to the next. Rather than attempt a summary of the entire discussion, the following treatment emphasizes the end product of the group as it resulted from the third meeting.

Integration and Communication in Global Change Research (Inreach)

The group first took on the question of integration and communication within global change research, that is, integration and communication between scientists. Here the needs were perceived primarily in terms of interdisciplinary exchanges. In the interdisciplinary case, we recognized scientist-to-scientist transactions as being, in effect, exchanges between experts and non-experts, where each party is an expert in his or her domain and a non-expert in the other's domain. Like scientist-policy and scientist-public communication, interdisciplinary communication and integration are often problematic, and might benefit by specific actions on the part of the GIS community.

Early in discussion, several people advanced the concept that process models establish the framework for integration and communication between scientists in different disciplines. Global process models are central to global change research and their importance cannot be overstressed. They provide the holistic conceptualizations, such as the principles of conservation of mass and energy, that must drive research. The capabilities of GIS for spatial analysis must be supportive of process-based science, and methods of spatial analysis must be selected within the broad framework of its conceptualizations, and disciplined to them.

For example, spatial analytic tools are needed to facilitate interpolation, extrapolation, and sampling to fill in information where data are sparse. Tools are needed for spatially-oriented varieties of model validity and sensitivity testing where data are too sparse for credible interpolation. It is important that the tools used for such analysis be informed by process models; the tendency of GIS software to provide generic solutions to such tasks, based on principles of geometry rather than an understanding of processes operating on the Earth system, was seen as a signficant impediment and a suitable topic for research. So-called "smart" interpolators that make use of intelligence derived from other information sources and understanding of process are one example of the tools that are needed in this area.

At the same time, the group stressed that the need for such tools is most apparent in areas where data are hard to come by or incomplete, particularly in the areas of social research associated with global change. In other areas, such as those that rely on remote sensing, the apparent abundance of data may suggest that such tools are unimportant.

Integration and Communication between Global Change Researchers and the Wider Community (Outreach)

It was the sense of the group that integration and communication were not ends in and of themselves, but were important as part of the process of applying the increased spatial understanding afforded by GIS technology to the service of social needs. In particular, there is an acute need for improved understanding and management of the processes of global change. The emphasis of the discussion was on integration and communication between people or groups with different traditions and different perspectives on global change. Three groups were identified loosely for the purposes of discussion: policy- and-decision makers, the general public, and scientists.

It was noted that needs varied between communities. In science, the needs were for integration of data with models and transfer of knowledge and tools across domains of expertise. Global change research is inherently multidisciplinary, and creates perhaps unprecedented needs for communication across the barriers created by differences of terminology, data models, process models, and scientific paradigms. These problems are made worse rather than easier by electronic communication, which allows even greater geographic and disciplinary separation to exist between the originators, custodians, and consumers of models and data.

In relating to the public, there are strong needs for better tools for communication, including visualization aids, jargon-free means of conveying understanding and knowledge, means of conveying uncertainty associated with scientific information and understanding, and generally more successful strategies for the media. These must include a willingness to accept public feedback:

for example, if public interest is predominantly on "how will this affect me and my neighborhood", we cannot expect great public interest in globally generalized scenarios. If we cannot produce point-specific information, we are going to have to get better at conveying the reasons and implications of our inability to be precise.

It was emphasized that having and using the tools does not make one right or effective, and that the deployment of GIS technology should be focused on bidirectional exchanges based on mutualism, for which we used the term "strategic alliance". Strategic alliances might, and should, run in many directions, but effective linkage of users to technicians is of paramount importance. For example, the Sequoia 2000 Project brought together natural scientists with computer scientists in the design of a strategy for terabyte databases.

It is essential that communication out (broadcasting) be balanced by communication in (feedback/listening). The needs for democratization (communication between science and the public) and decision support (effective communication between science and decision-making) were emphasized in this context. Discussion emphasized that terms such as "needs assessment" and "decision support" must be considered as real-world processes, encumbered with the complexities of politics and human nature. Recommendations and solutions must not be presented as technical abstractions, but as answers to real needs. For example, it was pointed out that decision-makers are far more interested in decision support that provides a basis for sharing of responsibility than in scientifically optimal decisions based on extensive and rigorous analysis. If one makes a decision based on some scientifically-validated model and that model later proves wrong, one would want the basis for that decision to be understandable to one's constituency, so that some of the responsibility for the resulting mistake can be shifted onto the scientific community.

The group noted that the scientific community lack expertise in dealing with the general public, and are often disdainful of expertise in journalism, public relations, and popular multi-media communication. Integration and communication with the public was under-represented in our discussion. It was strongly recommended that this imbalance be made up for in the second specialist meeting. In particular, the next specialist meeting should include, along with the obvious assortment of computer and data specialists and policy analysts, specialists who could deal with the broader aspects of communication in the electronic age, such as applied psychologists, policy analysts, experts in risk assessment, journalists, and marketing specialists.

To promote integration and communication, and the spatial intelligence they might bring to society, the group recommended the following process. First, a parallel activity involving assessment of needs and inventory of tools is needed. This should consider both needs and tools in the broadest sense. For example, on the needs side policy makers have a variety of needs that arise from the social accounting frameworks and incentive structures inherent in the policy process. In these frameworks, performance is evaluated by looking at the extent of achievement of targets or goals. In general, these goals are defined in broad or ubiquitous spatial terms: for example, pollutant concentrations must not exceed a specified threshold. Achievement, however, tends to be defined in spatially explicit fashion, for example by the points in a monitoring network.

Recognition of the needs implicit in this framework is a prerequisite for successful and widespread dissemination of GIS within the policy community.

The group recognized that among ourselves we did not span the range of expertise required to define these needs intelligently, or to specify the products or procedures required to satisfy them. It reiterated its earlier suggestion above that the next specialist meeting include specialists who could deal with the broader aspects of communication. Likewise, on the tools side, focus should not be restricted to the software products that are marketed as GIS by their producers, but should extend also to the mechanisms that may translate GIS-derived results into forms that can be digested by the public and the policy community. Visual communication was recognized as being of predominant importance. Commercial art software, including products such as drawing packages, games (SimCity and SimWorld), and photographic manipulation packages (Photoshop) were recognized as important for transformation of the products of science into products with policy utility or popular appeal. On the science side, the inventory should treat products such as IDL, MatLab, NCAR-Graphics, PV-Wave, and S-Plus, which are commonly employed to deal with statistical, visualization, and other aspects of spatial data handling but are not normally identified as GIS because of their limited functionality.

A synthesis of the needs survey and tools inventory should lead to a summary of "best practices", perhaps in the form of an online handbook or guidance system. This would cover the frequently encountered and critical issues of spatial analysis as relating to global change, and provide up-to-date information on current best solutions to them. It was concluded that at least two products were needed, one targeted to scientists and one targeted at decision-makers and the general public. CIESIN was identified as a possible host organization, as they have invested heavily in communication and dissemination infrastructure for global change research and policy-making.

This proposed effort to identify best practices could yield several important spinoffs. It could lead to the identification of gaps in the technical system, leading to further research initiatives and activities to bridge those gaps. It could yield useful information for development of a common language to deal with data and metadata (we assumed that the data and data modeling group were doing justice to this subject and did not take discussion very far). It could promote the building of strategic alliances between scientists of different disciplines, between scientists and decision-makers, and between scientists and people who work with the general public. Although diagrammed as linear, the entire process was recognized as iterative. Identification of gaps should feed back to best practices and improvement of tools and practice; strategic alliance building should lead to better assessment of needs and better definition of what useful functions GIS tools (broadly defined) can achieve; development of common languages should ameliorate many of the impediments to progress and to communication.

APPENDIX 1: LIST OF PARTICIPANTS

Dr. Richard Appelbaum
Director, Community and Organization Research Institute
University of California
Santa Barbara, CA 93106
PH: (805) 893-7230 FAX: (805) 893-2790
appelbau@alishaw.ucsb.edu

Dr. Richard Aspinall
Macaulay Land Use Research Institute
Craigiebuckler
Aberdeen
AB9 2QJ, Scotland, UK
PH: (0224) 318611 FAX: (0224)311556
mi019@mluri.sari.ac.UK

Dr. Thomas Baerwald
NSF, Directorate for Geosciences
4201 Wilson Blvd.; Room 705
Arlington, VA 22230
PH: (703) 306-1502 FAX: (703) 306-0372
tbaerwal@nsf.gov

Dr. Larry Band
Department of Geography
University of Toronto
Toronto, Ontario
Canada M5S1A1
PH: (416) 978-3375 FAX: (416) 978-6729
lband@eos.geog.utoronto.ca

Dr. Kate Beard
NCGIA/Univ of Maine
348 Boardman Hall
Orono, ME 04469-5711
PH: (207) 581-2149 FAX: (207) 581-2206
beard@mecan1.maine.edu

Dr. Richard Berk
Program in Statistics
Room 8118, MSB
University of California
Los Angeles, CA 90024
PH: (310) 206-9544
berk@stat.ucla.edu

Dr. Norman B. Bliss
Science and Applications Branch
EROS Data Center
Sioux Falls, SD 57198
PH: (605) 594-6034   FAX: (605) 594-6589
bliss@dgl.cr.usgs.gov

Dr. Francis P. Bretherton
Space Sciences Engineering Center
University of Wisconsin
1225 W. Dayton St.
Madison, WI 53706
PH: (608) 262-7497   FAX: (608) 262-5974
fbretherton@ssec.wisc.edu

Dr. Robert S. Chen
Project Scientist, Socioeconomic Data and Applications Center
Associate Director, Interdisciplinary Data Resources Division
Consortium for International Earth Science Information Network
2250 Pierce Road
University Center, Michigan 48710
PH: (517) 797-2611   FAX: (517) 797-2622
bob.chen@ciesin.org

Mr. Charles Convis
ESRI, Conservation Program
380 New York Street
Redlands, CA 92373
PH: (909) 793-2853   FAX: (909) 793-5953
cconvis@esri.com

Dr. Peter Cornillon
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882
PH: (401) 792-6283 FAX: (401) 792-6728
pete@uri.gso.uri.edu

Dr. Frank W. Davis
Dept of Geography
Univ of California
Santa Barbara, CA 93106-4060
PH: (805) 893-3438 FAX: (805) 893-3146
fd@geog.ucsb.edu

Dr. Liping Di
Principal Scientist
Hughes STX
7701 Greenbelt Road Suite 400
Greenbelt, MD 20770
PH: (301) 441-4104 FAX: (301) 441-1853
lpd@ulabsgi.gsfc.nasa.gov

Dr. Jeff Dozier
Department of Geography
University of California
Santa Barbara, CA 93106-4060
PH: (805) 893-7363 FAX: (805) 893-7612
dozier@geog.ucsb.edu

Dr. Daniele Ehrlich
IRSA/JRC Inst. for Remote Sensing Applications
Joint Research Center
21020 Ispra (VA)
Italy
PH: +39-332-785018 FAX: +39-332-789073
daniele.ehrlich@jrc.it

Dr. Jack Estes
USGS
National Mapping Division
516 National Center
Reston, VA 22092
PH: (703) 648-5752   FAX: (703) 648-5792
jestes1@usgs.gov

Dr. Tim Foresman
Department of Geography
University of Maryland, Baltimore Co.
Baltimore, MD 21228
PH: (410) 455-3149   FAX: (410) 455-1056
foresman@umbc.edu

Dr. Rong Fu
Assistant Professor
Department of Atmospheric Sciences
University of Arizona
Tucson, AZ 85721
PH: (602) 621-6955   FAX: (602) 621-6833
fu@air.atmo.arizona.edu

Mr. Jerry Garegnani
Office of Mission to Planet Earth
NASA Headquarters, Code YD
300 East St. SW
Washington, DC 20546
PH: (202) 358-0770   FAX: (202) 358-3098
jgaregna@mtpe.hq.nasa.gov

Dr. Catherine Gautier
Department of Geography
University of California
Santa Barbara, CA 93106-4060
PH: (805) 893-4912   FAX: (805) 893-2528
gautier@icess.ucsb.edu

Dr. Leonard Gaydos
NASA Ames Research Center
242-2
Moffett, CA 94035
PH: (415) 604-6368   FAX: (415) 604-4680
len@gaia.arc.nasa.gov

Dr. Michael Goodchild
Director, NCGIA
University of California
3510 Phelps Hall
Santa Barbara, CA 93106-4060
PH: (805) 893-8049   FAX: (805) 893-7095
good@ncgia.ucsb.edu

Dr. Carolyn Hunsaker
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6038
PH: (615) 574-7365   FAX: (615) 576-8646
cth@ornl.gov

Dr. David Kirtland
U.S. Geological Survey
519 National Center
Reston, VA 22094
PH: (703) 648-4712   FAX: (703) 648-5542
dkirtlan@usgs.gov

Dr. Timothy Kittel
Climate System Modeling Program
UCAR
Box 3000
Boulder, CO 80307-3000
PH: (303) 497-1606   FAX: (303) 497-1695
kittel@ncar.ucar.edu

Dr. George Leavesley
USGS, WRD
Box 25046, MS 412
Denver Federal Center
Denver, CO 80225
PH: (303) 236-5026 FAX: (303) 236-5034
george@snow.cr.usgs.gov

Dr. Brian G. Lees
Department of Geography School of Resource and Env. Management
The Australian National University
Canberra ACT 0200 Australia
PH: 06 249 3795 FAX: 06 249 3770
Brian.Lees@anu.edu.au

Mr. Millington Lockwood
NOAA National Oceans Service Code NX2
1305 East West Highway
Bldg. SSMC 4, Rm 13363
Silver Spring, MD 20910
PH: (301) 713-3070 FAX: (301) 713-4307
mlockwood@ocean.nos.noaa.gov

Dr. David R. Maidment
CRWR
Balcomes Research Center
University of Texas - Austin
Austin, TX 78712
PH: (512) 471-0065 FAX: (512) 471-0072
maidment@crwr.utexas.edu

Dr. Kenneth McGwire
Desert Research Institute
Biological Sciences Center
7010 Dandini Blvd.
Reno, NV 89512
PH: (702) 673-7324 FAX: (702) 673-7397
kenm@maxey.unr.edu

Dr. Roberta Miller
CIESIN
2250 Pierce Rd
University Center, MI 48710
PH: (517) 797-2604 FAX: (517) 797-2622
roberta.miller@ciesin.org

Mr. John O'Connor
World Bank
1818 H Street NW, Bldg S Rm 5041
Washington, DC 20433
PH: (202) 473-3805 FAX: (202) 477-0565
joconnor2@worldbank.org

Dr. Anand Patwardhan
Carnegie Mellon University
Dept of Engineering and Public Policy
Pittsburgh, PA 15213
PH: (412) 268-2670 FAX: (412) 268-3757
ap10+@andrew.cmu.edu

Dr. Chris Potter
NASA Ames Research Center
MS 242-4
Moffet Field, CA 94035
PH: (415) 604-6164 FAX: (415) 604-4680
cpotter@gaia.arc.nasa.gov

Mr. Robert G. Quayle
Global Climate Lab
National Climatic Data Center
151 Patton Ave.
Asheville, NC 28801-5001
rquayle@ncdc.noaa.gov

Dr. Jenny Robinson
Department of Geography
SUNY, NCGIA
301 Wilkeson Quad
Buffalo, NY 14261-0023
PH: (716) 645-2545 x56 FAX: (716) 645-5957
jrobin@geog.buffalo.edu

Mr. Ashton Shortridge
NCGIA
Univ of California
3510 Phelps Hall
Santa Barbara, CA 93106-4060
PH: (805) 893-8652   FAX: (805) 893-8617
ashton@geog.ucsb.edu

Dr. Ashbindu Singh
UNEP/Grid Sioux Falls
EROS Data Center
Sioux Falls, SD 57198
PH: (605) 594-6107   FAX: (605) 594-6589
grid@grid1.cr.usgs.gov

Dr. Soroosh Sorooshian
Department of Hydrology & Water Resources
University of Arizona
Building 11
Tucson, AZ 85721
PH: (602) 621-7120   FAX: (602) 621-1422
soroosh@hwr.arizona.edu

Dr. Louis Steyaert
USGS
521 National Center
Reston, VA 22092
PH: (703) 648-4515
lsteyaer@resdgs1.er.usgs.gov

Dr. Peter S. Thacher
Visiting Fellow, World Resources Institute
54 Gold Street
Stonington, CT 06378
PH: (203) 535-4787   FAX: (203) 535-0633
pthacher@igc.apc.org

Dr. Waldo Tobler
Research Professor Emeritus of Geography
Univ of California
Dept of Geography
Santa Barbara, CA 93106-4060
PH: (805) 893-3831 FAX: (805) 893-3146
tobler@geog.ucsb.edu

Dr. John Townshend
Chairman, Department of Geography
University of Maryland, College Park
1113 Lefrak Hall
College Park, MD 20742
PH: (301) 405-4050 FAX: (301) 405-9299
jt59@umail.umd.edu

Mr. Bill Wallace
TERRA Lab/CIESIN
1201 Oakridge Dr., Suite 101
Ft. Collins, CO 80525
PH: (303) 282-5480 FAX: (303) 282-5499
wwallace@terra.colostate.edu

Dr. Cort J. Willmott
Department of Geography
University of Delaware
Newark, DEL 19716
PH: (302) 831-2294 FAX: (302) 831-6654
by00920@udelvm.udel.edu

Ms. Harumi Yanagimachi
Faculty of Economics
Shinshu University
3-1-1 Asahi
Matsumoto-shi, Nagano
390 Japan
PH: +81 263 35 4600 FAX: +81 263 36 7220
hyanagi@gipwcc.shinshu-u.ac.jp

APPENDIX 2: POSITION PAPERS

This appendix presents the position papers prepared by the specialist meeting participants in advance of the meeting, and circulated prior to their arrival. The editors of this report felt that they would have the most value if included in this original form, and they have not therefore been edited to reflect the discussions at the meeting.

Richard Appelbaum:

I am currently involved in two inter-related projects which are aimed at understanding the changing spatial arrangements that underlie economic activities - one focused on Los Angeles, the other on global trading patterns. As presently conceived, these projects are indirectly related to two of the eight topical areas for this Initiative: Demography-Population-Migration, and Policy/Decision-Making. I believe that GIS has a major role to play in understanding the changing spatial organization of business, both locally and globally; and that this in turn has important implications for urbanization and migration, and policies aimed at directing and mitigating their effects.

Los Angeles as an "industrial district": I have developed a GIS focused on the apparel industry in Los Angeles county. Several thousand manufacturers (who design clothing) and contractors (who fabricate it) were identified from a variety of public and industry sources, and ARC/INFO was used to build a street coverage from the 1990 US Census TIGER files. By identifying the ethnicity of the ownership of each firm, I was then able to observe and measure industry clustering along ethnic lines. This, in turn, addresses certain theoretical issues in the economic literature on "flexible accumulation," which argues for the importance of personal social networks in accounting for the success or failure of economic regions (termed "industrial districts" in the literature). Ethnicity arguably plays an important role in forging such networks. This research has policy as well as theoretical implications: since the apparel industry is currently one of the largest and fastest-growing segments of manufacturing in Los Angeles, understanding its spatial dynamics holds some promise for governmental efforts to stimulate and direct its growth. (The Mayor has recently appointed a roundtable focused on the industry, which he is personally chairing.)

Changing patterns of global trade: Drawing on bi-national import-export trade statistics for selected commodities, I have attempted to model the determinants of trade flows between nations. This is important because advances in information technology have led to an acceleration in the globalized production of a growing range of goods and services, a trend which partly accounts for economic decline in industrial nations (so-called "deindustrialization") as well as economic resurgence in countries that have recently pursued an export-driven path to industrialization (e.g., the newly-industrializing countries - NICs - of East Asia). Los Angeles-based apparel manufacturers, for example, can now make clothing anywhere in the world, from low-wage factories in Los Angeles to far lower-wage factories in China. (This is the focus of my own research, but the implications can be generalized to all low-wage industries.) The "friction of space" has been altered and reduced in recent years, with significant impact on the global spatial distribution of economic growth. Understanding and modeling aspects of the emerging global economy should provide insights into the changing global geography of industrialization and urbanization, important human underpinnings of global physical change.

As these examples hopefully illustrate, GIS has two roles to play in furthering our understanding of the connections between human economic activities and global change. First, it provides a technology for modeling the spatial determinants of economic activities, from a local to a global scale. Since in my view economic activities are a root cause of the human dimensions of global change, such modeling (currently undeveloped) is of some importance. Second, GIS has enormous heuristic value in graphically representing such processes, as a way of dramatizing their impact to policy-makers, students, and the general public. A dynamic GIS could powerfully illustrate the changing relationship between the global organization of economic production, space, human populations, transportation and communications, and other factors. As our understanding of the complex relationships between such "human dimensions" and physical change develops, the latter might also be incorporated into such dynamic representations.

Richard J Aspinall:

This paper describes and discusses a series of generic scientific and cultural/organisational issues that emerged during an integrated, multi-disciplinary research programme funded between 1991 and 1994 by the Scottish Office Agriculture and Fisheries Department on 'Impacts of Climate Change in Scotland'. The programme objectives were to develop a scientific perspective on possible socio-economic and environmental impacts of climate change in Scotland for communication to policy advisers in the Scottish Office. The fundamental interest of policy advisors was in impacts of climate change for different land use sectors in different places in Scotland; this concern was for the geographic pattern of impacts, and outputs required a geographic expression to satisfy the programme objectives. GIS serves this purpose.

Scientists from a range of science and social science disciplines were involved in the programme and a corresponding variety of methodological approaches were used. Models were used to predict impacts at a range of geographic scales related to land management and planning from the individual plant or animal, through farm, estate and watershed, to regional and national (Scotland). Existing models were used extensively although the majority were not spatial, but focussed instead on time- related processes (eg crop growth) or analysis of sets of conditions for a site (eg linear programming models of farm economics). Model types included mathematical models describing processes using differential equations, statistical and spatial analyses, linear programming, rule-based models, and causal graphs. Production of different arable crops, grazing lands and livestock, timber production for commercial forestry, farm economics, wildlife distribution, and sensitivity of soils to use of agricultural machinery were examined Time increments in models were variously daily, monthly, seasonal and annual.

A single GIS project served two central purposes in this programme: i) database development and management to support the data needs of models and to express model outputs spatially, and ii) as the core of integration efforts that relate outputs from the different models for different land use sectors. These are roles that GIS is technically well-suited to support, although a series of scientific and cultural/organisational issues arose which impacted this core position.

Database development and management. GIS was used i) to develop and maintain a detailed geographic database describing climate, topographic and other environmental conditions for the land area of Scotland, ii) to support the geographic framework for socio-economic analyses of farming activity and land management and iii) to provide data for models of both existing conditions and that predict possible impacts of climate change scenarios.

A geographically extensive database of present-day climate was developed from meteorological station data using geostatistical methods coupled with GIS and included detailed descriptions of spatial data quality that provide input to sensitivity analyses in mathematical and other modeling. The GIS also contained analytical routines that allowed climate change scenarios to be developed for Scotland. The spatial resolution of General Circulation Models was also too coarse to discriminate geographic variation within Scotland. The routines developed used analysis of the existing statistical and spatial pattern of variation in Scotlands climate to disaggregate GCM output to provide detailed regionalisation of climate changes predicted by GCMs. These data were input to models to predict impacts of change. Data for models that needed weather data for short time increments (daily, weekly) were based on statistical weather generators developed from weather records for four meteorological stations in the agricultural area of Scotland; the GIS was used to establish the geographic area for which each weather generator was relevant. GIS could not supply weather generator-type data for all locations which was seen as a limitation of the GIS facility by other scientists (rather than a data limitation). In part this was an opinion linked to competition between organisations involved.

Incorporating data quality descriptors increases the volume of the database by a factor of at least 2, raising the system management overhead. It did however provide an opportunity to add confidence limits to model outputs. This proved to be a significant intellectual, cultural (discipline-based), and technical challenge for the different scientists in the component projects. They were not familiar with carrying out sensitivity analyses in which (spatial) data quality is involved. Instead, they expected uncertainty and model sensitivity to behave statistically and reside exclusively in the parameters and computational behaviour of their models. Much of the confusion experienced by these scientists could be attributed to them not 'thinking spatially' and although this confusion was apparent through many aspects of the programme it was most apparent in discussions about linking models and model outputs to the GIS. It handicapped development of integrated solutions as scientists withdrew from involvement in the GIS project deeming it 'non-scientific'.

The data management function was not designed at the start of the project which resulted in the GIS team spending time and effort adding data and functions as difference models became active in other projects. This placed pressure on the GIS project and created disillusion in modelers who expected the GIS to make data available instantly. A period of group planning at the outset of the programme that focussed on the practical, technical and timetabling aspects of **linkage** between projects would have been completely beneficial.

Integration. The GIS also was the integrating core of the research programme, allowing interaction of outputs from a diverse range of models developed by the different component projects. Outputs were related through geographic location - all model outputs were mapped with a common georeferencing system either by using GIS to map outputs from models or by developing models using spatial analytical and other functions within the GIS.

Taking model outputs and mapping them was the method preferred by the majority of the scientists in the programme. This reflects their related perceptions of i) their mathematical models as an aspatial, mechanistic and objective expression of deep knowledge about processes that can be applied uniformly in all locations, ii) spatial variation as either an irrelevance or something that exhibits standard statistical behaviour, and iii) GIS as no more than a 'mapping tool' for producing attractive images. Generally, the GIS was restricted to a dual role of data source, that was assumed to contain all necessary data in an appropriate format for any model, and mapping tool. Further, individual scientists on specific component projects were also less interested in integration of output than the scientists of the GIS project who had the specific objective of achieving the integration required in the whole programme. This reflected an understandable focus of individual scientists on their own research rather than on the whole programme and a history of individual disciplines which seldom develop an holistic approach based on synthesis. Shared multidisciplinary objectives, a sympathy with spatial logic and thinking, and a deeper awareness of the potential arising from coupling models with GIS may have been developed by an initial phase of system design in which all projects contribute and during which joint responsibilities are established. Such an exercise would help to establish an appropriate GIS and develop wider awareness of spatial issues relevant to the project. Achieving integration based on a holistic approach using synthesis is precisely where GIS offers outstanding technical opportunites in Global Change Modeling from which multi-disciplinary groups can benefit. Inititatives in project design and management that encourage this as an integral objective of all component projects would contribute to this success.

Thomas J. Baerwald:

Geographic information systems (GISs) have been rapidly adopted as an important tool for conducting research by different sets of users. Governments at all levels and numerous businesses, such as utilities and transportation companies, have invested heavily in GISs and made them integral parts of their operations and planning. Many researchers in a number of scientific disciplines also have embraced GISs, with cultural anthropology, archeology, and ecology being notable examples. But adoption of geographic information systems have been far less common in many other industries and disciplines.

What accounts for these differences in receptivity toward geographic information systems? Many studies have tended to focus on issues related to the acceptance and adoption of GISs as new technologies, thereby placing emphasis on "systems" aspects of GISs. I believe that the real problem lies elsewhere, however, with the most crucial factor being the degree to which industries or disciplines are "geographic." For a variety of reasons, certain intellectual communities have been far less likely to emphasize geographic aspects of the problems on which they focus their attention. As a result, they have perceived relatively little gain from the use of geographic information systems. If spatial questions are not close to the heart of the problems addressed by researchers, other means of storing, analyzing, and presenting information are likely to serve them as well as or better than GISs.

Geographers and scientists in closely related disciplines have wrestled with the need to broaden understandings of the value and complementarity of geographic perspectives, and they likely will do so long into the future. While that crusade continues, however, much can be done to move forward work in those areas where geographic questions already are central. I therefore believe that much of the potential for the use of GISs in global change research lies in using these technologies to address those questions that are most geographical.

One major set of questions for which I believe GISs can make major contributions to the advancement of global change research relate to the conduct of analyses across different geographic scales. Unlike environmental studies that focus on interactions among different systems within a constrained set of areas, global change research ranges across myriad geographic dimensions. The complex interactions that alter the land-use and land-cover patterns of a fine-grained mosaic of parcels contribute toward changes in atmospheric chemistry that ultimately may alter global climatic patterns. Conversely, the ramifications of changes in weather and climate patterns identified as taking place over large parts of continents must ultimately be understood in terms of the responses of small watersheds.

Significant issues regarding the ways that data gathered at different geographic scales are handled in GISs need to be resolved, however. In some cases, the association of data across different spatial units is straightforward, but many other kinds of data must be treated with far greater care. Special attention must be given, for example, to the treatment of data from differentially-sized areal units and also to operations that relate both aggregated and disaggregated data. The ease with which complex calculations can be performed on GISs often leads researchers to conduct analyses before they have determined whether data can be subjected to specific kinds of operations. Much remains to be done in order to improve the ways that GISs can be used for the analyses across different geographic scales that are essential parts of global change research, but the value of making progress along these lines will be great.

Also of importance is the development of more effective techniques for conducting analyses across different temporal scales. Global change research is fundamentally research on processes on the way that different systems interact with each other over time. GISs can trace the characteristics of those systems over space, but to make real contributions to our knowledge of the processes of global change, they must be able to track those characteristics and locations over time. The storage and processing demands of handling spatial data at one point in time can overwhelm the capacities of even large computers. To insist that they be able to do that for numerous different time periods seems beyond reason. But developing the capabilities to handle detailed data over large areas and multiple points of time is absolutely necessary if GISs are to become the kind of analytic tool that global change research requires. More attention needs to be given to exploring the ways that the redundancies and other distinctive characteristics of temporal data can be used to facilitate their management. This kind of research would require similar efforts to those undertaken as part of the NCGIA's fifth initiative, which explored ways to take advantage of the special characteristics of spatial data in order to advance computational capabilities for effectively dealing with large spatial databases.

GISs can also play a valuable role in facilitating research on the human dimensions of global change. Although comprehensive data needs required for research on human systems have never been articulated as fully as the data needs for natural systems analyses, assertions I've heard that claim that few appropriate socio-economic databases exist are incorrect. An enormous amount of data that might be used in human dimensions research exists, but it generally has not been assembled into formats that permit its association and use in the examination of critical problems. A critical gap separates most remotely sensed data from other kinds of information that might make it especially useful. Satellite imagery, for example, has been used effectively to help monitor patterns of land use, and high-resolution aerial photography can distinguish individual structures. These data generally cannot identify how many people reside in a dwelling, however, nor can they usually identify what kinds of industrial activity are taking place within a structure or what amounts of water are being used to irrigate agricultural parcels. GISs offer the potential to directly relate the locations of parcels and structures identified by remote sensors with other geo-referenced data, such as utility, tax, and assessment records. In order to assemble powerful new sets of data relating to changing patterns of human activity, new techniques need to be developed to help relate the remotely sensed data, which have excellent locational but limited substantive value, with other kinds of data, which often are substantially rich despite their minimal locational content.

For my last point, I would like to commend the specialist meeting's organizers for outlining an exciting, challenging, and significant set of scientific objectives for this meeting and the overall initiative. At the same time, I would like to issue a warning. For what may well be very valid reasons, the topical areas that provide the structure for the initial sessions of the meeting have been organized around different natural and human systems, each of which tend to be the primary emphases of specific groups or disciplines. The well-developed and still-evolving knowledge of the dynamics of each of these systems is essential, but the real challenge of global change research is to better understand the linkages among those disciplines. The advancement of knowledge on system interactions necessarily involves interdisciplinary research.

GISs can help facilitate interdisciplinary efforts, because they often provide a means for improving communications across the disciplines. A hydrologist, ecologist, and sociologist, for example, each ask dramatically different questions about vastly different phenomena. The jargon each uses may seem impenetrable to the others, as may some of the theories, concepts, and techniques that each uses in the conduct of their research. But if they are asked to explore how water, natural lifeforms, and human occupants of the same area relate to each other, one of the best ways for them to profitably interact would be by finding "common ground" in the visual comparison of maps displaying geographic information about the region. By analyzing similarities and differences between the spatial patterns of the systems they study, these scientists are likely to identify those conditions where certain types of interactions are particularly pronounced. And if the GIS they are using has the capability to allow them to follow changing spatial patterns over time, they likely will be well on their way to identifying and explaining the processes that relate the various systems.

The potential utility of GISs in global change research is enormous. To take the fullest advantage of this potential, however, we need to use GISs to push on the margins of our knowledge, not to loll in the quiet comfort of the cores. Our discussions focusing on different groups of systems should be occasions when we challenge ourselves. We should ask ourselves, "What can I learn about the uses of GIS in conducting research on these systems to better understand interactions between those systems and the ones in which I am most interested?" The discussions focusing on topics most remote from our own expertise are the ones for which we should be most alert; they are not the times to catch up on sleep or on phone calls back to our offices.

Larry Band:

An integrated assessment of land surface processes is a crucial component of global change research. Regional exchange of mass, energy and momentum between the atmosphere and the earth's surface is highly dependent on the topographic and geologic structure of the land, vegetation cover and soil patterns. A major challenge to the global change modeling community is an assessment and representation of the inherent heterogeneity of these patterns, which exist over a range of spatial scales. A number of recent studies have indicated that the processes determining the areal average net flux of water, carbon and energy between the atmosphere and land surface can be very sensitive to the level of averaging or aggregation of surface properties used in modeling strategies. As GIS are designed to facilitate the combination of spatial data from a range of sources and scales (or resolutions), the methods of data representation and processing used within specific spatial data models can have significant impacts on simulation results.

Consider a hypothetical model of some surface flux process, *p(x)*, where x is a vector of surface and atmospheric variables. As an example, *p* may a model or function to determine evapotranspiration and *x* can incorporate terms describing the topography (slope and aspect), soil hydraulic parameters, albedo, leaf area index (LAI), canopy physiological parameters, etc. From numerous empirical studies, we know that these variables often vary at length scales measured in meters to hundreds of meters. However, typically many of the model variables are only available in the form of highly generalized thematic maps or from coarse resolution satellite sensor information. In these cases there is significant generalization and averaging of the surface attributes. Where *p(x)* is not linear this loss of distributional information of model variables may lead to significant bias into computed areally averaged flux rates:

$$E[p(x)] \neq p(E[x])$$

If the spatial variance of the components of *x* can be described by some multivariate distribution function, *f(x)*, we can integrate *p(x)* over the distribution function to derive the areal expectation:

$$E[p(x)] = \int_x p(x)f(x)dx$$

In GIS this can be modifed into an areally weighted summation over all surface features (pixels, polygons) or over a discrete representation of the distribution function. There are a number of other methods available to incorporate distributional information on key model variables, to certain restrictions to gain an unbiased estimate of the flux rate if (1) holds. The distributional information required depends on the specific forms of p(x). Posing the problem in this manner indicates the utility of a GIS can be assessed in terms of how well it can be used to sample and estimate f(x).

Kate M. Beard:

The application of GIS for global change research has great potential as there is need for coordinated storage, analysis, and display functions for spatially referenced data. For this potential to be fully realized GIS must evolve through some well directed research efforts. This paper points to just a few areas which warrant some attention.

Data access issues

The volume and diversity of data pertinent to global change research is huge and growing. Electronic access to these data sets is developing but there is room for improvement. Improved access involves both technical and policy issues. Access could be facilitated by using geographic location as the organizing principle and location as a primary key. Many of the data sets currently exist as separate collections with different modes of access, mostly non-spatial. There is no simple search mechanism to identify where a wide range of data sets from several different domains (e.g.

weather data, elevation data, landcover, pollen samples, core data, fire histories, etc) coincide spatially and/or temporally. A uniform interface that supports spatial display, browse, and query functions for a wide range of data sets could enhance the search for and assembly of pertinent data. Such an interface requires work in spatial referencing and spatial display described in other sections of this paper.

Another component of the access issue is metadata. The expanding collections of digital data become valuable for global change research only if they can be reliably integrated or interrelated and this requires knowledge of metadata. Standards for spatial metadata have been developed but such standards are not observed across all data collection activities or different and incompatible standards may apply. Spatial metadata content has been reasonably well worked out, but implementations have not. Metadata descriptions will be relatively straightforward for homogeneous and static data collections. Longitudinal series, datasets which are frequently updated, and updated in a piecemeal fashion will have more complex metadata descriptions. Some efforts are warranted in promoting standards for metadata, facilitating collection and documentation of metadata, and assuring that the standards are observed by contributors of data sets. The larger scientific community needs standards and given a global perspective international standards and agreements come into play.

Spatial referencing issues

Global applications have rigorous requirements for spatial referencing systems. The referencing systems must be free of size, shape, and location restrictions. Conventional cartographic projections and plane coordinate systems suffer several shortcomings as spatial referencing systems for global spatial analysis, including discontinuities, low precision computations, and non-uniformity in finite elements. Cartographic projections also do not model the near space geometry. Desirable characteristics for a global spatial referencing scheme include unrestricted numerical representation for any size object, global coverage without regions of numerical instability, ability to represent spatial relationships in an unbounded spheroidal domain, support for variable levels of spatial resolution, and ability to model time/space relationships of surface, aeronautical, and orbital movements. Several finite element schemes for the globe have been developed but do not meet all the above criteria.

Current collections of data exist in various spatial referencing schemes (different projections, different datums, geocodes, and sometimes unknown) and substantial effort will be involved in converting these to a common geodetic reference frame. Development of transformations to facilitate this conversion may be warranted

Spatial analysis issues

Spatial analysis on the globe will require a robust spatial referencing system such as that discussed above. Such a reference frame is essential for neighborhood, adjacency, and connectivity requirements for interaction and other models. Many of the current analytical tools within GIS will not be functional for globe data sets. For example, map algebra functions assume a regular planar grid. The extension of these operations for global data sets will require an effective finite element scheme for the globe.

Most current GIS employ a map model. While analyses based on this model, such as map algebra, have had some success this model has limitations. One limitation is the cartographic heritage of most inputs to this model. Cartographic products do not support quality assessment as links to original measurements have in most cases been lost. A number of global change data sets are point based observations which through various interpolation methods or numeric models are converted to surface representations. While these representations are graphically similar to cartographic products the link to original observations is maintained and the process is replicable. A suite of tools for making these transformations assuring that quality variables are tracked from original observations should be incorporated as GIS functions.

GIS should expand to incorporate more than just a map model. As an analytical tool it could be improved by incorporation or closer association with numeric or physical models. A number of researchers have described integrated model management or modeling support system (MSS) that store models in a database organized by model type. Users can select and assemble models from a model base to carry out complex analyses. Such systems deserve consideration for expansion and improvement.

One variation on this strategy in service of global change analysis would be organization of a suite of models by process scale. The prediction of change and the consequences of change at a global scale can require an understanding of the behavior of phenomena across very different scales of space, time, and ecological organization. The problem is to account for pattern observed at one level of detail in term of mechanisms operating at other scales. The analysis relies on integration of multi-temporal and multi-spatial scale data. By interfacing a set of models one could begin to interrelate phenomena acting on different scales. The role of atomic models in the system would be to isolate behaviors at specific scales. Each model should be sufficiently simple to capture behavior of a variable at a particular scale with an assemblage of models approaching the behavior of a phenomenon across a set of scales. Such model assemblages could then be used to simulate patterns and to assess how a set of processes interact to produce a particular pattern. Such simulations could also be used to assess how information is transferred across scales, what information is preserved and what information is lost.

Spatial display issues

Display of global views presents some interesting problems. Are synoptic views of global spatial distributions possible without the distortion effects of projections? Patterns in areas of high density in spatial distributions may be lost in global views. An expanded set of interface tools which address such issues through zooming, panning, linked windows and other devices may benefit visual analysis of global patterns.

Richard A. Berk:

My hands-on experience most relevant to this meeting is with data at regional scales, particularly data on metropolitan areas. While it is certainly handy to have displays of single variables in time and space, I am largely concerned with relationships between variables are that spatially and temporally coded. For example, I am currently looking at how residential water use in Los Angeles is related to such factors as temperature, rainfall, soil moisture, the price of water, conservation appeals, and life style decisions. All of these vary by location and time. Note that there is a reciprocal relationship with regional meteorology and climate on the one hand and water use on the other: the causal direction "goes both ways." And regional meteorology and climate are obviously linked to global climate.

From working with these sorts of regional databases, I offer the following observations in no particular order. I also apologize in advance if I am not being sufficiently responsive to the call for two page position papers.

1. Temporal and spatial aggregation is a key substantive issue, and not just a technical annoyance. For example, the decisions that people make about outdoor watering in part depend on some moving average of temperature and rainfall in preceding days. Exactly how that moving average is to be computed requires an understanding of the cues to which people respond.

2. I wonder if GIS systems could be used a lot more to handle unconventional spatial metrics. For example, in common speech people talk of the distance from LA to Santa Barbara as about 90 minutes on the freeway. To take this still farther, one might be able to represent a city using social distance (e.g., median income instead of longitude and median education instead of latitude). It would then be instructive to see how census tracts were shuffled around in a social distance metric rather than longitude and latitude. One would then have one kind of "map" of social distance for that city. One could do the same thing for race/ethnicity: percent Latino for latitude and percent black for longitude. A comparison of the two social distance maps might be sort of fun.

3. For analyses of the sort I do, a spatial representation is useful for statistical diagnostics. To take a simple example, if I am applying some fitting procedure to the data, it is handy to be able to display the residuals in space so that the pattern of problematic points in geographic space can be studied: where is the fit good and where is it bad? Where do the leverage points lie? Likewise for the full array of diagnostics.

4. The kind of maps provided in GIS need to be designed to handle more abstract representation of data. For example, one important issue in multivariate statistical analysis is how to reduce the dimensionality of a problem (e.g., using sliced inverse regression). One might redraw maps with the same goal. For instance, if a linear combination of longitude and latitude usefully accounts for some response variable of interest (e.g., pollution hot spots) that linear combination can become a new single dimension where two separate dimensions were used before. In effect, a two dimensional map with spikes for hot spots now becomes a profile map. To take simpler example, one might alter the represented size given to nominal spatial units depending on the weight given to that unit. The new and altered map would be reshaped to reflect that weight. Thus, one could imagine a map of Southern California where the size of each spatial unit depended upon its contribution to air pollution.

5. More generally, the very exciting newer work in statistical graphics needs to be integrated with GIS technology (See for example, W.S. Cleveland, *Visualizing Data*; R.D. Cook and S. Weisberg, *An Introduction to Regression Graphics*). It's a natural marriage.

6. Resampling procedures such as the bootstrap need to be built into GIS packages. We should be able to produce a sequence of maps capturing the uncertainty in a dataset and then a summary map in which the variability in the sequence of maps is displayed in space. This would help answers such questions as: where is there more uncertainty and where is there less uncertainty?

7. When dealing with lack of independence in the data, space is much more lumpy than time. For example, water use can change dramatically and abruptly across adjacent neighborhoods (e.g., Beverly Hills to West Hollywood). The lumpy nature of space raises hell with the usual sorts of statistical fixes. One important issue is when it is better to simply ignore the lack of independence rather than force fit some spatial model.

Norman D. Bliss:

I am a Principal Scientist with Hughes STX Corporation at the U.S. Geological Survey's (USGS) Earth Resources Observation Systems (EROS) Data Center. My work is funded by the U.S. Global Change Research Program, through the Department of the Interior, USGS, National Mapping Division.

I have been involved in developing and analyzing national and global soil data bases. Selected contributions include:

1. State Soil Geographic (STATSGO) data base (1:250,000)
   Developed by: Soil Conservation Service (now Natural Resource Conservation Service)
   Released on CD-ROM by NRCS this week (49 states + Puerto Rico).
   My role: Assist in design for attributes, develop algorithms for analysis in Arc/Info, including calculation of soil organic carbon.

2. Soil map of Alaska (1:1,000,000)
   Developed by: Soil Conservation Service
   Digitized by: EROS Data Center
   My role: Oversee digitizing and attribute data base development

3. Soil Map of Mexico (1:1,000,000)
   Digitized by: EROS Data Center
   My role: Oversee digitizing, design attribute data base, corrections to attributes, calculation of soil organic carbon

4. Soil and vegetation maps of Brazil (1:5,000,000)
   Digitized by: EROS Data Center
   My role: Oversee digitizing and attribute data base development

5. FAO Soil Map of the World (1:5,000,000)
   Developed by: Food and Agriculture Organization of the United Nations
   Digitized by: ESRI, 1984
   My role: Reprojections, global analyses of soil slopes, reformat to give proportions of the co-occurrence of texture, slope, and depth within one-degree cells for use by climate modelers (GLOBTEX), apply the Fertility Capability Classification System of Dr. Stan Buol (North Carolina State).
6. Soil Carbon Map of North America (1:1,000,000 to 1:10,000,000)
   Development in progress by myself, SCS (Lincoln, NE), Agriculture Canada (Ottawa), and INEGI (Aguascalientes, Mexico).
   Purpose: Develop the most detailed continental scale map for soil organic carbon to give a spatial distribution of the soil carbon pool for biogeochemical cycling studies.
   My role: Develop and apply algorithms for the U.S. and Mexico portions, to match the methods used in Canada.

7. Soil and Terrain (SOTER) Digital Data Base of the world (1:1,000,000)
   Under development by the International Society of Soil Science (ISSS) in cooperation with the International Soil Reference and Information Center (ISRIC), FAO, and the United Nations Environment Program.

My role: Produce prototype SOTER products, advise on procedures manual, participate in SOTER working group of ISSS, schedule research for application of remote sensing, digital elevation models, and the STATSGO data to develop a SOTER data set for the United States.

Soil data are needed in at least four major areas of global change research: 1) Climate and hydrological systems, 2) biogeochemical cycling, 3) ecosystem dynamics, and 4) human interactions. For each of these areas, I will highlight examples from the above data sets, although there are other possibilities.

1) Climate and hydrologic systems

Knowledge of soil properties is essential to understanding the moisture flux at the surface in atmospheric simulation models. I am working with researchers at Penn State and elsewhere to format STATSGO data for use in mesoscale models (being tested for sites in North America). I developed a global soil texture (GLOBTEX) data set for use by researchers in NASA's International Satellite Land Surface Climatology Project (ISLSCP). I have also participated in characterizing the soils of the Missouri and upper Mississippi basins for the Scientific Assessment and Strategy Team, commissioned by the White House to study the 1993 floods.

2) Biogeochemical cycling

The pool of soil carbon (1600 Pg) is approximately twice the size of the pool of atmospheric carbon (750 Pg), so that a one percent change in soil carbon storage would be reflected as a two percent change in the carbon in the atmosphere (before ocean uptake). With the possibility of global warming, soils may become drier and warmer, conditions that tend to cause the release of carbon dioxide and methane to the atmosphere. These greenhouse gases could then contribute to additional warming in a positive feedback relationship. The development of the soil carbon map of North America is a first step toward the spatial extrapolation of site-specific studies of gas exchange in soils.

3) Ecological Systems and Dynamics

I have worked with Dr. Larry Tieszen, Augustana College, to make maps of the proportion of C3 and C4 photosynthetic types of plants in the Great Plains, as part of a study on the ecological changes in grasslands with climate change.

4) Human interactions

The application of the Fertility Capability Classification system to the FAO Soil Map of the World is a step toward a better understanding of the capabilities and limitations of the Earth's land for supporting agriculture, and thus human populations. The development of the SOTER data base, if adequately funded, would further contribute to this effort.

Although I believe that great progress has been made in the last few years by the participation of the departments of the Federal Government in the U.S. Global Change Research Program, it is possible to identify some impediments that have limited the rate of progress below its potential. The impediments may be categorized as scientific, technical, and funding structure.

A major scientific impediment is the difficulty with which researchers come together across disciplines. It takes a great effort, in part because the terminologies used by each discipline tend to be focused on data collection at one spatial scale, and there is not an adequate scientific notation and language for specifying the scale and precision of data collected at one scale and extrapolated or summarized at another scale. Researchers such as soil physicist Johann Bouma have begun to explicitly confront these scale issues by diagramming the path of a calculation across scales, as well as the quantitative-qualitative, and deterministic-probabilistic dimensions of models. I am also intrigued by the possibility that representations of distributions, rather than single values for data elements will aid in aggregation from one scale to another. I have applied this to the characterization of soil slopes in a 13 state region. Models may need to be altered to accept distributions as inputs, because it requires a paradigm shift from the assumption of homogeneous spatial units to heterogeneous spatial units. The assumption of heterogeneity is more robust, however, because as Jack Estes said at the last Pecora meeting in Sioux Falls, "Even an electron micrograph has mixed pixels." Given a representation in terms of a distribution, it is possible to aggregate spatial units with less loss of information.

A major technical impediment to the use of GIS in global change studies is a weakness in available tools for recognizing complex patterns in spatial data. There is a strong need to define ecological regions based on combinations of variables such as climate, geology, topography, soils, and land cover. These regions will be a basis for monitoring global changes, as well as regional and local human influences on the landscape. For example, attempts to define "Soil Quality" (comparable to air quality or water quality), will require stratification of the landscape into units with similar functional situations. My efforts to use a 1-km resolution land cover data set in conjunction with the STATSGO data set would be aided by additional technical tools for understanding the spatial structure of the land cover data.

A major funding structure impediment for the U.S. Global Change Research Program is based on the nature of the biases of the Federal departments and agencies which are charged with implementing the program. Many of the agencies come from scientific, land management, space exploration, or regulatory perspectives that have strong traditions. Global change research is seen as an addition to this work load, and there is a fear among managers that this may be a passing fad, and if significant resources are committed to it, it will be at the expense of resources for their traditional legislative mandates. I am not sure of the solution for this impediment. There is a genuine effort on the part of some managers in some agencies to make sure that good interagency and cross disciplinary work is done, but there are other cases in which adherence to traditional roles and responsibilities leaves gaps in the scientific investigations needed for understanding global environmental processes.

I would welcome the opportunity to discuss these and other ideas as part of this NCGIA initiative.

Francis Bretherton:

1. Critical issues for the application of GIS in Global Change Research are (a) the data models that can be effectively supported; and (b) the ease of import/export into data structures adapted for atmospheric transport models.
2. Traditional GIS has served as: (a) a visualization tool; (b) a substrate for simple modeling; (c) a database manager; and (d) following mandatory standards from the Federal Committee on Geographic Data, increasingly as a data exchange format / straitjacket.

3. The principal integration tool of global change research is modeling, i.e. expressing specialized or local knowledge about processes in mathematical/numerical terms, which then can be assimilated into a global scale, interdisciplinary, quantitative, framework for answering "what if?" questions. This framework, an Earth Sytem Model, (ESM) has to combine subsystem models of the land surface, atmosphere, oceans, and ice, as well as physical, chemical, biological and socio-economic processes. Almost everything can be geo-referenced to some degree of precision, but time and frequently height are generally as important as the horizontal coordinates, and, with a multitude of dependent variables, the modeling space is most accurately be described as 5-dimensional, as opposed to the 3-dimensional data model underlying traditional GIS systems. Because of the global scope, the horizontal resolution that can be explictly handled is limited by computing requirements to at best 50-100 km, and more often 250-500 km. With that goes a time resolution that is set by the fastest transport velocity in the model. For the atmospheric component this is at least 100 m/s, leading to explicit steps forward in time every few minutes to an hour. ESMs are now being developed with modular subsystem components running on different grids and timesteps, but interconnecting through standardized interfaces.

4. The archetypal issue for ES modeling is the interaction between process at different spatial and temporal scales, seen most acutely in relation to land surface sub-models. Local variables, e.g. topography, vegetation cover, human settlements, etc. vary significantly on scales of tens of meters. For use in an ESM, a function of such variables (e.g. the evaporative flux of water) must typically be averaged over space.

For a linear function of local variables, a unifomly distributed random sample would be sufficient, but in the more common case of a non-linear function a much more careful and exhaustive calculation is required, including consideration of the effects of rare but important cases, of interpolation procedures for missing data, etc. GIS tools can be very useful sorting through such issues. Conversely, if what happens locally is independent at different locations, the value of a global scale variable, such as temperature at fixed height, can simply be distributed to each location as a parameter. However, if there are significant intermediate scale structures, a more elaborate, intermediate resolution, embedded model is required. Though some succesful examples of embedded models exist, the numerical techniques required are still relatively undeveloped.

5. Some types of process model

a. The traditional GIS is well adapted to relatively static models, involving two coordinates and multiple dependent variables (layers), and relatively simple spatial relationships (e.g. nearest neighbours). Examples would be (i) a digital elevation model and associated stream net; (ii) a landscape consisting of ecosystem polygons superimposed on soils and topography, used to infer edge habitats; (iii) a model of human settlements in terms of land use, transportation nets, economic activities.

b. More computationally demanding on GIS systems are dynamic 2-D polygon and net models. An example would be the hydrology of a watershed, requiring prediction of stream flows as a function of time following a rainfall event.

c. Still more demanding are dynamic 3-D models (visualized in 5-D), such as a simulation of turbulence in the atmospheric boundary layer. Height has to be treated symmetrically with (x,y), and finite difference algorithms must be carefully chosen to minimize aliassing errors. A traditional GIS might underlie such a model, but would not be suitable as the modeling environment. A clear and efficient interface is essential.

d. Earth system models involving linked subsystem models with standardized interfaces. It is very desirable that at least the land surface component be GIS based, to provide an interactive integration tool for disparate underlying data sets. How model computations will finally structured, e.g. on a uniform grid, on polygons, or as randomly positioned samples, will depend on studies of non-linearity and the importance of intermediate structures.

6. Some issues

a. How far can GIS technology accomodate a progression from 2-dimensional data structures to include height as a true independent variable, and also time? Extensions to include time are often event driven updates (i.e. nothing changes except discontinuously at irregular events), but global change models typically assume continuous time, in which the correct value comes from interpolation between regular samples.

b. Modelers want control over their algorithms and data structures, yet want to benefit from appropriate tools. Clear and efficient import/export from GIS systems would greatly increase their acceptance.

c. Scale aggregation/disaggregation issues are critical for establishing linkages between subsystem components of Earth system models. Translating different space and time scales across such an interface involves both interpolation and averaging, including models for treating missing or aggregated data, and the propagation of uncertainty. These are also important issues for GIS systems, and shared research is appropriate.

Robert S. Chen:

Research on global environmental change has long recognized the spatial and temporal characteristics of environmental processes critical to the geosphere-biosphere system. More recently, there has been increased focus on interactions between scales, e.g., between global- and regional-scale climatic and land-surface change.

It is clear too that humans and human systems have critical interactions with the environment across time, space, and especially across scales. Of special note is that such interactions occur not just in "physical" space and time, but also in economic, cultural, political, and other realms not quite as objectively measurable but no less complex. These human realms are experiencing global changes of a magnitude and speed that are comparable to, and in some cases even more dramatic, than global environmental change - at least from an anthropogenic viewpoint. Rapid population growth, widespread economic and political transformations, continuing advances in communications, medicine, warfare, and other technologies, and ongoing reshaping of social and religious norms, national identity, humanitarian principles, and environmental responsibilities are occurring in concert with a changing physical environment. Understanding the full range of dynamic linkages between such global changes in both the human and environmental realms is a difficult challenge.

Finding appropriate analytic data and tools to address this challenge is itself a nontrivial matter. Data from both the natural and social sciences are generally sparse in time, space, or both. Levels of resolution, sampling, aggregation, and consistency vary widely. Units and methods of observation differ. For example, when humans are the subject of study, it is usually important to take into account the spatial and temporal range of their activity; their political, economic, cultural, ethnic, familial, and/or linguistic affiliations and connections to other individuals as well as their geographic proximity; their ability to perceive and adapt to changing conditions; and their rights to confidentiality and appropriate use of research data concerning them. Since much socioeconomic data are collected for economic, political, or other administrative purposes, data quality and interpretation often depend in part on how well the relevant administrative bodies can track the population under their jurisdiction over time and, related to this, the precise geographic boundaries that define the jurisdiction over time. Given the need to understand the changing nature of human/environment interactions, careful attention is therefore needed to how administrative boundaries and associated populations have varied in the past and how they might change in the future.

Ongoing developments in GIS and recent applications suggest the importance of this set of tools for global change research. Current technologies and associated data provide powerful methods for the analysis and visualization of spatially-oriented data. But to address the complexities of global change, improvements are needed on a number of fronts:

- First and most obvious, treatment of time as well as space in a seamless fashion. For example, the China in Time and Space (CITAS) project, in collaboration with CIESIN and several institutions in China, has been working to develop a historical GIS for China that can deal with spatial data going back a millenium.

- Second, better tools for integrating environmental and socioeconomic data. For example, CIESIN has helped to support work at NCGIA on gridding of population data and on improving coverages for Public Use Microdata Areas. Work is currently under way to develop "batch" methods for gridding of demographic data and to improve tools for Internet access to spatial and temporal data. New approaches are needed to address scale issues and "non-physical" interactions.

- Third, more widely accessible data on subnational administrative boundaries and their changes in both time and space. For example, CIESIN has recently released an ftp archive of processed TIGER92 boundary files for the U.S. down to the Census block level. Development of a more accessible public domain version of Digital Chart of the World is critical. Historical data on national and colonial borders have been coded by the Correlates of War Project at the University of Michigan, but are not tied to spatial boundary files.

- Fourth, development of more sophisticated tools for analysis of time series spatial data. Global change research increasingly requires integration of data developed using different assumptions, sampling schemes, scales, observational methods, coordinate systems, and so forth. Simple correlations and comparisons no longer seem adequate. Adaptation of time series methods in a spatial context would provide researchers with better ways to assess the dynamic interactions between highly interrelated processes.

- Fifth, creation of mechanisms for preserving confidentiality yet permitting detailed spatial analysis of socioeconomic data in conjunction with environmental factors. For example, CIESIN has been exploring the possibility of providing data integration services to researchers without ever actually accessing any confidential data directly.

- Finally, examination of how GIS-based spatial and temporal analyses can fit into overall "integrated" assessments of global change, taking into account not only direct interactions between human activities and global environmental change, but also the wider societal, policy-oriented context of global change (broadly defined). Ongoing efforts at developing integrated assessment models have begun to address important distributional issues (in both space and time), but their ability to capture dynamic spatial and temporal interactions is still limited.

Charles Convis:

I am in the difficult position of apparently having been invited because I had nothing encouraging or constructive to say about global warming and GIS. For what it is worth, I will try to reproduce the conversation which led to my invitation.

I am skeptical that further research will make any substantive difference in the various human behaviors which cause global environmental problems. This skepticism is especially exacerbated when dealing with leading (bleeding) edge technologies like GIS and remote sensing. Technology always seems to be too big, too complex and too oversold to make a difference. At the same time, it is obviously the most attractive place to spend one's time and research dollars. I say this having spent 2 decades messing about with computers in developing countries and now messing about at ESRI which is one of the top centers for GIS development and research in the world. The technology is so stimulating and so challenging that for people with no other social skills like myself it is the only world we ever want to live in. It is the easiest thing in the world to solve complex problems because we have the chance to develop an algorithm with that most elusive character of the scientist's art, elegance. Unfortunately, solving things because we can apply ever more elegant tools doesn't appear to be leading us to planetary salvation, mainly because we happen to be sharing it with 5 billion other people who couldn't really care less about elegance.

I think that the place where effort is most needed is in the delivery of simple messages using simple technologies like pencil and paper at the local level. This is generally tedious, tiresome work over a long haul which is not especially stimulating and therefore is often slighted by the research community. Yet the public perception and motivation to act at the global level lies at the core of the social changes we will need if we are to survive as a global society. I find it hard to see how more information will result in any change when the general perception has been one of information overload, and if society didn't get the message way back at "Silent Spring" maybe the problem wasn't the lack of information but the lack of effective ways to integrate that information into local affairs.

I think local NGO's play the most overlooked, most critical role in this effort. These are people of the community, who know this community and its desires and fears. They are also pathologically underfunded and often ignored. It is rare enough to find them interested in global environmental information, rarer still to find them with the technological and professional capacity to handle this information. They can be a challenge to work with since they are often volunteers and often don't operate from the same world view as we do, based on deadlines and deliverables. I would like to see a lot more attention devoted to producing traditional paper map products which derive from and respond to the local information needs of NGO's, where they are able to explain them. I would like to see a lot more effort devoted to on-site training and technology transfer to help improve their information management capabilities. We are not talking about internet hookups here, we are talking about supplying maps and compasses, Munsell charts and hygrometers, books and computers, and lots of basic training. I would like to see a lot more funding allocated to simple staff and logistical support for local NGO's, especially in developing countries and southern hemisphere countries where they are most often overlooked by aid agencies.

As a faculative field ecologist and an obligate nerd, I look forward to hearing about the latest advances in the science and the technology, but unless these new tools are closely tied to thoughtful programs for disseminating them and making them useful and accessible at the local level, I wonder how much difference they will make.

Peter Cornillon:

Within the last 3 years the explosive growth of the Internet has resulted in a dramatic increase in the number of systems providing on-line information and access to research data. Whether through anonymous ftp, the World Wide Web, (WWW), or on-line data systems researchers now have the ability to access data resources distributed world-wide from workstations sitting in their offices and labs. For example, within the oceanographic community, individual researchers at academic institutions such as the University of Hawaii, the University of Colorado, Scripps Institute of Oceanography and the University of Rhode Island are making large data sets available on-line (i.e; NOAA series satellite AVHRR data). Federal agencies are also developing distributed data systems within the context of Global Change (e.g; NASA's Mission to Planet Earth, NOAA's Climate and Global Change) with the intention of providing on-line access to federal archives. These systems exploit the fact that the Internet provides the connectivity and infrastructure which supports distributed data access and management.

However, while a researcher can access on-line systems and their resources, he or she can not use one system to communicate or exchange information with other systems easily. Because the systems were independently produced with virtually no coordination among the developers each system supports its own unique formats and protocols. The result is that even systems which provide the same dataset resources (e.g.; the AVHRR systems above) are incompatible and can not exchange information with each other. In many regards this is to be expected since the implementation possibilities that a new technology presents need to be explored in order to determine which path is most advantageous. The problem now is how to coordinate access to these different systems and their resources. A further lack of coordination in the development of systems will cause a further divergence of systems, formats and protocols and further complicate providing interoperability between systems. From the researcher's point of view this path leads to a confusion of independent systems, formats and protocols that is counter productive in terms of meeting their need for easy and direct access to data.

Other critical issues within the context of data access are, what data is scientifically important and who are the providers of these data? The answeres to these questions significantly impact the architectural design and implementation criteria of on-line data management/delivery systems. The operational design of many large data management systems (e.g.; the EOSDIS Core System, Sequoia 2000) specify a very sharp distinction between data providers and data users. In these system models there are many more data users than data providers with the general flow of information being one-way, from the servers of large provider systems to the client application of the users. The architecture of these systems does not readily accommodate users transferring data to the provider systems nor directly to other users. There are several reasons to question this model of distributed data management, the first being the success of the WWW, with its ability to enable literally millions of individuals to be both users and providers of information over the network. The second is the simple fact that researchers are data producers. They invest considerable effort in 'cleaning up', calibrating and processing raw data to generate em high quality datasets for their own research. The time and knowledge they put into massaging their data significantly increases its scientific value thus making it a very valuable asset to be shared with the research community as a whole. Finally, funding agencies are placing significant emphasis (and backing it up with funding) on programs that will address issues of global change. Programs such as NASA's Earth Observing System and Mission to Planet Earth and NOAA's Climate and Global Change Program are challenging researchers to develop integrated approaches to the study of the Earth and the global environment. For these large collaborative and interdisciplinary efforts to be successful researchers must be able to readily exchange their most up-to-date data with one another. Again, researchers need to be in both the roles of user and provider of data.

These issues of data access, system-to-system interoperability and the role of individual researchers as data providers are actively being discussed by researchers, data system developers and data archive managers within the oceanographic community. In October 1993, issues associated with developing an interoperable, distributed system for accessing oceanographic research data were explored in detail at a workshop held at the W. Alton Jones Campus of the University of Rhode Island. The most important outcome of the workshop was the formation of a the Distributed Oceanographic Data System, DODS, development team. This development team was tasked with the responsibility of generating a detailed system design and building the core components of a distributed data system which would meet the requirements set down by the workshop attendees and provide easy and direct access to the research data resources of individual researchers as well as large federal archives over the Internet.

The Distributed Oceanographic Data System, DODS, is being jointly developed by researchers at the University of Rhode Island Graduate School of Oceanography and the Massachusetts Institute of Technology and will enable a research scientist, using his or her own data analysis application, to directly access distributed research data on the Internet. DODS will transform existing user applications - those now being used everyday to do research - into client agents of the WWW. It does this using the novel approach of extending the functionality of widely used application programmer interfaces (APIs). The DODS versions of these APIs append a client-server network interface to an API's existing procedural interface. User applications which use DODS compliant APIs become WWW clients capable of accessing data files transparently over the WWW with the same ease as they do local files. By utilizing WWW protocols DODS expands the domain of WWW access to include scientific processing and analysis applications and at the same time extends the functionality of the WWW beyond its traditional WWW browsers to include procedure based access. DODS not only permits researchers to take advantage of the ever increasing amounts of research data being made available on-line but also allows them to do so using the very application tools that are critical to the execution of their research.

The report on the workshop, design documents and white papers on aspects of the DODS development effort are available on the WWW at http://lake.mit.edu/dods.html.

Frank W. Davis:

The U.S. Global Change Program is organized into eight coupled research areas: Observing the Earth System; Data and Information Systems; Understanding Earth Processes; Predicting Changes; Understanding Consequences; Assessing Policies and Options; International Interactions; and Education and Public Outreach. These offer a useful framework for evaluating multiple roles for GIS in ecological dimensions of global change research.

Observing the Earth System. Issues of data volume and data integration abound. Examples of the important role of GIS include: automated image navigation; screening and resampling of remote or ground data; merging historical with modern remotely sensed measurements; automated feature extraction to reduce demands on human analysts. Many elements of biodiversity such as biotic composition can only be observed at ground locations (e.g., species occurrences). We will depend heavily on GIS-based interpolation to evaluate distribution and trends of such elements. A number of interpolation methods have been tried, but much research is needed on how to evaluate and compare different predicted distributions.

Data and Information Systems. The I-15 announcement focuses on the key topics in this area. Formidable technical and institutional hurdles must be overcome to integrate geophysical data sets with biological (e.g., museum collections, taxonomic and genetic databases) and socioeconomic databases for regional biodiversity assessment and policy formulation. The dynamic and local to regional nature of these databases raises many issues regarding data sharing via electronic networks.

Understanding Earth Processes. Maintenance or loss of biodiversity is largely driven by very local processes. Broader events, for example the extinction of a species or the regional decline of an ecological group such as neotropical migrant birds, are typically the cumulative expression of processes at much finer scales. The interaction of local factors and processes with regional to global climate changes is not well understood. Spatially explicit ecological models offer a means of studying impacts of climatic variation on populations in patchy environments. Representation of local processes over very large areas raises issues of data volume and reliability, and of computational demands. Much work is needed on ways to summarize local ecological processes within larger modeling units to facilitate analysis over large regions.

Predicting Changes. Near term changes in ecosystems and biodiversity will be driven far more by human activities than climatic change. Global climate models are imperfect but far better than current socioeconomic models for predicting future patterns of human population densities, agricultural development, or natural resource exploitation (with or without climate change). Our greatest need is for development of a new generation of predictive, GIS-based, regional ecosystem models that couple atmospheric, ecosystem, and socioeconomic processes.

Understanding Consequences. Virtually all predictive models that attempt to be realistic have a very large number of parameters. There is continuing need for better tools to analyze model sensitivity and error propagation, and for tools that allow the user to quickly pose and visually evaluate alternative future scenarios.

Assessing Policies and Options. Large, interdisciplinary models are scientifically appealing but often too complex, unwieldy, or lack enough credible data to support policy formulation or decision making. A number of simpler approaches have been proposed such as Bayesian networks, decision trees, etc. Such models can be effectively employed in a GIS environment to assess different policies and options, but research is needed on how to best couple them to GIS data to allow the user to easily develop and evaluate alternative model formulations.

International Interactions. Although many ecological and biodiversity issues are international in scope, there is relatively little coordination among countries in terms of data sharing, ecological monitoring and management. The biggest problem is lack of political will to share data. There is also a critical lack of funding to collect and manage environmental data. Standard global data sets on land use, wildlife habitats, topography and soils would go a long way towards better coordination. International standards for ecological measurements, monitoring and mapping strategies, as well as standards pertaining to spatial data handling, would also go a long way towards improving international interactions.

Education and Public Outreach. Public understanding of global change issues requires a fairly high level of geographic literacy. Printed maps, images, and atlases will be a primary means of communicating data and information. Research needs include improved means for production, dissemination, and education as to the use and interpretation of these geospatial products. Closely related is ongoing research into design and implementation of digital spatial libraries.

Liping Di:

Geographic information systems and related technologies have been used to analyze, interpret, and model scientific phenomena for over a decade. Although studies of global change phenomena are often conducted with complex computer programs custom-tailored to create intricate models on super computers, GISs are playing an increasing role in global change research. In this paper I outline my personal experience on strengthens and weaknesses of GIS in global change studies.

During the past several years, I was involved intensively in global change studies using GISs. My research extended from developing GIS-ready global change database to detecting biospheric signals of global climate change, with a research focus on modeling interactions among ecosystem, hydrological cycle, and climate using GIS. One example of my studies was to model land surface processes and vegetation-climate interactions. The model used the integration of climatic, biogeochemical, hydrological, and ecological data. Results of such studies have been published in scientific journals. The attached one-page resume lists some of my most recent related publications on those topics. Besides using GIS directly in the global change study, I also used GIS to explore the data quality problem by modeling the phenomena which the data were supposed to describe.

The GIS systems used in my studies included GRASS, ERDAS, and IDRISI. During the research, some new GIS functions were developed to remedy the limitation of current GIS functionality. Those functions were used to find the relationship among global change phenomena and are available through NOAA National Geophysical Data Center (NGDC).

The degree of success of my studies shows that GIS can be effective tools for global change research, especially when functions are added to enhance the modeling capabilities of GIS and GIS-ready global change databases are available.

Strengths of GIS in global change studies

Based on my personal experience on global change studies using GIS, I believe that GIS and related tools can make great contribution to global change studies. The major strengths of GIS in the global change studies include:

1. *Inexpensive and widely available*. GISs provide an inexpensive and widely available tool to vast numbers of scientists and the general public to explore global change phenomena. The traditional global change studies are often conducted on super computers with customer-tailored software. Those facilities are only available at well-equipped laboratories for few scientists. The development and maintenance of such hardware and software systems are very expensive. Scientific GIS software can now cost less than $1000 for highly capable software running on inexpensive personal computers and UNIX workstations. GISs, when combined with GIS-ready global change databases, provide scientists with access to global change study on popular personal computers and workstations.

2. *Functionality*. Although they are cheap, GIS packages have significant functionality in analysis, integration, modeling the environmental phenomena. Those functionality are very useful in the global change study. Because of their generality, GISs usually have the integration of analysis and modeling capacities which are hardly found in any single traditional global change modeling package. Due to the multi-discipline nature of global change studies, the integration of functions will greatly facility the global
change research.

3. *Complement to the traditional methods of modeling global change*. Traditional methods of modeling global climate and global change involve significant temporal detail and very coarse three-dimensional spatial information. GIS can complement such modeling by providing far

greater two-dimensional spatial sophistication, often but not necessarily at the cost of temporal and 3-D spatial detail. The ability to increase two-dimensional resolutions of boundary layers such as land-atmosphere, shoreline, and ocean-atmosphere interfaces, is a valuable complement to existing methods which sacrifice such detail for increased four-dimensional processing throughput.

4. *Interactability*. Interactability of GIS supplements traditional global circulation models and mesoscale forcings in ability to explore and improve data quality, rapid exploration of submodels and overall models, and convenient discussion and rapid modification of models. This interactive approach to global environmental modeling complements the approach of dynamic process models while enabling the scientist to rigorously assess the character of data used as boundary conditions in other models on widely available personal computers and workstations.

5. *The visualization and flexible processing capabilities*. Traditional global change modeling systems usually have very crude presentations of model results and studies of single parameters often employ very simple hardcopy or computerized graphics displays such as coarse-resolution monochrome contour maps. Because of the significant ability of GIS in scientific visualization and in flexible preparing and processing of multi-thematic data, GIS can significant increase the productivity of traditional modeling efforts by serving as the front-end of the traditional systems.

The major weaknesses of GIS in global change research

1. *Lack of three or higher dimensional modeling capability*. Studies of global climate and global change usually require three or higher dimensional modeling of global phenomena. The current GISs normally lack such capacities.

2. *Lack of the dynamic process modeling capability*. The goal of global change research is to predict the change through understanding the processes among the components of Earth systems. This kind of studies models the processes of the Earth systems as a function of time. The current GIS are good at static modeling but lack of such dynamic modeling capability.

3. *The ability to handle the huge amount of data*. The database structures in current GISs are not suitable for handling the huge amount of data involved in the global change studies. The structures are also not adequate for storing high-dimensional process data.

4. *Data interoperability*. The data used in the global change studies are multi-discipline and exist in diverse formats. The ability for a GIS to ingest such data into the system is very limited. In addition, each GIS has its internal data format. The data interoperability will be a great problem for GIS in the global change studies. The development of data standards such as STDS and HDF can ease but not completely solve the format problem. My recent study in Data Description Language (DDL) approach might solve the problem.

5. *Existing general-purpose functions may not be optimized for global change studies*. Additional empirical correlation and neural network techniques can be added to GIS to facilitate global change

studies using GIS. Many GISs have capabilities to develop global environmental models. These capabilities can be enhanced, as shown by the addition of GIS functions in my previous research to widely available GISs. Many of the functions needed to enhance models in GIS exist in statistics packages, data base management systems, or other existing programs. However, integration of such capabilities directly into GIS facilitates model development.

6. *Lack of GIS-ready global change database*. There are very few GIS-ready global change databases available currently. NGDC, in cooperation with a large number of laboratories and individual scientists developed an approach that facilitates global change study with inexpensive personal computers and workstations. This approach led to the development of an integrated, scientifically peer-reviewed, public domain database containing several different indicators of the global environment designed for use with scientific GIS. In addition, NGDC is currently working with Chinese scientists to produce a GIS-ready global change database of China.

Daniele Ehrlich:

The Monitoring Tropical Vegetation unit (MTV) at the Joint Research Center uses remotely sensed information together with ancillary datasets within a GIS framework for studying surface features related to vegetation distribution, functioning, and conditions. Fields of applications are ecosystem productivity, biogeochemical cycles, biomass burning, continental and regional land cover mapping, tropical forest monitoring and terrestrial and atmospheric modeling. Most of the activities are in support of global change studies.

The research activities are centred around four projects: Tropical Ecosystem Environmental Observation by Satellite (TREES), Fire in Global Resource and Environmental Monitoring (FIRE), Monitoring Environment with Remote Sensing and Cartography over Africa Tropical regions (MERCATOR), Terrestrial Environmental and Atmospheric Modeling (TEAM). Linkage between the various research teams is maintained at the MTV level through a convergence of research objectives, interactions between modeling and observations, the sharing of data sets and continuous interactions between staff members.

The MTV research activities are supported by a centralised geographic information system. This GIS is continuously updated and maintained with maps derived from satellite image analysis and with digital data sets exchanged or purchased from other institutions. GIS at MTV runs mainly on ARC/INFO and ERDAS/Imagine software interfaced with other commercial software and in-house developed routines. Data and software live on a cluster of Sun Sparc stations, with SUN OS 4.1.3 operating system and Open windows 3.0 (Motif) graphic user interface.

GIS at MTV include global vector data layers such as coastlines, administrative boundaries, road/river network, population density, meteorological stations and thematic data layers from image processing exercises. Image processing is carried out on an extensive image data set that includes high and low resolution satellite data as well as radar images over the tropical belt and Africa. Recent data layers produced at MTV include a rain forest distribution map for the entire tropical belt, a map of active fires for 10 years over the African continent, land cover map of the main African biomes and a land cover change map for Africa.

Combining data sets at different scale, of different geographical extent, and with different data format is a continuous challenge in the development of a GIS at MTV. Data integration exercises include map transformations to accommodate data sets with different map projection; integration of raster data derived from satellite data image processing with ancillary vector data; and combining data sets at diverse spatial resolution for the different modeling exercises.

A subset of the GIS database at MTV is currently being used for modeling processes such as tropical deforestation, land degradation, and fire trace gas emissions. The most developed GIS project at MTV is the Vegetation Fire Information System (VFIS) in support of the Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO). EXPRESSO is an interdisciplinary experiment designed to quantify the flux of trace gases over a range of spatial scales and estimate their impact locally, regionally, and globally. The experiment will include laboratory process studies to define the variables which may affect biogenic emission fluxes, laboratory kinetic studies to better define the atmospheric fates and field campaigns. The first field campaign will take place in January 1995. The field campaign will represent an international collaboration to be led by French and US scientists, and be conducted in collaboration with scientists in Africa. MTV will integrate the data collected in the field campaign into VFIS that will be used to model fluxes of trace gas and aerosols from savannah fires. VFIS is currently focusing on a 2000 x 2000 km area centred on Central African Republic. The study site will eventually be expanded to the entire African continent.

John E. Estes:

There is a revolution going on today in the mapping sciences, a revolution that has, in effect, taken mapping from green eyeshades, scribe, and peel coat into the digital realm of computers, geospatial analysis and Geographic Information Systems (GIS). This revolution is being driven by the need for improved information concerning the nature, rates, and areal extent of changes occurring in the world around us, changes which cross and touch all levels of society. In addition to their use as "ground truth" in image analysis, maps depicting the spatial arrangement and areal extent of components of our global environment are important as we seek to improve investments made by private enterprise, military operations, environmental planning, resources management, and public policy decision making.

Yet, adequate maps do not exist for many areas of the world today. Depending upon scale, thematic content, and timeliness this is equally true in both developed and developing countries. Many people find this hard to believe. We assume that the map we require exists, contains the information we seek, is accurate and up-to-date. But as soon as a map is made, or data about the Earth is collected it is dated. Some mapped information is more perishable that others, e.g. continental outlines as opposed to forest clear cutting. The value of data is many times related to its currency. Yet, much of today's map data are, for many purposes, too outdated. Reasons for this lack of current map data are varied, complex, and include issues related to national security, national sovereignty, institutional infrastructures, public sector/private sector competition, international copyright agreements, and even religion.

At two recent conferences, 1) an Aspen Global Change Institute workshop and 2) an International Symposium on Core Data Needs For Environmental Assessment and Sustainable Development Strategies, discussions revealed a consensus that current basic data in map form are not adequate for many areas of the globe; that while these data could support a variety of scientific and applications oriented studies, one study or use can generally support the cost of producing the data set. The development of these data sets using today's technologies and infrastructure are often both labor and technology intensive, and as a result expensive. Both meetings agreed on a limited list of core data that are needed to support a variety of uses. These data types include land use/land cover, demographics, topography, hydrology, climatology, soils, water quality, air quality, infrastructure, and economic data.

Bangkok meeting participants made specific recommendations concerning the need to give priority to the production of these data sets and to move use forward in providing better map products to the global user community. These included recommendations to both national and international funding agencies to develop policies and mechanisms to encourage the generation of these core data sets; that nations should be encouraged to cooperate in the creation of these data sets; and that national and international capacity building was essential to the creation, use, and long term maintenance of these data sets.

This summer and fall two meetings will be held which will have sessions where the issues raised in both Aspen and Bangkok will be discussed. The first is a Cambridge Conference with the heads of national mapping organizations and selected invited participants. The second is the International Astronautical Meetings in Oslo, Norway. In Oslo, participants will be from major space agencies and private industries that are moving forward with plans for sensor systems that will facilitate the production of global data that can be processed into map information. It is our hope that both of these meetings will help move the process of the development of high quality global maps forward.

Now, more than ever, we need to break through the myths that surround mapping, myths that perpetuate the notion that the maps we need exist, are accessible, up-to-date, accurate, and inexpensive; mapping is easy; and there is little research to do in the mapping sciences. We all need to become more aware that mapping is an important, complex, expensive, and time consuming task, a task that we believe we are not performing today in an acceptable fashion. We need to put more resources into research directed at innovative ways to create and update map data.

What is required is the resources and institutional support to address the use of maps for verifying hyperspectral data, and the use of hyperspectral data for mapping in a meaningful way.

Tim Foresman:

GIS has been touted as a tool that can play many roles in global change research. What is needed is a means to understanding more precisely how this tool can be effectively applied to the challenges of ecosystem studies and protection at local to global scales. Clearly the means defined for this objective must provide a convincing methodology or paradigm for approaching the multiple dimensions associated with ecological systems. At the same time, the methodology must attend to calibration and comprehension of the multiple parameters or categories that define our understanding of environmental perturbations and the causes linked to loss of biodiversity. These categories include human habitation, resources utilization and economic activity, transportation development, urban sprawl and consumption, population dynamics and demographics, and land use policies.

Ecological modeling has made significant progress from the steady-state, compartmental, and flow analysis models of the late 1960s and early 1970s. Contemporary models for ecosystems have advanced along with computational efficiencies of computers to facilitate assessment of dynamic feedback processes for simulated ecosystem behaviors as measured by biomass, species, or energy consumption. Variations of ecosystem modeling provide means for defining ecological responses to human-induced perturbation. These responses can be expressed in a variety of units including present economic worth as determined for forestry, fisheries, and recreational use as well as for resource exploitation and remedial cleanups of damaged or poisoned areas. These models, however, lack effective spatial database linkage mechanisms required for quantitative understanding of the multiple environmental dimensions associated with human transformation processes, rates, and changes. The fundamental capability to link ecosystems compartmental dynamics with spatial and temporal dimensions remains a major challenge for environmental scientists.

Land use dynamics are inextricably tied to human behavior. These behaviors have many cultural variables that preclude simple empirical modeling. Different land management policies and environmental protection mandates provide one set of parameters to consider in evaluating land transformation impacts on biodiversity and ecosystems. Political, economic, and cultural practices influencing population pressures represent another important set of parameters. These human-related parameters impacting the environment are not well understood in relationship to the behavior or spatial patterns resulting from these dynamic processes. Edge or boundary shapes and transition conditions are extremely important to the resultant ecosystem response. What are the residual obstacles to ecosystems' requisite functional interconnections when roads are built or expanded, urban areas expand, and major resource decisions are made for mining, forestry, and energy development? What are the residual spatial interconnects available, such as hydrologic networks, greenways, and protection areas for species genetic interactions and population homeostasis? These questions require concrete understanding of the space and time components identified with land use/land cover and human interactions.

A methodology is being investigated, based on advanced spatial analysis techniques, to accurately document, evaluate, and visualize the land-use changes resulting from the dynamics of urban and rural growth patterns for Maryland's most populated corridor between Baltimore and Washington, DC. This effort is directed at advancing our understanding of how to effectively capture the information necessary to implement scientific models (cell based, numerical, etc.), such as ecological and sociological models related to human-induced transformations. This effort grew out of a USGS study on Human-Induced Land Transformations (HILT) focused on the San Francisco-Sacramento area. A spatially referenced database of human-induced land transformation factors along the Baltimore-Washington corridor will be created primarily from the existing spatial data sources maintained by federal agencies. Protocols will be examined and established to promote the use of these types of databases as long-term baseline modeling resources for multiple growth dynamics, environmental impact assessments, and ecological studies. Visualization techniques will be explored for promotion of understanding of population growth patterns along the Baltimore-Washington corridor related to major influences of transportation, topography, demographics, and industrial/economic processes. This program will demonstrate the effective application of geo-referencing tools, remotely sensed data, demographic records, and transportation models to study the major anthropogenic impacts since the time of European settlement on the American continent.

A collection of Maryland historic maps, dating four centuries back, will be digitally encoded and rectified to the State Plane Coordinate common mapping base. The series of maps will focus on the Baltimore-Washington corridor. Various layers of information will be extracted from the map series, including: transportation networks, urban centers, agriculture patterns, special economic zones, and miscellaneous event-driven geographic items. Satellite data will be used to provide information on these data layers changes for the period of 1972 to the present. Census records will be correlated to the historic cartographic records of populated centers and growth rates. Recent digital records of Maryland's land use will be utilized to augment and calibrate the growth model defined from the assembled information sources. Satellite imagery will provide the most recent land cover information.

Solutions to understanding and protecting biodiversity and maintaining healthy ecosystems must be based on existing and evolving spatial data infrastructures, as has been aptly demonstrated under the Gap Analysis Program. Approaches to ecological modeling that leverage the tools of GIS and remote sensing in accordance with national program agendas have a better chance for long-term success. Success will depend upon the cooperation of scientists and government managers and consensus on environmental protection paradigms to follow.

Rong Fu:

I am working for the Institute of Atmospheric Physics (IAP) and the Institute for the Study of Planetary Earth (ISPE) at the University of Arizona. The climate change research under the coordination of ISPE includes
climate modeling, satellite observations, process studies of the land-atmosphere interface, especially the processes that are important to the tropical deforestation. My current research, with Robert Dickinson, involves analyzing the process that controls clouds-land surface interaction as one of the most important aspects of land-atmospheric coupling, and validating climate models, particularly, CCM, using combined satellite remote sensing, meteorological observations, and observations from special field programs. These researches are central to the climate change research at ISPE.

The data sets involved in my research can be classified into three groups. They are satellite data, conventional meteorological data and in situ data from special field projects. Among the satellite data sets, I have used ISCCP, ERBE and TOVS. ISCCP provides global satellite observations of clouds at both 30km (B3) and 2.5 degree (C1, now called D1) spatial resolution every 3 hours for almost ten years from July 1983.

I have worked with B3 and C1 data. B3 data have a better spatial resolution to study convective-related clouds since their resolution is close to the spatial scale of the mesoscale convective system. However, the B3 data set provides only the visible and infrared radiances, instead of cloud physical properties, and has much bigger volume (about 200 GB for now, and will increase at rate of 20GB/yr as the length of data extends.

I used to read the data directly from the tapes and calculated my semi-final or final products at the same time. This process was done in an IBM mainframe computer environment. Currently, we are working on this data set on an IBM RS/6000 workstation network. We purchased 18GB of hard disk to bring the total hard disk space to about 30 GB. Robert Dickinson is purchasing a extabyte tape mass storage system. With these facilities, we expect to handle this data set in a much more efficient way. ISCCP C1 data set has much coarser spatial resolution, but can provide cloud properties. It’s a much easier data set because of the smaller volume and more careful calibrations. To combine the advantages of B3 and C1, ISCCP produced the DX data set that has high spatial resolution as B3 and cloud properties as C1 (visible and infrared radiances are also provided). The volume of this data set is about 5 times bigger than B3 (about 1 TB). We are planning to get a small portion (a few months for North and South Americas) of the DX data and analyze them using the IBM RS/6000 workstations and exabyte tape mass storage system. ERBE and TOVS data are relatively small compared to ISCCP, although the TOVS pathfinder daily data we plan to work with have considerable volume.

The conventional meteorological data sets we use include global radiosonde data that provide vertical profiles of temperature, humidity, winds and geopotential heights at about 1000 sites world wide, and surface measurements of precipitation selected regions (US and Amazon).

We have the global radiosonde data set for the last twenty years in house. The volume of this data set is about 20 GB, much smaller than ISCCP B3 data, but cleaning and analyzing the data requires considerable time and experience. We have developed a computer program to check and remove errors in a more rigorous way and also interpolate the radiosonde measurements to the standard levels.

We plan to combine the satellite measurements of clouds, water vapor, and surface conditions, including surface temperature, humidity and vegetation index, with the vertical profiles of atmospheric thermal and dynamic variables. This will enable us to systematically examine different aspects of surface-atmosphere-clouds interaction. The consistency between different independent data sets will enhance our confidence about our results and inconsistency between data sets will help us find out the problems in our analyses. To do so, we need to gather the data sets from different sources and with different formats, and then synchronize them and form new data sets. This is a time consuming job for individual scientists. It would be very helpful if this type of data can be provided by data or information centers that have much better experience and expertise of handling data in different formats and at a larger scale.

Our current graphic software includes NCAR graphics, IDL, GrADS on IBM and DEC workstations, and Delta graphic and Spyclass for Mac. We are still looking for the best graphic software for efficient browse through large data sets. Without requiring a 3D graphic card, GrADS seems to be the choice now. We will keep looking for a more convenient graphic software which will enable us to conduct standard statistical analyses and browse through data by moving and clicking the mouse.

Jerry J. Garegnani:

Global change research is the study of how complex inter-relationships make up a whole Earth system and how that system reacts to or is influenced by other whole systems such as a whole ecosystem, a whole climate system, a whole biochemical system. Global Change research is not limited to the study of individual links or relationships within a system but seeks to understand, in an interdisciplinary way, how these links affect each other; how they affect links in other systems; and how the whole Earth system operates.

If an image of impossible complexity begins to form, then a challenge of global change research clearly becomes that of managing the data and information on multiple relationships in a way that reveals the nature of the whole system and allows for predicting the response of the system to changes in sub-system relationships. This challenge is made more difficult by the dynamic nature of the Earth systems, both short term and long term, such as biological life cycles, diurnal cycles, seasonal changes, geologic events, and long term changes in environmental conditions. Additionally, separating the natural Earth dynamics from human-induced change is a critical research objective, and adds another dimension of complexity (Asrar and Dozier, 1994). This challenge necessitates that the researcher look for a tool that can assist in determining relationships across time and space, utilizing multiple data sources, and provide the means for interactive modeling (Goodchild et al., 1993). This is what makes the Geographic Information System (GIS) suited as a research tool for the study of Global Change.

Many compelling reasons should lead the research community to embrace GIS as a tool for the study of global change. The increase in computational power from advancing technology as well as the reduction in cost for hardware and software make the GIS tool available and attractive. From the NASA perspective, with the availability of the Earth Observation System Data Information System (EOSDIS), researchers will be encouraged to provide more than the traditional peer-reviewed papers as a final product. NASA will also be looking for access to a well documented data set that can be made available to other researchers in a digital format which is transferable to other data systems. GIS tools can help researchers fulfill this requirement.

There are, however, barriers to the use of GIS. Some barriers are technical, involving data standards and interchange ability, while other barriers require new approaches to research. One barrier to expanded use of geographic analysis stems partly from the GIS focus on geographic features. Although this focus is acceptable to the Earth science community, the longevity of global change research depends upon the ability to integrate economic and social information and to state results in terms that can be understood and acted upon by elected decision makers. Where economic and social data are collected by governments of defined political boundaries, Earth science data usually adheres to natural features, and systems for global change must be able to integrate the two so as to facilitate interdisciplinary study (Rockwell, 1994). Also, since the GIS's available today have been developed for the environmental planning community, the research community is not fully aware of the capabilities of these systems.

On the technical side, GIS has seen its most significant growth from applications requiring high resolution, small area coverage and must be adapted to global scale data. Issues such as interchange formats that deal with vector and raster data, metadata requirements, statistical analysis capability, and handling of multi-temporal data have yet to be completely resolved. New data visualization techniques are necessary which can relate scientifically derived information to decision makers who may have little science background. Although advancements are being made in these technical areas, integration of the results is necessary to provide a tool that researchers can use to find the data they need across a distributed network, access it, analyze it and display the results.

The budgetary survival of global change research depends upon delivery of objective and scientifically accurate results being conveyed to political decision makers in the near term, thereby creating an urgency for an improved GIS, that can perform this global scale data integration.

References:

Asrar, G., and J. Dozier (1994) *Science Strategy for the Earth Observing System*. AIP Press, Woodbury New York.

Goodchild, M.F., B.O. Parks, and L.T. Steyaert (1993) *Environmental Modeling with GIS*. Oxford University Press, New York.

Rockwell, R.C. (1994) The planet and painted globe. *Human Dimensions Quarterly* 1(2): 1-4.

Catherine Gautier:

There are many issues that need specific attention with regards to global environmental research and GIS. This paper only addresses very large database access, manipulation, and visualization issues. Very large databases of terabyte sizes are becoming common in global environmental research, even before the launch of the next generation of space instruments aboard the EOS platforms. These data come from high resolution remote sensing sensors flown aboard aircraft (e.g., AVIRIS, HIS), but also from numerical models of various earth system processes. One area in which these databases are starting to flourish is that of radiative transfer. This results from the fact that highly spectrally resolved radiative transfer models have been developed over the last decade and tested (ICRCCM) so that they now have reached a level of accuracy that renders them useful for a number of climate applications. One of those applications deals with the role of radiative processes in climate and climate change prediction and more specifically the interaction of radiation with matter. For instance, high spectral resolution (line-by-line) models now allow the calculation of longwave fluxes necessary for computing atmospheric heating rates (one of the energy components of the atmosphere) in climate models and or the simulation of satellite radiances of future generation sensors. While extremely computer time consuming, these computations are now routinely made and extremely large databases generated which have a variety of applications from high speed radiation computations in climate models to fast retrievals from multi-channel (~2000) satellite radiances obtained by spectrometers or interferometers. Other recent applications include simulations of radiative processes through 3-D clouds in the shortwave spectral region which can now be performed with some accuracy and help address important issues such as shortwave absorption in the atmosphere. This involves Monte Carlo techniques whereby billions of photons are individually followed in their interactions with clouds (and any other absorber or scatterer present in their path) through simulated clouds of varying geometries. These two types of radiative transfer simulations can produce terabyte databases which need to be cogently analyzed and interpreted for physical understanding. In many cases, the database analyses require applying mathematical functions on and display of the entire database at once (e.g., rapid retrieval algorithms). Another type of very large database that requires comprehensive analysis is composed of the intermediate and final stages of the long-term simulations performed by climate models.

Most of the tools needed to perform these types of manipulations (access, processing, analysis) exist outside GIS but for small data sets only. Tools to handle such very large databases do not exist at the moment. Some of the characteristics for these tools include easy access to the database, complete characterization of the data (including metadata or ancillary information), interactive and exploratory visualization capabilities. The Sequoia 2000 project is looking at some approaches to these issues.

Another application of importance in global environmental research is the combination of data from multiple sensors to address multidisciplinary science questions. Indeed, satellite data as well as more conventional data are presently used in combined forms to diagnose complex processes. The example of cloud process studies is used for illustration purposes here. Clouds can be defined differently depending on which instrument is used to observe them or on the properties used to represent them. Their interaction with radiation can be used to estimate their extent or geometry. For instance, it is their scattering or reflecting properties that are observed with short wavelengths; these depend on liquid water droplets or ice crystals size distributions as well as the radiative properties of these particles at these wavelengths. In the infrared wavelength region, it is the top temperature of clouds that affects the radiation observed. With radar observations, it is the large droplets that provide the signal. In-situ measurements of particle size distributions or liquid water amount represent the most direct way of characterizing clouds. General circulation models characterize them as regions of ascending motion with certain water vapor concentrations (e.g., near saturation). To visually represent clouds and help understand how they form and evolve, tools are needed which are capable of integrating these different physical representations of the same object and display them in a coherent manner that facilitates their understanding and the diagnostic of their effects on climate. Many earth processes require similar integration of data sets from different sensors with different resolution and representing different aspects of a process of significance to climate.

Leonard Gaydos:

The U.S. Geological Survey has sponsored a project investigating Human-Induced Land Transformations (HILT) for the past two years with funding from the U.S. Global Change Research Program. The goal of HILT is to map patterns and rates of major land use changes, particularly urbanization, at the regional scale for the last 200 years, and make predictions for the next 200 years. Early work has concentrated on designing and building databases, developing animations that convincingly show the dynamic processes, and designing a model that could predict regional land use change. Preliminary data on built-up area for the San Francisco region for the years 1850, 1900, 1940, 1962, 1974, and 1990 has been produced along with an animation based on linear interpolation of these data.

This work has pointed out challenges and promises of GIS for dealing with time-series data showing geographic patterns. One issue is how to deal with varying source materials one encounters in a project of this type. In the San Francisco example, original sources for determining urban extent included landscape paintings, textual descriptions of settlement, town plats, topographic maps, land use maps, aerial photographs, and Landsat. Even though sources might be varied, the interpretations from them must be consistent. What procedures could be used to ensure this and how could the uncertainties be passed on to data users? Another issue is data storage. The San Francisco data was compiled at 30m spatial resolution in raster form; interpolated data was created and stored at 300m spatial resolution at one year intervals. What are reasonable spatial and temporal scales to use and should a simple raster structure be used?

Initial dynamic data for San Francisco was limited to urban extent. Current work includes mapping of historic transportation routes, and there is interest in mapping wetlands and other land covers. What strategies should be used to include vector data over time? How can extensions of the transportation network be visualized? Urbanization is usually a one way process that proved relatively easy to portray. Wetlands may undergo several changes from natural to diked, to agriculture, to urban, etc. Furthermore, extensive areas may be diked at the same time. Interpolating change using linear methods will not work. Urban growth was interpolated linearly even though actual growth patterns are seldom linear. If temporal sampling is great enough, such an approach seems to work, but what other techniques could be used?

These are all practical problems associated with creating databases of dynamic geographic processes and are basic to using GIS for global change research. HILT also provides experience with inconsistencies between mapping of physical data and socioeconomic and cultural data. Much physical data is space-filling, most socio-economic data consists of multiple attributes for fixed data collection regions, like counties, countries, or census tracts. A huge challenge for scientists studying the Human Dimensions of Global Change is how to integrate the two data types. In particular, robust methods of using physical data to help disaggregate and interpolate socio-economic data are needed. This is true for the static case of understanding, for example, population densities and their correlation with physical features of the landscape, but is even more important for examining these relationships over time. HILT is just now beginning to address the problem. One desired product is creation of population density surfaces over time based on census data and land use patterns.

Modeling is an important component of the Global Change program. The problem of disparate data types (socio-economic vs. physical) haunts progress. Many models work well in the raster domain, so are another reason for working towards disaggregation of socio-economic data. Issues of scale abound. What are appropriate resolutions to model geographic changes? HILT has a component that has developed and is calibrating a cellular automata model of regional urban growth that relies on sparse data (topography, initial settlements and roads, water features).

Experience gained with HILT is that GIS is necessary for conducting Global Change research that tries to understand pattern, process, and correlation of variable. Creating a geographic model of change is a particular challenge. Most GIS implementations and underlying software have not been designed for such tasks. Much must be learned and disseminated concerning data structure, formats, and appropriate spatial and temporal scales. NCGIA will provide a much needed framework for researchers to make progress on these vital issues.

Carolyn T. Hunsaker:

I am addressing my comments towards issues that I think are especially relevant to the use of GIS in ecological studies; however, some of these are just as important for other disciplines. To begin with, I have to comment on what is "global change" for ecosystems. Ecological hierarchy theory provides a useful framework for ordering scale complexities. Ideally we should look at three scales: the one of primary interest, and a level above and below. For "global" studies this presents somewhat of a problem; however, I suggest that the reality of the situation for ecosystems is that we will be working at continental and regional scales while keeping global aspects in mind.

A few general statements will help set the stage for my specific comments on the use of GIS in ecological studies for global change. In the past few years data sets and GIS technology have just started to be available to allow efficient regional and continental scale studies. Extensive and consistent, high-quality data sets will continue to be the major limitation for ecologists. Aside from biogeographers, only recently (last ten years) have many ecologists started to look at large geographic areas (e.g., landscape ecologists). Thus, while we have some theory about ecosystem processes at these scales, theory is not extensive and empirical applications of the theory are lacking. Also, while many ecologists are starting to use GIS, many of them are lacking in knowledge of basic geographic principles - a fact that limits their effectiveness.

Effective ecological research at regional to global scales requires a tool such as GIS. Landscape ecology focuses on understanding the relationship between landscape structure and ecosystem processes; GIS makes this research possible for large geographic areas and large data sets. Also, I believe that GIS will play an important role in allowing scientists to make complex analyses and modeling exercises understandable to nonscientists through both simple and sophisticated visualization capabilities. These are some of the advantages that GIS brings to global change research.

It can be hard to separate data and modeling issues from those of GIS because they are interrelated; Hunsaker et al. (1993) review these with regard to ecological modeling, and Goodchild et al. (1993) present a summary based on opinions from many scientists engaged in modeling with GIS. One often mentioned need is an integrated GIS that provides at a minimum a basic set of tools for environmental modeling and error analysis. There are four major impediments within current GIS technology that I want to highlight because I believe they hinder ecological research for regional to global scales (i.e., there are neither readily accessible nor generally acceptable approaches to these issues).

1) Methods to quantify and visualize error/uncertainty in spatial data and how error propagates through GIS operations and ecological models that incorporate spatial associations (Ehlschlaeger and Goodchild 1994).

2) Theoretical/computational structures that facilitate analyses across spatial scales (both data resolution and geographic extent) in a structured, hierarchical manner.

3) Ability to merge raster and vector data structures. For example, many landscape pattern metrics are calculated on raster data because of adjacency relationships; however, we should also look at how linear systems such as roads of different sizes (most accurately represented in vector format) fragment or change the landscape pattern.

4) Data for natural resources and human/economic resources are collected on different spatial units. The merging of these data for analyses and modeling over large geographic areas must be addressed for historic data and future data collection. Although some work has been done in this area, the importance of this issue is often overlooked (Gelinas 1988).

References

Ehlschlaeger, C.R., and M.F. Goodchild (1994) Dealing with uncertainty in categorical coverage maps: defining, visualizing, and managing errors. *Proceedings of 2nd ACM Workshop on Advances in Geographic Information Systems, 1-2 December 1994*.

Goodchild, M.F., B.O. Parks, and L.T. Steyaert (eds) (1993) *Environmental Modeling with GIS.* Oxford University Press, New York.

Gelinas, R. (1988) Development and application of "environomic units": hybrid map units designed to integrate environmental and socio-economic data for land modelling. In R. Gelinas, D. Bond, and B. Smit, editors, *Perspectives on Land Modelling*. Polyscience Publications, Montreal, pp. 69-85.

Hunsaker, C.T., R.A. Nisbet, D.C.L. Lam, J.A. Browder, W.L. Baker, M.G. Turner, and D.B. Botkin (1993) In M.F. Goodchild, B.O. Parks, and L.T. Steyaert (eds), *Environmental Modeling with GIS*. Oxford University Press, New York, pp. 248-265.

David A. Kirtland:

The U.S. Global Change Research Program is promoting research to improve vulnerability assessments for sensitive regions, methods for integrated assessments, and understanding and evaluating the role of terrestrial ecosystems in global change. Data describing the land surface and techniques to model, analyze, and predict changes in the land are needed to assess and understand terrestrial systems, land-atmosphere interactions, and the human impacts on both. The U.S. Geological Survey is contributing to this research by building global land characteristics databases and developing techniques to monitor, analyze, and predict patterns of change in the landscape. These activities focus on the development of global 1km data sets of land cover characteristics, topography, and soils; historical urban land use change and urban growth simulation modeling; mapping vulnerability in semi-arid lands; developing tools and techniques for integrative terrestrial process modeling; integrating GIS and environmental modeling; and improving land-atmosphere interactions models.

A major research question involves understanding how land surface processes behave at different scales. How do processes operating at the local level behave at smaller scales; and conversely, how do those operating at the global or regional levels behave at larger scales? Scaling from small to large areas, methods for integrating and aggregating data in space and time, as well as understanding the interrelationships of data sets in space and in time are all issues that need to be addressed. For example, the central theme of the Global Change Terrestrial Ecology Initiative is the development/use of comprehensive models of ecological and physical systems that link small-scale process models to large-scale ones. Research issues (drawn from the 1994 National Research Council report on *The Role of Terrestrial Ecosystems in Global Change, A Plan for Action*) include the following:

1. future distributions of ecosystems based on land use changes
2. geographically explicit regional models of ecosystem function and biogeochemical cycles, using remote sensing to extend the results to larger areas
3. developing and verifying relationships between vegetation reflectivity and production for different ecosystems due to regional and seasonal variations in leaf display
4. linking process models and GIS
5. the impacts of land use changes on climate, disturbance regimes, and ecosystem structure and distribution
6. understanding the global extent of land use changes to determine how humans respond to and affect further changes in the Earth system

Activities at both national and international levels that respond to research issues like those above require descriptive data about the land surface. Land characteristics data at multiple spatial and temporal resolutions are essential inputs to developing, testing, and using advanced Earth science models. These spatial data are also important to observational and monitoring activities designed to understand land surface processes. Advanced land surface process models also require data on other land surface properties, for example, albedo, slope, aspect, leaf area index (LAI), potential solar insolation, canopy resistance, surface roughness, soils information on rooting depth and water holding capacity, and the morphological and physiological characteristics of vegetation.

It is essential to develop capabilities to create and validate innovative land surface data sets at a variety of scales. These data sets should have distinct temporal components, adapt existing data sets, or convert primary data into derivative data sets. It is also essential to use a database approach that provides data at flexible scales for use in multiple parametrizations and classifications, grid cell resolutions, or spatial aggregations and integrations.

Research aimed at monitoring, analyzing, and predicting rates and patterns of landscape changes and developing the tools and techniques necessary to facilitate that research is a vital part of the program. For example, research on the implications of temporal changes of land use patterns or the monitoring of ecotone regions between biomes are important to human dimensions modeling and land-atmosphere interactions. The tools, methods, and research base for making estimates of these changes have not yet been adequately developed for use in providing the necessary information for policy-makers. GIS should play an increasingly important role in addressing these issues. As a tool that facilitates use of data for models, in monitoring schemes, and for visualization, GIS is already being succesfully applied. With the increased development of integrated Earth system modeling and analysis, physical and human data sets at several scales, some global in coverage, will be linked to investigate the interaction of phenomena. GIS should also be integrated with other tools useful for global change research such as image processing. Continued improvements are needed if GIS is to meet the requirements of these multiple roles.

Timothy G.F. Kittel:

I. Introduction

Crucial for assessing the potential response of ecosystem structure and function to altered climate and CO_2 forcing over larger domains is our ability to implement and analyze geographic- and time-dependent model simulations. The integration of ecosystem models, geographical information systems (GISs), and statistical analytical software can provide essential tools for managing and evaluating ecosystem model experiments.

Needed capabilities are: (1) spatial and statistical tools to develop physically-consistent data sets of boundary conditions and driving variables that cover large domains, yet realistically capture gradients and represent subgrid information; (2) methods to facilitate transfer and storage of model inputs and outputs that include model-GIS interfacing, time-referenced storage in GISs, and time-series decomposition storage techniques; and (3) analytic techniques to statistically evaluate both the geographical and temporal nature of modeled system responses.

II. Model Input Database Development

Accurate representation of the spatial distribution of driving variables and boundary conditions is needed for simulation of regional to global ecological dynamics. This can be difficult to achieve because of the paucity of extensive regional data and the coarse grid resolution needed to cover large domains. Simulations also require physical and spatial consistency across input data layers, such as among climate, vegetation, and elevation fields. This can be accomplished in part by using standard GIS functions (e.g., reprojection, resampling) to spatially co-register datasets, although only some GISs offer aggregation techniques such as averaging of sub-grid cell units. Physical consistency is, however, not always assured by such processing because data are often from different sources and created using different sampling techniques, resulting in differing spatial resolution and accuracy.

Two approaches to create spatially-consistent inputs are: (1) topographically-based spatial interpolation and (2) statistical representation of subgrid-scale heterogeneity.

Topographically-based interpolation of climate data. Because of the low density of weather stations in mountainous regions, spatial interpolation techniques that account only for the horizontal placement of stations do not adequately create gridded fields of climate variables that are strongly influenced by topography, such as temperature and precipitation. Approaches that account for the effects of elevation on temperature fields and orography on precipitation include the use of (1) standardized or regionally-determined lapse rates for temperature and precipitation (Running et al. 1987, Marks and Dozier 1992, Thornton and Running 1995), (2) aspect- (e.g., lee and windward) and region-dependent lapse rates for precipitation (Daly et al. 1994), and (3) thin-plate spline techniques (Hutchinson 1995). Such procedures are not currently included in commercially available GISs and could be facilitated by easy linkage to user-defined functions.

Statistical representation of subgrid heterogeneity in soil and land cover type. Boundary conditions, such as soil and land cover type, commonly exert non-linear control over ecological processes. For example, when these variables vary in space at scales finer than the simulation grid, grid averages may not adequately represent boundary conditions. When two distinct soil types occur in the same grid cell, averaging creates a set of soil properties that is not characteristic of any soil type present. An alternative is to represent the soil in a cell by dominant ("modal") soil types (Kittel et al. 1995a). Model experiments can be run either with the dominant soil or with a suite of dominant types where model outputs are weighted by the relative areal coverage of each type. The same approach can be applied to create bivariate histograms of the occurrence of soil and vegetation types within each cell to identify actual vegetation-soil type pairs (Kittel et al. 1995b, Ojima et al. in preparation).

Such statistical treatment of spatial heterogeneity and cross-correlation among variables that non-linearly control ecosystem processes allows implicit inclusion of subgrid information without increasing the resolution of model runs. While we have accomplished such a statistical sampling external to a GIS, using C code linked to S-Plus with S+Interface/CASIM (StatSci, Inc., Seattle, WA) (Kittel et al. 1995b), this process illustrates where tight coupling between GIS and statistical software could facilitate input dataset development.

III. Data Transfer and Storage Innovations

System-level interface between GISs and models. Seamless integration of software responsible for storage of model data layers with model code is needed to manage the cumbersome amount of input and output data for regional and global simulations. Tight coupling of these two research tools, GISs and models, allows automated and rapid exchange of inputs and outputs between application and database management software. This can be accomplished through a systems-level linkage between applications, a graphical user interface (GUI), and underlying data structures (e.g., Bromberg et al. 1995).

Time-referencing GIS capability. The need to evaluate transient results also impacts data transfer, storage, and analysis requirements. For example, the manner in which time-dependent information is stored affects how easily results can be analyzed. Temporal statistical operations on model results stored as separate map coverages for each point in time, as is common for GISs, are awkward at best. Temporal analyses can be expedited if data layers are time referenced by a GIS in a manner comparable to geographic referencing. Temporal referencing treats maps of the same coverage that vary in time as a continuum, so that time functions, such as time averaging and interpolation, can be performed on them as a set (Beller et al. 1991, Bromberg et al. 1995).

Output time-series decomposition. If an output series consists of repeated and overlaying temporal patterns, time-series decomposition techniques can reduce output storage requirements (Schimel et al. 1994). Output time series from, for example, multidecadal runs (50-500 years or longer) can be decomposed into mid- and long-term trends (e.g., 5-yr moving averages), seasonal cycle, other spectral components, and a residual series. This approach reduces output to be stored, if residuals are considered unimportant. Time series can be reconstructed from stored components for later analysis and individual components, such as the interdecadal trend, analyzed separately. Such decomposition techniques would be a valuable component of GIS used to handle time-referenced model output.

IV. Analysis of Model Results

Geographical analytical capabilities. Methods to evaluate spatial relationships in ecosystem model results include display of mapped responses, map differences, map comparison statistics (e.g., Kappa Index of Agreement), and animation. Both visualization and statistical techniques are valuable for revealing and evaluating responses in terms of (1) the spatial distribution of altered climate forcing, (2) the ecosystem's initial state, and (3) boundary conditions (vegetation and soil types). For example, stratification by vegetation type can be used to determine average responses by vegetation type and to address questions such as whether responses to uniform forcing (e.g., elevated CO_2) are even across a region or dependent on initial water or nutrient limitation.

Some of these spatial functions (display, differencing) are included in GISs. Other more complex statistical tasks can be accomplished externally through export of map files which are then brought into analytical software. However, this process becomes burdensome for large files and repeated cases and when GIS file structures are proprietary. This task is made more efficient through the enhancement of spatial analytical tools within a GIS or through two-way linkage of GIS and statistical software, such as S+GISLINK for ARC/INFO (StatSci, Inc., Seattle, WA) and as described by Bromberg et al. (1995).

Temporal analytical capabilities. Effective temporal methods for analysis of model output range from determination of time-mean averages, to more complex techniques for time-signal decomposition (as discussed in the previous section) and visualization, including animation of a map series. Power spectra, autoregression, and trend analyses are useful methods to evaluate short and long-period changes in model output time series. Multivariate techniques, such as analysis of spectral coherence and phase, can evaluate lag/lead relationships between variables, including those between forcings and system processes or between system components.

Acknowledgments

This paper was largely based on a paper presented at the Second NCGIA International Conference on Integrating GIS and Environmental Modeling (Kittel et al. 1995b). This work was supported by Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) sponsors (NASA, Electric Power Research Institute, USDA Forest Service), UCAR's Climate System Modeling Program (with funding from NSF and DOE), and the USGS-USFS TERRA Laboratory. Thanks go to A. Beller, B. Braswell, J. Bromberg, H. Fisher, L. Knapp, R. McKeown, D. Ojima, T. Painter, N. Rosenbloom, and D. Schimel for their valuable comments.

References

Beller, A., T. Giblin, K.V. Le, S. Litz, T. Kittel, and D.S. Schimel (1991) A temporal GIS prototype for global change research. In *GIS/LIS '91 Proceedings*, Vol. 2. pp 752-765.

Bromberg, J.G., R. McKeown, L. Knapp, T.G.F. Kittel, D.S. Ojima, and D.S. Schimel (1995) Integrating GIS and the CENTURY model to manage and analyze data. In *Proceedings, Second International Conference on Integrating Geographic Information Systems and Environmental Modeling*, in press.

Daly, C., R.P. Neilson, and D.L. Phillips (1994) A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. of Applied Meteorol.* 33(2): 140-158.

Hutchinson, M.F. (1995) In *Proceedings, Second International Conference on Integrating Geographic Information Systems and Environmental Modeling*, in press.

Kittel, T.G.F., N.A. Rosenbloom, T.H. Painter, D.S. Schimel, and VEMAP Modeling Participants (1995a) The VEMAP integrated database for modeling United States ecosystem/vegetation sensitivity to climate change. *Global Ecology and Biogeography Letters*, submitted.

Kittel, T.G.F, D.S. Ojima, D.S. Schimel, R. McKeown, J.G. Bromberg, T.H. Painter, N.A. Rosenbloom, W.J. Parton, and F. Giorgi (1995b) Model-GIS integration and data set development for assessing the vulnerability of terrestrial ecosystems to climate change. In *Proceedings, Second NCGIA International Conference on Integrating GIS and Environmental Modeling*, in press.

Marks, D. and J. Dozier (1992) Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada: 2. Snow cover energy balance. *Water Resources Res*. 28: 3043-3054.

Ojima, D.S., T.G.F. Kittel, D.S. Schimel, T. Painter, and B. McKeown. Ecosystem modeling of land cover patterns in the conterminous United States. *Ecological Applications*, in preparation.

Running, S.W., R.R. Nenami, and R.D. Hungerford (1987) Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulation of forest evapotranspiration and photosynthesis. *Can. J. For. Res*. 17: 472-483.

Schimel, D.S., T.G.F. Kittel, D.S. Ojima, F. Giorgi, A. Metherall, R.A. Pielke, C.V. Cole, and J.G. Bromberg (1994) Models, methods, and tools for regional models of the response of ecosystems to global change. In Wood, R.C. and J. Dumanski, ed., *Sustainable Land Management for the 21st Century*. Vol. 2, pp 227-238.

Thornton, P.E., and S.W. Running (1995) The generation of daily surfaces of meteorological variables over gridded terrain. *J. Hydrology*, submitted.

George H. Leavesley:

The focus of this paper is on the global change research topic "Hydrology and Water." I recently published a paper titled "Modeling the effects of climate change on water resources: A review," in the journal Climatic Change. The purpose of this paper was to characterize the current state of water resource modeling for use in simulating the effects of climate change and current climate variability. Methodologies were reviewed, deficiencies were discussed, and additional research needs were identified. I will use this journal article as the basis for my position paper.

Hydrologic models provide a framework in which to conceptualize and investigate the relationships between climate and water resources. A review of current studies that assess the impacts of climate change using hydrologic models indicates a number of problem areas common to the variety of models applied. These problem areas include parameter estimation, scale, model validation, climate scenario generation, data, and modeling system tools. GIS is currently used as a support tool in many of these areas. However, GIS could be used to a much greater extent to help provide solutions to these problems.

Parameter estimation: Models differ in their degree of complexity but share a common problem. Each has a number of parameters that must be estimated or calibrated for model application. Parameter calibration is not feasible for global change applications. Therefore, the development of hydrologic and ecosystem process formulations whose parameters can be estimated from measurable basin and climate characteristics is a critical need. GIS is currently used to characterize watersheds and landscapes but a major impediment is the identification of the relations between model parameters and physical measures that could be obtained from remotely sensed data and digital data bases. Part of the solution lies with a more physically based understanding of hydrologic processes and their interactions. When parameterizations are based on the physics of the process, the ability to measure or estimate parameter values from climate and basin characteristics is improved. It is only through the use of parameterizations that do not require calibration that the problems of climatic and geographic transferability of models can be resolved.

Scale: Prameter measurement and estimation techniques must be developed for application over a range of spatial and temporal scales. Knowledge of physical processes is most extensive at the laboratory, point, and small plot scales. Extrapolation of this understanding to larger scales must consider the effects of spatial heterogeneity in the parameterization of processes at the larger scales. In moving from the points to hillslopes to grid cells or small basins, different sets of physical laws may dominate at each of these scales. The variability and applicability of parameters and process formulations must be understood across the wide range of scales over which climate change impacts will be assessed. GIS provides the tools to aggregate and disaggregate scales but a major need is to understand which process components and which conceptualizations of these components are most robust at the various scales.

Model validation: Currently, models are evaluated on their ability to reproduce historic time series of observed streamflow or other hydrologic variables. However, for conditions that are representative of a potential climate change, observations will not be available a priori, and the climate, as well as the physical characteristics of a basin, may be significantly different from those used in the parameter calibration procedure. The problem of defining quantitative measures of model performance in terms of its ability to adequately simulate new conditions is formidable. Distributed-parameter models are a major concern in that parameters are assigned to multiple spaces but the model is validated using a single streamflow hydrograph which integrates the total basin response. Time series of spatial measures are needed to compliment streamflow and assist in the validation of spatially distributed parameter estimates. GIS currently is used to identify land-use variability and has been used with satellite measures of snow covered area to help validate distributed snowmelt model parameters. More spatial measures need to be developed or applied to facilitate the evaluation of hydrologic and ecosystem process parameterizations over a wide range of scales. Quantitative measures of uncertainty in these distributed parameters are also needed to provide an estimate of confidence limits on model results. These would be of value in the application of model results in risk and policy analyses.

Climate scenario generation: The preferred source of data for use in the assessment of the impacts of climate change is the general circulation model (GCM). However, most GCM's simulate reasonable average annual and seasonal features of present climate over large geographic areas but are less reliable in simulating smaller spatial and temporal scale features that are relevant to impact assessment. Making an assumption of confidence in GCM output, a major problem for GIS application is the disaggregation of GCM or mesoscale model results to the spatial and temporal scale of hydrologic model application. This includes spatial scales of 1-10km and temporal scales of hours to days for time series lengths of 50-100 years. Removing the uncertainties in current scenarios is dependent on improvements in both GCMs and scenario generation procedures.

Data: Simulation capabilities have generally exceeded available databases. Detailed data sets in a variety of climatic and physiographic regions collected at a range of spatial and temporal scales are critical to improving our understanding of hydrologic processes and to testing and validating the more physically based models that are being developed. GIS can provide the tools to create such databases but a major impediment is the limited availability of ground-truth data to assure some measure of quality in a global or even continental scale effort. The development of field based data collection programs jointly with model development efforts has been cited by numerous researchers as a critical need in the research and development of improved physically based models. A data area in which advances will have a significant effect on hydrologic modeling is the coupling of GIS and remote sensing.

Modeling tools: Modular modeling systems need to be developed to facilitate interdisciplinary research on the full range of modeling problems and to provide a framework in which to apply solutions to the range of assessment questions. In a modular framework, researchers in a variety of disciplines can develop and test model components to investigate questions in their own areas of expertise as well as work cooperatively on multidisciplinary problems without each researcher having to develop the complete modeling system. Continued advances in hydrology and related sciences, in computer technology, and in data resources will expand the need for a dynamic set of tools to incorporate these advances in a wide range of interdisciplinary research and operational applications. Modular system approaches provide the flexible framework in which to integrate these advances in both research and operational applications. In addition, these systems can be coupled with databases, GISs, and expert systems to provide an interactive modeling tool to assist users in processing data, initiating model runs, and analyzing model results using a variety of statistical and graphical techniques. A variety of resource management and risk analysis models could also be incorporated in the modular system for use in evaluating alternative resource management policies and in developing short- and long-term resource management plans. Major impediments to developing these systems is a lack of a standard data structure for GIS data and data exchange and the limited availability of a full range of GIS tools at the program library level for incorporation into user-developed systems.

Brian G. Lees:

Detecting change in ecosystems as a result of global change is a classic signal detection problem. We are looking for a change in signal which can confirm, or otherwise, model predictions. The smaller the change we can detect, the more rapidly we can refine our predictive models. Our primary aim therefore is to increase the sensitivity and selectivity of our change detection techniques. Our secondary aim is to make sure that these techniques remain consistent from patch scales to the global scale. This is a difficult, but important, requirement.

In many important and sensitive ecosystems conventional remote sensing techniques are unsuitable for detecting small changes. The traditional "global" solutions lack sensitivity and selectivity.

Sensitivity

Unstructured global approaches using techniques such as NDVI are powerful, but blunt, instruments for detecting change. Information on the attribute "change" generated in this way is very generalised. However, remote sensing is the only practicable tool we have available which can give us rapid, cost-effective and broad coverage of the planet. We need to use it as effectively as possible. In many ecosystems the tallest stratum has the greatest inertia in response to climatic change and such change is often reflected most rapidly in the lowest stratum. This has always been a significant problem in attempts to reconstruct fine-scale palaeoclimatic variation using palynology and is an equally serious hindrance in detecting change in ecosystems using remote sensing. The lower stratum of any multi-layered mixture of growth forms and species is the least visible to remote sensing and therefore only provides a small contribution to the overall signal. Yet this is the most important component of the signal we need to monitor.

Selectivity

Not only is the target signal a minor contributor to the overall signal received by remote sensing platforms, but the models used are unable to transform spectral response into the level of ecological information required due to the high degree of spatial non-stationarity in the data. The spectral classes generated by conventional remote sensing techniques at times have some relation to the information classes required by ecologists, but the link is casual rather than causal. The underlying model assumption that reflectance (colour) relates to particular species is true for only limited areas of parameter space.

Stratification

In order to successfully detect change in this target signal we need to develop methodologies which allow us to control for the causes of this spatial non-stationarity. This approach is not new. Anyone who has selectively masked out land cover types prior to the analysis of a target group is trying to reduce the spatial non-stationarity of the derived solution. What is proposed is several orders of magnitude more complex, but uses similar logic. The degree of stratification needed to significantly reduce spatial non-stationarity to a level where the sensitivity and selectivity of derived solutions is increased to the level required to detect minor change is beyond manual and subjective procedures. The level of stratification required can only be achieved using an automated method.

Attribute scale/process relationships

A hierarchical stratification of Euclidean space into polygons based on, at the top, biogeographic zones, then bioclimatic regions, areas of similar lithology, wetness, and disturbance, then areas of similar illumination, will allow us to move from global to patch scales by progressively partitioning space to reduce spatial non-stationarity. The stratification requires definition of a hierarchy of datasets. There is a scale/process relationship here which will vary from ecosystem to ecosystem, but since we are looking at a tree structure this is not a problem. Each branch of the tree can have a unique sequence of attributes on which the recursive partitioning of space can take place. Indeed, this is the whole point of this type of model where attribute datasets nest within each other depending upon the attribute scale/process relationships of each ecosystem and topographic unit.

Automated stratification

However, attempts to approach this in a very deterministic way introduce significant errors and redundancy. A more effective strategy is to build the structure by inductive reasoning, closely monitored by expert knowledge and field information. This allows us to build a much more complex structure which can target individual species, rather than associations or communities. In addition to greatly increasing the sensitivity and selectivity of the method for change detection this removes many of the sources of error identified in our early trials. Importantly, the strategy of inducing the structure from observations means that the effective terminal mapping units can be defined at the most effective, and not necessarily the largest, scale. Without exception our experimental results show that this approach successfully orders attribute scale and attribute importance to produce a set of nested datasets relevant to the target entity. This not only minimises model spatial non-stationarity but also allows one to test scaling questions.

A common sequence of attribute groups is, from the top down, climate, geology, topographic derivatives, remote sensing, and hydrological variables. Although there are some twenty-one climate indices, five major topographic indices and so on, only those which have a significant effect on the target entity are drawn on to partition the data space. Many of these spatial datasets are the results of quite complex modeling and the inductive modeling is sensitive to attribute scale and scale related errors.

Summary

It is clear from work so far that the sort of climate surface modeling which has been carried out in Australia over the past decade or so is a vital base dataset for this type of modeling. Modeling the climate indices relies on a high quality DEM at a scale of 1:100,000 or 1:250,000. In areas where these are significant, micro-climatic variation at scales larger than this correlates highly with derivatives of DEMs used for hydrological and geometric indices.

Our experience suggests that the less precise, but more accurate, geology data at similar scales is more widely applicable than the legacy soil landscape mapping data. In erosional landscapes, where most of our work has been carried out, topographic and hydrological indices are important at scales of about 1:25,000. From our experience, it seems probable that in depositional landscapes geochemical and radiometric datasets will replace topographic and terrain-derived hydrological indices in importance. If this is so, then there would appear to be no requirement for global coverage of DEMs at this large scale.

Where mapped geology is only available at 1:250,000, slope values become a significant attribute for partitioning at scales of about 1:25,000. In many lithologies, the slope attribute has a useful relationship to geology and structure and can act as an analog. Conversely, wetness indices appear rather less useful than expected. This may be due to the understood, but significant, errors arising from the assumption of local subsurface homogeneity.

Our effort in improving these techniques on local test datasets has concentrated on two areas. The first is in progressively improving the datasets used for partitioning. The second is in testing automatic inductive methods for partitioning these datasets to reduce the spatial non-stationarity. It has become evident that there is a significant difference in model behavior and the scale and type of important attributes between erosional and depositional landscapes. We have spent the last five years working in erosional landscapes and are now about to start work on depositional landscapes.

The paper would outline our findings so far and report the results of our experimental testing of a range of adaptive pattern recognition tools used to structure the nested datasets. These include inductive reasoning, decision trees, neural networks and genetic algorithms. In particular, the paper would discuss quite specifically the type, scale and quality of datsets required to implement this approach more broadly.

Millington Lockwood:

Introduction

Numerous opportunities exist to utilize Geographic Information Systems (GIS) to address climate and global change research topics, especially at the coastal and sub-regional level. However, there is a "perception" at the working level that GIS has limitations due to database size, computational ability, and difficulties in dealing with dynamic data of concern to those who are modeling or predicting phenomena relating to climate change.

Examination of the climate and global change community has identified a number of issues that have created barriers or impediments to examining (much less using) GIS technology for reaching research objectives. These barriers have been divided into 3 general categories for the purposes of additional discussion and analysis. Case studies involved with NOAA's global change research plan are used to illustrate various points. These examples are not meant to point the finger at any individual or organization, but rather are only used to stimulate further discussion at the workshop. Suggestions are offered as a point of departure for the purposes of identifying means of overcoming the barriers to full implementation of GIS technology within the global change research community. Opinions expressed within this paper are the sole responsibility of the author and do not represent, nor should they be interpreted as, an official agency position.

Discussion

Categories of GIS barriers - "Perceptions Become Realities":

1. Ignorance of technological capabilities of Geographic Information Systems

Discussions with colleagues in the research laboratories and examination of the data application components of the organization reveal that there is limited practical "hands-on" knowledge of Geographic Information Systems. While there are elements of the organization that have considerable GIS expertise they do not appear to be "recognized" nor organized since they are not associated with a research project. This organizational paradox seems to be the result of institutional barriers and senior management's ignorance of the possible applications of GIS technology-- as well as a perception of the typical role of a data center . Most organizations have been dealing with large main frame computer installations and are networked to one of the national super computer installations. There is a common feeling that GIS, and practitioners thereof, are highly specialized, mystical gurus, and are identified as graphic artists or cartographers concerned only with map-making. The typical attitude toward data management and data centers is that they have little knowledge of the scientific world and they serve only as a repository and data archive. The scientific community is slow to accept "information" science as "real" science.

2. Inherent nature of research vs. GIS (mapping) programs: funding, management, organizational and infrastructure issues

Research activities tend to be proposal driven and are focused toward achieving a scientific understanding of basic environmental phenomena. Often times these proposals, funded by various agencies, are only focused upon achieving scientific results and the means of achieving them are limited to known technologies that are recognized and endorsed by the peer review process. Furthermore the cost of introducing new technologies into an activity is normally the responsibility of the principal investigator and must be taken from the research budget and is not funded by the agency's infrastructure support. Scientist tend to be focused upon data collection and analysis and are unwilling to sacrifice their meager research budgets on new technology that does not appear to meet their objectives, or more likely, they did not use it in graduate school!

3. GIS does not support large, multi dimensional, time variant, dynamic applications

Research activities in the climate and global change arena are concerned with very large area (small scale) global phenomena that do not lend themselves to typical GIS solutions. GIS applications have been limited to (and are best at) relatively large scale, regional or sub-regional solutions that primarily involve highly accurate and high resolution "Geo-spatial" data.

GIS are driven by precision (especially in the geographic location) in order to reproduce or overlay graphical information with a high degree of spatial accuracy. GIS and the spatial data community are driven by (some say obsessed with) the need to standardize - it often seems as if standards are an end unto themselves or support an application that has little bearing on scientific research. Furthermore, the scientific community tends to be impatient with the paced, methodical approach to the development of standards.

For the most part scientific issues that are being addressed by the research community do not require this type of accuracy for their analysis.

Possible solution to resolve barriers:

There must be improved communications and education between the "GIS World" (pun notwithstanding) and the scientific community in general and the climate and global change community in particular. This could begin at a very low level by attending and hosting workshops at scientific gatherings (e.g., AGU or AMS) or focused meeting with principal investigators in their laboratories. GIS facilities (equipment, expertise, and database management) could be established within research organizations supported by a third party, or as part of infrastructure support analogous to libraries or the NOAA National Data Centers for the purposes of demonstrating or prototyping applications, strengths, and weaknesses of GIS technology to solve problems, and providing support to the scientific community.

Another approach would be to begin to use GIS technology to solve some very localized issues that require a high degree of spatial accuracy and have applications world wide. Items that have been suggested relate to sea level rise and/or local subsidence, examining the results of local phenomena on global environment, e.g. output from the 1993 Mississippi flood or the eruption of Mt. Pinatubo in the Philippines, analysis of ice edge and thickness, coastal erosion, topographic, and bathymetric data. Categories of data have been suggested by the Global Ocean Observing System (GOOS) community.

Conclusion

GIS should not be thought of as an either/or technology but should be considered as a tool or technique that is available to address a host of issues ranging from simple graphic display of monitoring stations to complex modeling of global phenomena. It is important to build a partnership and a symbiotic relationship between the GIS community and the global climate change community in order to foster improved relationships and fully exploit the potential of GIS to solve global environmental problems.

Illustrative References and Sources of Additional Information:

Earth Magazine (1995) Virtual Earth - How well do computers simulate the real thing? *Earth Magazine* Vol. 3. No. 2.

Flemming, N.C. (1995) Making a Case for GOOS. *Sea Technology* Vol. 36, No. 1.

GIS World (1995) Special Issue - Access Remote Sensing Data for GIS. *GIS World* Vol. 8 No. 2.

GIS World (1993) *1994 International GIS Source Book*. GIS World, Inc. Ft. Collins CO, 691 pp.

Levitus, S., M.E. Conkright, R.D. Gelfeld, and T. Boyer (1994) World Ocean Atlas 1994 presents new ocean climatologies. *NOAA Earth Systems Monitor* Vol. 5 No.2.

Li, R. and N.K. Saxena (1993) Development of an integrated marine geographic information system. *Marine Geodesy* 16(4): 293-308.

National Research Council (1993) *Toward a Coordinated Spatial Data Infrastructure for the Nation*. National Academy Press, Washington, DC, 171 pp.

NOAA (1995) Decadal-to-centennial change, NOAA's vision to provide science-based advice to policy makers by detecting and assessing decadal-to-centennial change in the global environment. *NOAA Mosaic Home Page.*

NOAA (1994) NOAA Input to a Strategy for the U.S. Coastal Module of the Global Ocean Observing System. NOAA Working Group for a U.S. Coastal GOOS Module.

UNESCO-WMO (1994) Global Climate Observing System Newsletter, Joint Planning Office Vol. 2.

David R. Maidment:

I have been interested in the application of GIS to hydrology and water resources for some years and I have been teaching a graduate course called "GIS in Water Resources" at the University of Texas each year since 1991. I am involved in international activities in this field as follows:

- Member of a UNESCO Committee on GIS in Hydrology and Water Resources planning for Phase V of the International Hydrology Program, 1995-2000.

- Working on a project supported by the UN Food and Agriculture Organization entitled: "FAO/UNESCO Water Balance of Africa". For 1994-95 we are constructing a water balance model of the Niger basin in West Africa.

- Serving as an Associate Rapporteur to the World Meteorological Organization's Commission on Hydrology for GIS in operational hydrology.

- A member of the organizing committee for the HydroGIS '96 Conference in Vienna, Austria, sponsored by the International Association for Scientific Hydrology.

In addition to these international activities, I have a number of related projects in the United States dealing with GIS analysis of groundwater quality in Texas, surface water quality in the Midwest, and a spatial water balance of Texas. I have designed the following eight-step system by which all of these projects are organized. The first four steps deal with defining the goals of the project and setting up the digital description of the project in GIS. The second four steps deal with the simulation of the movement of water and its constituents through the environment, and with presenting the results of simulation.

Analysis steps

(1) *Project design*: defining the database, the scope of the project in time and space, and the GIS-hydrology models to be employed.

(2) *Surface description*: defining the characteristics of the land surface terrain, soils, land cover, stream network and watersheds.

(3) *Subsurface description*: defining the hydrogeologic structures through which groundwater flows.

(4) *Hydrologic data description*: building coverages of point locations of gages for precipitation, streamflow and water quality. Interpolation of point data onto continuous surfaces.

(5) *Water balance*: the partitioning of precipitation into evaporation, infiltration and surface runoff. The associated energy balance and mass balance of constituents at the land surface.

(6) *Water flow*: the flow of water through the landscape. Simulation of single events like large floods. Continuous flow simulation through time.

(7) *Constituent transport*: transport of sediment and dissolved chemicals with the flow.

(8) *Presentation of results*: maps, visualization of dynamic changes in time and space.

The present status of GIS utilization in global hydrology studies

Of the 8 steps presented above, the strongest area is Step 2 where continental and global Digital Elevation Models and the Digital Chart of the World are providing an excellent base for modeling of large areas. We are using the USGS 30" DEM of Africa as the base for our Water Balance of Africa project, and the GIS grid tools in Arc/Info to do the processing. Within the US we similarly use the DMA 3" DEM in a standard way. We have CD-ROMs of global soils, climate, and atmospheric moisture flow of data. We have access to global runoff data through the Global Runoff Data Center in Koblenz, Germany. We have found the DEM approach to setting up the units for analysis to be a very powerful standardized analysis frame which is consistent across spatial scales.

The areas that are weak are:

Step (1) There is no such thing existing as a global hydrology or water resources model. Such a model would track the motion of water through the hydrologic cycle over the earth. At this point, the conception of how such a model could be created is not completely clear.

Step (3) Digital mapping of subsurface geology is insufficient to do much meaningful analysis in the subsurface.

Step (4) Techniques for spatial interpolation of point data at continental scale are needed, especially interpolation taking terrain into account. The construction of mean annual and mean monthly climatic grids is needed. Understanding of how to construct time series of spatial climatic fields is needed so as to reconstruct the time-varying fields over the land surface of the Earth which are sampled by point gages. Better understanding of the relation between correlation in time of spatially-averaged quantities and correlation in space of time-averaged quantities would help.

Step (5) There is no global model of the land surface water balance except for those created with Global Climate Models which are not closed by mass balancing of soil moisture and runoff in an adequate way. The connection between global climate modeling and surface water resources is not well understood. The effect of global climate change on land surface water resources is not quantified. A proper mass balance of soil water, surface water and subsurface water is needed at the continental and global scale.

Step (6) There is little understanding of how to model the transmission of water in large river systems like the Amazon and the Niger. The effects of these rivers in moving water at the continental scale are largely unaccounted for in global climate modeling.

Step (7) The continental scale movement of sediment and chemicals awaits a satisfactory solution to large scale modeling of water movement through the landscape.

Step (8) Better techniques for dynamic visualization of spatially varying processes are needed to comprehend the patterns of interaction of processes in time and space.

I'd be pleased to contribute to discussion and research in these or related areas.

Kenneth McGwire:

I address the objective of NCGIA I15 by drawing primarily from the perspective of ecological research requirements. However, given our understanding of the Earth as a complex system of interdependent environmental and social processes many of the issues cross traditional disciplinary boundaries. In this summary statement I single out four general areas where I believe I15 can make progress.

Spatial analysis to establish global change

The term "global change" has come into liberal use in both the public and scientific communities. However, there is generally weak understanding of the meanings of "global" and "change." At what point is it legitimate to claim a process is global or representative of a change? When does it become clear that local and regional effects are part of a larger pattern? What model of temporal dynamics exists from which to establish change? The assumption of a steady state environment from which any variation is classified as change is naive.

I15 could directly address these issues by defining an agenda of research priorities in spatial analysis for the identification and correlation of low frequency/wide area variations in disparate data sources. This would entail drawing from the growing base of knowledge in three dimensional and temporal GIS analysis. What must be identified is that set of techniques which can be effectively used to quantify and represent changes over time and space. There is a great deal of cartographic history in the two dimensional representation of such phenomena, with examples including the migration of populations or movements of military forces over time. This sort of capability must be generalized to handle global representations and should be quantitative in implementation, relying for example on the 1st and 2nd derivatives of spatial/temporal patterns. A foundation for this work can be drawn from disciplines, such as oceanography or meteorology, which routinely deal with three dimensional, time varying patterns.

A challenge to be dealt with in such implementations will be the development of spatial techniques which combine discontinuous and continuous landscape representations in describing the operative scales of a phenomenon. For example, methods cannot be directly adapted from modeling of fluid dynamics because such techniques generally assume the existence of continuous 1st and 2nd order derivatives of a process. This requirement cannot be met with the types of data which are collected to represent social and economic processes. By bringing together physical and socio-demographic communities, I15 could identify which social data might be disaggregated in a more systematic manner (e.g. Tobler's pyncnophilactic interpolations of population) or what techniques can be used to bridge the gap between these data sources.

I would also suggest that a large amount of information has already been developed on specific, long term changes ranging from ice cores to pollen records which has not been effectively integrated for analysis by the scientific community. I believe that the creation of a spatio-temporal library of long period environmental dynamics must be developed. I believe that if would be of immense value if I15 could motivate the creation of such a product which would optimally be packaged with a set of tools for quantitative comparisons and visualizations across data sources, as described in the previous two paragraphs. I am currently working with personnel in the LTER system to develop a proposal for a data model of long term spatial and temporal variability of the Great Basin. This interactive historical database would cover the last 40,000 years of change as indicated by evidence ranging from packrat middens to geomorphic studies. Hugh Calkins of NCGIA has been involved in the development of this idea and I believe that it is an excellent example to bring to the I15 table.

Data availability and synthesis

Clearly, global change research is dependent on a vast amount of data. The availability and quality of data sources will be an issue in the ongoing global change agenda. There are significant technical limitations which should be addressed with respect to the types of conceptual and computational structures used to both characterize and synthesize these data. Various disciplines are developing sophisticated regional and global scale models, and some of these efforts already cross traditional disciplinary boundaries. However, a systematic approach to further integration will require identification of key variables and processes, and the spatial/temporal scales at which they are applicable. What is the minimum level of disaggregation needed by climate modelers in order to adequately characterize social processes such as deforestation? Which gaps in our characterization of the temporal and spatial domains of global processes are most limiting?

The "object oriented" computational paradigm might be examined with respect to integration requirements. The object oriented data model provides an excellent foundation due to its inherent modularity and ability to provide differing analytical functionality based on the types of data which are input. This paradigm might be used to separately encapsulate a system from its mechanisms for interactions with other systems. Thus, new understanding of a process like CO_2 fertilization may simply require modification of that class of objects which relate to leaf/atmosphere interactions, without requiring a systematic review of all programming code. Objects representing different processes could be "published" through the Internet and circulated much more freely among the scientific community than existing monolithic approaches.

More effective global synthesis and representation would also be achieved with the further development of data models for three dimensional representations of the global system. Global tesselations, such as Goodchild and Yang, still remain inherently two dimensional, and three dimensional representations such as voxels are not adequate for representations of the globe. NASA investigators are currently applying planetary mapping schemes developed for space research to the study of the Earth system. Such methods are based on a spherical coordinate system to which data can be mapped on-the-fly. However, at a recent meeting it was clear that there was insufficient attention being focussed on the appropriate methods required to interpolate or tesselate these data when combining multiple data sources. Further, this type of approach works best at coarse resolutions where surface topography does not significantly affect the computation of geometrical models between representations. I15 could examine the taxonomy of global representations, the effective domain of each representational model, and methods to effectively nest representations across scales.

I15 should also address the policy issues associated with data availability. One aspect of this would emphasize I15's role in promoting communication across disciplines regarding the types of data that are being developed around the world, what critical measurements are missing, and what standards are required. A further issue that must be dealt with in the development of the U.S. Global Change Research Program is the role of national sovereignty in data collection and subsequent policy development. The availability of high quality spatial data has been limited in part by national interests and security. In the United States positive steps are being taken by the current administration through mechanisms such as the Government Applications Task Force (GATF) to make data available which have been sequestered under the euphemism of "national assets." Recent governmental authorization of higher resolution satellite imagery by commercial entities such as Lockheed also shows promise. However, in many nations of the world access to environmental and economic data is much more restrictive. In November of 1994 a meeting is being held in Bangkok, Thailand which will be sponsored by the United Nations. This meeting is to address the development of a global spatial data infrastructure. It is critical that such efforts be promoted and that guidance on the types and quality of data to be produced be effectively communicated from the scientific community. I15 could play a valuable role by providing input in such policy level planning.

Transition zones and change detection

In addition to improving the conceptual and computational modeling of system interactions, it is important that we further develop our ability to monitor actual changes in these systems. Are hypothesized trends actually taking place? What adjustments must be made to the models? This effort would be dependent on the use of economic indicators of social transition zones, ground-based remote measures of anthropogenic effects such as air pollution, and remotely sensed observations of landscape change. Ideally all of these approaches would be integrated. Such approaches continue to be developed relatively independently of each other under the funding of agencies such as EPA, DOE, and NASA. I15 could work to identify methods to integrate these disparate efforts and to identify which areas require further conceptual development and data generation. Among the concerns in this review would be the sensitivity of various indicators to change and their stability with respect to spurious differentiations. For example, my recent work with Bob Frohn at UCSB has identified several limitations with the use of specific landscape metrics which have been approved by the EPA as being "tested and ready for implementation" in their Environmental Monitoring and Assessment Program.

The monitoring of transitional zones also raises issues mentioned in my first topic of "spatial analysis to establish global change." Changes may occur over a broad range of scales, and identification of a "global change" effect often proves difficult given the high frequency variations of existing natural and social processes. I have recently been working on this topic with respect to the monitoring of ecotones. In order to characterize the mental construct of an ecotone it is critical to establish a model of spatial variability across a transition zone. This work involves relating vegetation patch dynamics to semi-variograms derived from satellite imagery. Subregions of the study area are dynamically generalized to capture coarse scale transitions while maintaining the greatest possible spatial precision. I15 could provide a valuable role in identifying a suite of approaches for characterizing various types of spatial and temporal transitions and promoting cross-discipline communication for the development of novel implementations.

Information flow

The ideal of creating a process-based description of the integrated global system that would allow one to input a projection of industrial emissions from each nation of the world and get out a reasonable estimate of the cost to the state of Florida due to a rise in sea level is a daunting task due to the complexities of interactions, sensitive dependence to initial conditions, and accumulating uncertainty in the modeling process. Yet, such a flow from volumes of data to handfuls of information is the fundamental goal of a national global change research agenda. Attention should be focussed on defining a hierarchy of policy information requirements and mapping these to various levels of implementation in the research arena. Ongoing support of the U.S. Global Change Research effort will be dependent on a perception by policy makers that meaningful information will be derived to support decision making. Despite the creation of an organization with just this mandate (CIESIN), I15 could provide a valuable contribution by working to model the flow from data product to decision-making product and the consequent loss in information along this pathway. For example, landscape metrics are being promoted as an indicator of landscape condition for decision makers, however, practically none of the published research adequately addresses the loss of information on parameter variance when reducing to a single indicator variable.

Roberta Miller:

The issues already identified in connection with this research initiative are clearly on target. From the perspective of understanding human interactions in global change, however, I would give particular emphasis to a set of issues across the initiative related to temporal coverage of socioeconomic data. Some of the problems I raise may more properly be called epistemological rather than GIS problems, yet they must be examined in connection with the technical problems obstructing the use of GIS in global change research if GIS is to be useful as a research tool.

A. *Use of GIS in studies of change over time.* Much of the data collection now underway for use in studies of global change involves obtaining contemporary observations and building time series from these baselines. Studies of human interactions in global change, however, require georeferenced time series data now if the dynamics of current global change are to be understood. A major contribution to studies of global change would be a GIS capabilitiy that could easily deal with historic socioeconomic times series data. Problems in accomplishing this are related to the fact that the temporal resolution of various data series differs considerably from country to country and, within national statistical systems, from one type of data to another. The combination of varience over time and across variables is a significant problem.

B. *Integration of space-based data with socioeconomic data in a GIS.* A second need is to bring space-based data into the same data system as socioeconomic data to permit analysis of human interactions with terrestrial and other physical processes of change. This issue is complicated by at least two factors. First, socioeconomic data and data collected by space-based instruments are spatially callibrated in different ways. Space-based data can be arrayed on a rational, consistent, and tidy grid. Socioeconomic data are generally collected by governments for political and administrative purposes. As a result, they are available over political and administrative units whose boundaries are a historical legacy of wars, natural surface features such as rivers, legislation and land grants, and, in the case of gerrymandering, political expediency. It is difficult to place these two types of data in the same GIS. A second problem is that socioeconomic data are available annually or every decade, but not continuously as are many types of space-based or other natural science data. Moreover, the temporal frequency of space-based data can be held constant for all features under study, whereas it almost inevitably varies in socioeconomic data. Not only do these variations make linking time series in GIS difficult, but they also mean that regional impacts of global change can be compared far more easily in their physical manifestations than in their socioeconomic manifestations.

C. *Problems of scale and homogeneity.* Spatial representation of socioeconomic characteristics requires aggregation and summation of characteristics across disparate geographic units. The result displayed in a GIS may give the appearence of an underlying homogeneity within the unit, when in fact, the characteristics at issue may be very unevenly distributed. The problem could be avoided by reducing the size of the units in the GIS, but the need for consistency in units of analysis over time may require larger rather than smaller spatial units. Moreover, the requirements of privacy and confidentiality in much socioeconomic data result in the surpression of geographic identifiers and limit the extent to which the units can be reduced in size.

John O'Connor:

The phrase "think globally but act locally" is a good starting point for any aspects of ESD including global change research. Still, most policies are set nationally, an intermediate spatial scale. Decision-makers, particularly those sandwiched in at the national level, must digest thoughts, policies, and actions couched in terms of such different senses of place (global, national, and local for ease of reference). And one should recall the golden rule: those with the gold rule. These points convince me that the future of GIS lies in helping national policy-makers solve problems, not in what a purist might call research.

It follows that I think the global context will come more from fitting national efforts together than from a truly global approach. Even for globally circulating assets, water and air, even beyond national boundaries, that is probably more true than not. There will be what we are calling "global overlays" on many issues but the foundation must be national (even if most large and heterogenous nations then choose to devolve many reporting matters to the local level).

Decision-makers tend to operate on a given spatial scale. Further segmentation by sector or topic is normal but the advent of ESD "layers" of study have encouraged inter-disciplinary efforts in each geographic scale. Global climate and economic modelers now work with each other and international agencies, sustainable cities projects synthesize reports from many sources to inform city managers, national sustainable development councils build consensus among previously detached groups of stakeholders, and so on. The next challenge, and one where GIS has a comparative advantage and something close to research is needed, is extending the expert-nonexpert dialogue across spatial scales.

The importance of this dialog in successful inter-disciplinary studies needs to be stressed. Each of us is expert in some domain(s) but nonexpert in most. GIS fosters the dialogue when it (i) collates (an early step in data assimilation) and (ii) disseminates visually what had seemed disparate information sets (with differing spatial coverage being one source of disparity).

We should be clear what the key is: experts reduce the complexity of their respective specialized datasets to inform (put form in) the actions of nonexperts. Since human communication is mostly through language, words are the main way to do this.

Decision-makers need a tool, which I call GIS broadly defined, that gives geographic coherence to all the information they must assimilate, including text. For example, deciding whether an environmental assessement (text) accords with the "facts" (tabulated data and GIS images) is a globally recurrent task. And global change research is at least as much about globally recurrent issues (e.g., deforestation) as those that are truly global (e.g. ozone layer depletion). Most GIS software for text management, indeed for data assimlation in general, seems quaint. The discussion of standards, copyright, etc., strikes me as some years behind the curve for most information technologies. Forming strategic alliances with or outsourcing data collation tasks to more experienced players in these aspects of information management, rather than competing with them, seems prudent.

On the other hand, GIS is way ahead in recognizing that making decisions without visualization is like fighting with one hand tied behind your back. A third of the brain is dedicated to visualization (according to a recent PBS special on seeing); as much as 80% is used to some extent in the process (Super-learning 2000, Ostrander & Schroeder, Delacourte Press, 1994, page 139). GIS is unique among ESD tools in looking for the convergence between the way the mind works and visualization techniques. This is why other information specialists would wish to form strategic alliance with or outsource work to GIS experts.

Such negotiations will go more smoothly once GIS experts recognize that information requirements shift as thoughts lead to actions. Decision-making tends to proceed up an information spiral: (i) problem identification, (ii) policy formulation, (iii) implementation, and (iv) evaluation, which spawns a higher level of problem identification. As an example in global change research, deforestation may be identified as a problem in a given location and manmade fires may be the obvious proximate cause. Even crude and infrequent measures of deforestation and demographics may be enough to conclude that population pressure and poverty are the underlying cause, with people clearing land for farming and housing; which would mean it is time to move to the second phase, of looking for solutions.

GIS experts have a reputation of proposing ever more precise identification of the problem (e.g., finer grain measurement of forest cover, etc.) rather than moving on to policy formulation. Re-entry at the implementation stage happens but largely at the discretion of those responsible for discrete segments of work, or what we call task managers. This is useful and important but necessarily small-scale in terms of funding opportunities since each task manager has a modest pool of resources and a narrow range of objectives.

Low-cost GIS software has responded admirably and there ought to be better ways of capturing the information processed in this way. There are even some tools emerging, which I call decision support systems, that both follow the spiral and act as magnets drawing data from distinct decision-making episodes. But the root problem remains: Unlike text- and indicator-based tools, GIS drops out at crucial points in the decision-making spiral.

To become a ubiquitous tool in policy-making, GIS needs to stretch from its strongholds in problem identification and implementation towards policy formulation and evaluation, respectively. These stretches match fairly well with first a "top-down" and then a "bottom up" approach to strategic alliances.

Top-down alliances can be formed by more effective participation in shaping global-level ESD exercises gaining momentum at the international level. This is essentially the link from problem identification to policy formulation. Examples that come to mind, of efforts that could use more GIS-type input, are the Global Environmental Outlook exercise of UNEP (with the Dutch RIVM and others handling much of the GIS work); the 2050 Project sponsored jointly by WRI, Brookings, and Santa Fe Institute; a somewhat similar coalition effort by Bob Costanza and Bruce Hannon, among others; and UNU's Millennium Project. All of these efforts need to be loosely confederated as well, but the essential point is that extensive and largely overlapping efforts are underway with similar problems of scale, variable quality of information, etc. They tend of necessity to look for global datasets but are increasingly finding that the accuracy (if not the precision) of datasets is greater if they are cobbled together from national sets that seem better able to link with human activities. There are also a few efforts that begin with a coherent sense of geography, notably an EarthMap proposal taking shape under the leadership of Bill Wood at the US State Department, which need to forge stronger links to other disciplines.

But the really exciting possibilities for GIS, in my view, lie in bottom-up alliances with the exploding number of community-based, participation-oriented exercises that are appearing. This can begin as extensions from implementation to evaluation, with an emphasis on evaluation by those thought to benefit most from policies/programs being implemented. The initial expansion would be in low-cost PC systems but it would lead to greater attention to feedback mechanisms for reporting from presumed beneficiaries to those (usually government at some level) who dispense resources, which is the weakest part of the information spiral almost everywhere. Quality control would certainly be a technical issue but in general things would then move to where the pressing need would be for those used to operating on large-scale GIS, who would simply have a quantum jump in the amount of "ground-truthing" information they would need to reconcile with remote sensing reports.

GIS experts have no difficulty imagining an information system wherein myriads of independent decision-making units enter into dialogue either individually or in various "influence clusters," where geographic proximity will often be a main determinant of how they cluster. While we are still a long way from such a system, I think it is the thing to come. And I envy those, like GIS experts, who come naturally by a clear sense of place. I hope I15 will help them assume their natural leadership role in showing the rest of us how this might be done, and in looking beyond short term problems to what is important and do-able in the medium-term.

Anand Patwardhan:

Introduction

In this note I shall identify the issues relating to the use and impediments to the use of GIS in two areas of global change research: (a) impact modeling and assessment, and (b) policy formulation and decision-making. I will be guided by my perception of the information needs within these two areas, and I will try and relate these needs to the five scientific objectives of Initiative 15.

Cross-cutting issues

Before proceeding to the two areas, I would like to identify some issues that are common to both, and which need to be addressed in any discussion of the applications of GIS. There are three key issues:

Uncertainty: Representation and inclusion of uncertainty in the analysis. From a decision-making perspective it is perhaps as important, if not more, to provide uncertainty bounds for a variable of interest, in addition to a nominal value. Consequently, the decision-support system (of which a GIS would be an integral part) needs to support probabilistic descriptions of phenomena, the ability to perform stochastic simulations, and the tools for sensitivity and uncertainty analysis. This is relevant as much for impact assessment as for policy evaluation, since climate change impacts are input to decision models.

Integration of different kinds of data: While data integration has been recognized as an area of concern (scientific objectives 1 and 2 - Technical Impediments & Global Data), it is important to focus on this area in the context of impact assessment and decision-making. Typically, it is necessary to integrate socio-economic information with data regarding biogeochemical and physical characteristics and information about the effect of climate change on these characteristics. These data are often at very different scales and with different attributes including data quality and availability.

Dynamics: This issue is particularly relevant for impact assessment, where it is not only necessary to describe the resources at risk, but to also describe their evolution through time, in response to various endogenous (e.g., adaptation) and exogenous (e.g., population change, economic growth) forcings. Consequently, it is necessary to model both the long and short range interactions in a regional system, in addition to the dynamics. The lack of dynamics in GIS has been regarded as the most serious limitation to its use as a socio-economic decision tool (White and Engelen 1992). It is necessary to explore innovative approaches such as cellular automata (Couclelis 1985), and their coupling to a GIS, an approach that has been used for exploratory modeling of climate change impacts on a Caribbean island (Engelen, White et al., 1993). Such an approach may also be valuable for non-socioeconomic impacts such as ecosystem impacts.

Impact assessment issues

Impact assessment is one of the areas in global change research where I believe GIS can play an important role, but has not as yet. Apart from the cross-cutting issues described earlier, there are two issues related more specifically to impact assessment:

Scaling/aggregation: Impacts occur in a location-specific fashion. However, quantitative estimates of impacts are usually required at state, national, regional or global scales, and it is necessary to scale and aggregate the impacts. Just as it is necessary to support the detailed description of the impacts, it is also necessary to allow for appropriate scaling and aggregation.

Variability/extreme events: It is being increasingly recognized that the most significant climate change impacts are likely to result from changes in the pattern of extreme climate (meteorological, hydrological) events, such as floods, tropical storms, droughts, temperature exceedences and the like. In order to effectively model and represent extreme events, it is important to have a framework where temporal variations in climate variables may be accommodated. Linked to the issue of dynamics, in the case of extreme events it is necessary to describe the spatial and temporal patterns of their occurrence. Also, depending on the event, very different temporal and/or spatial resolutions may be required.

Decision-making issues

Most policy assessments of global change have been performed using simple, aggregate models of the coupled climate-economy system, with components such as zero- or one-dimensional climate models, aggregate energy-economic models and simple functional forms for climate impacts (Dowlatabadi and Morgan 1993; Hope, Anderson et al. 1993; Alcamo 1994; Nordhaus 1994). Indeed, environments to support decision-making need to allow for the interactive and iterative specification of model structure and for the graphical display of results and uncertainties. A good example of such an environment is DEMOS (Henrion, Morgan et al. 1986) , which has been used to develop a comprehensive integrated climate change assessment model (Dowlatabadi and Morgan 1993). For the effective use of GIS in the policy context these user interface and decision support issues need to be addressed. The situation is further worsened by the lack of awareness of the potential of GIS in the global change policy community, perhaps due to disciplinary constraints, and perhaps due to the characteristics of the technology itself such as cost and difficulty and complexity of use. While the first scientific objective of the initiative (Technical Impediments) addresses some of these issues, more attention is required from a decision support perspective.

References

Alcamo, J., eds (1994) *IMAGE 2.0: Integrated Modeling of Global Climate Change*. Dordrecht/Boston/London, Kluwer Academic Publishers.

Couclelis, H. (1985) Cellular worlds: a framework for modeling micro-macro dynamics. *Environment and Planning A* 17: 585-596.

Dowlatabadi, H., and G. Morgan (1993) A model framework for integrated studies of the climate problem. *Energy Policy* 21(3): 209-221.

Dowlatabadi, H., and M.G. Morgan (1993) Integrated assessment of climate change. *Science* 259(5103): 1813.

Engelen, G., R. White, et al. (1993) Exploratory modeling of socio-economics impacts of climate change. Chapter 5.3. in G. Maul, editor, *Climate Change in the Intra-Americas*. Edward Arnold, Sevenoaks, pp. 306-324.

Henrion, M., M.G. Morgan, et al. (1986) Evaluating an information dystem for policy modeling and uncertainty analysis. *Journal of the American Society for Information Science* 37(5): 319-330.

Hope, C.W., J. Anderson, et al. (1993) Policy analysis of the greenhouse effect: an application of the PAGE model. *Energy Policy* 21(3): 327-338.

Nordhaus, W.D. (1994) *Managing the Global Commons: The Economics of Climate Change.* MIT Press, Cambridge, MA.

White, R. and G. Engelen (1992) Cellular dynamics and GIS: modeling spatial complexity. Research Institute for Knowledge Systems, Maastricht, The Netherlands.

Christopher S. Potter:

This paper is written from the perspective of an ecologist with the goal of improved quantitative representation and further understanding of the role of terrestrial ecosystems in contributing to changes in global biogeochemical cycles and atmospheric trace gas fluxes. I draw on experience in simulation of ecosystem biogeochemistry using a loose coupling of GIS, remotely sensed data inputs, and process-based model formulations to outline what I see as important areas for research on changes of truly global levels using GIS over the next few years. I preface these comments with the recognition that, while numerous challenges facing ecological modelers and remote sensing scientists in this pursuit are chiefly technological and computational in nature, many other gaps in our knowledge base remain in the areas of biological mechanisms and feedbacks to the atmosphere and oceans, reconciliation of scale limitations and dependencies, and uncertainties in the historical and actual state of the Earth's land surface, particularly related to the post-industrial impact of human populations. I would submit that there is no technological silver bullet for these nagging gaps - they must be overcome by doing good science together, as fast as possible.

Hence, my first impression of the "scientific objectives" of the initiative outlined in the meeting announcement is that the topics listed therein are related largely to challenging computational and information science issues, as opposed to being motivated primarily by pressing global change science issues. Although the final analysis may show them to be on the mark, the current objectives are technology- and methodology-driven and do not leave the reader with a clear indication that their formation follows from critical evaluation of necessary advances in global environmental science for policy development. I assume that evaluation and refinement of the objectives is the main purpose for this meeting of natural, physical, and human systems specialists. The remainder of my comments are organized accordingly.

For the purposes of modeling global biogeochemistry and greenhouse gas fluxes, I see priority areas for GIS-based research falling into the broad categories of (1) ecosystem-to-ecosystem relations and (2) biosphere-atmosphere-hydrosphere relations. Important ecosystem-to-ecosystem relations include: history and prediction of large scale fire movement and alteration of biogeochemical characteristics in burning/burned areas; major vegetation changes in response to elevated CO_2 levels, climate, and invasions of exotic species; changes in the land cover attributable to human use, management, and fragmentation of ecosystems; movements of pests and pathogens with associated effects on the structure and function of ecosystems. There are many processes implied in these relations that may operate at the population and community level of ecological organization. Beyond building and tracking data sets, GIS will play a role in understanding and integrating the spatial relationships that facilitate and constrain these processes. Examples of such studies upon which to build include: Baker et al. (1991) *Ecol. Model*. 56:109-125; Cohen et al. (1994) in *Environ. Info. Manag. Anal*. pp. 483-496; Clark et al. (1995) *Photogr. Engin. Remote Sens*. 60:1355-1367.

Biosphere-atmosphere-hydrosphere relations include: three-dimensional exchange of carbon, nutrients, and energy among terrestrial ecosystems, aquatic ecosystems, boundary layers and the troposphere; reaction and transport of chemicals along root-soil-water interfaces with vector-based routing of flows; scaling of landscape-level exchange to regional and continental levels.

Prototype examples of such studies include: RHESSys, Nemani et al. (1993) in *Environ. Model. with GIS* pp. 296-304; the Carnegie Ames Stanford Approach (CASA), Potter et al. (1993) *Global Biogeochem. Cycles* 7(4):811-841; Maidment (1993) in *Environ. Model. with GIS* pp. 147-167. Variable spatial and temporal resolution is a requirement to nest the transient small scale reactions that produce trace gases within the slower biogeochemical processes that operate over large areas. In the diagram below, I have outlined the system we have used in global biogeochemical modeling studies based on raster GIS. Vector-based model computations have yet to be added in the manner that would permit flow of carbon and nutrients along the interfaces of air-plant-soil-water.

Figure 1. CASA framework for spatial ecosystem modeling and evaluation of potential aggregation errors in environmental information systems.

Robert G. Quayle (with assistance from Alan L. McNab and Thomas R. Karl):

Generalized GIS requirements

1. Time series and synoptic data slices must be readily accommodated. If this requires optimization for either time series or synoptic data, consideration should be given to developing two closely linked parallel systems.

2. Data must be linked multidimensionally in time, space, and by variable.

3. Effective operation of GISs must not require full-time investment of a GIS programmer. More high-level tools are required so computer-literate non-GIS scientists can use GIS tools much as they now use math and stat packages.

4. Related to 3 above, it is important to provide hooks so analysis schemes and dynamic models can be easily incorporated into GISs (and vice versa).

A Specific GIS Use in Precipitation Research

The National Climatic Data Center has established a Surface Reference Data Center (SRDC) project as a contribution to an international climatological research program to compare surface-based estimates of precipitation with satellite precipitation estimates. Seven countries have provided precipitation data for test-site areas to the SRDC. Each test-site covers an area that is approximately 5 degrees of latitude by 5 degrees of longitude. The test-site data consist of 5-day and monthly raingauge totals for the period 1986-1995. The goal of the project is to calculate area average precipitation from these raingauge data.

A Geographic Information System (GRASS) is used in both the data preparation and area integration procedures in the project. Data preparation consists of identifying and excluding errors in the original point data. The area integration procedure uses four methods to calculate area average precipitation from the point raingauge data: simple averages, Thiessen averages, Kriging, and an analysis model called "PRISM" (using slope-elevation vs. precipitation regressions and a Digital Elevation Model). Most of the uncertainty in the final validation data analyses is introduced by the area integration of point precipitation totals.

The SRDC project has brought to light GIS shortcomings in the following two general areas of climatological research:

1) *Using a GIS with other programs*. The SRDC project uses several unix shell scripts to link the GRASS GIS to the PRISM analysis program. The analysis program has no geographical query and display capability, while the GIS has none of PRISM's specialized analysis and modeling capabilities. However, the links built between the GIS and analysis programs allow them to be seen as a single program: data are input, analyses are produced and displayed, and ad hoc geographical

queries concerning the original data and the analyses can be answered. The queries include such items as map algebra, geographic subsetting, and distance calculations. One of the key features of the links is their ease of use. The scripts make it unnecessary to use cumbersome procedures to take the output from one program and import it (perhaps after one or two intermediate steps) into another program.

Unfortunately, the unix links between the programs required skillful programming as opposed to easily-used "connection features" offered by the analysis program and the GIS. Building such links takes a sizeable programming commitment.

2) *Number of data sets and analyses*. The SRDC deals with 5-day precipitation analyses for 10 areas for a ten year period, i.e., (365/5)x10x10 = 7300 analyses. This simple calculation does not include additional intermediate analyses, different versions of analyses, or the analyses of non-rainfall parameters. Even if these analyses are grouped (perhaps by year or season), the basic number of analyses that should easily be at a researcher's disposal is at least in the hundreds.

Although it is certainly possible to work with large numbers of maps and data sets in the SRDC GIS, in practice it is very cumbersome. Even a reduced number of analyses (on the order of 100) cannot be easily manipulated in the current SRDC GIS environment. This problem is another aspect of the general problem of using a GIS in research that involves a significant time dimension - the ability to easily access a large number of analyses, including the ability to use time as a significant dimension in the manipulation operations. We would welcome the opportunity to serve as co-PIs with GIS developers seeking to solve these problems for our ongoing climate research projects.

Jenny Robinson:

My association with global change dates to the 1970s, when I worked as a reviewer and critic of global social systems models, specializing on environmental aspects, and participated in the Global 2000 Presidential Commission Study. I first encountered GIS while doing my doctoral dissertation (1984-1987) at UCSB under the direction of the late David Simonett (the founder of NCGIA), and conducted at the National Center for Atmospheric Research.

My dissertation dealt with methods for quantitative assessment of the role of fire on Earth. Simonett urged me not to use GIS, because existing software and data sources were woefully inadequate to the task, but instead to sketch out the information flows needed for a comprehensive global fire accounting/monitoring system at the continental-to-global level.

Since doing my dissertation, I have been watching for signs of encroachment of GIS into the information milieu of global change research. After UCSB/NCAR, I spent three years at the Earth System Science Center (ESSC) at Penn State University. My work there tended toward paleobiogeochemical modeling, where GCM's, NCAR Graphics, and a variety of visualization tools were used to relate paleogeography and paleogeochemical information to atmospheric general circulation models. These were inherently spatial problems, but no one considered using GIS. The applications were sufficiently idiosyncratic there was no reason to expect existing software to fit the task, and the programmers involved were quite comfortable hacking together something using combinations of programming and callable routines. Meanwhile, I watched colleagues go through considerable agony trying to use GIS as a front end for 2.5 dimensional hydrological models at different scales.

After ESSC, I spent two years in the Applied Landscape Ecology Section of the Environmental Research Center of Leipzig (UFZ). At UFZ, GIS had been sold as a medium for integrated research on data from environmental, social, economic, and other realms. The gap between what was promised and what was delivered was scandalously immense, and precipitated a major review of our section from the German Federal Government.

In general, I conclude that unless one stretches the definition of GIS to take in the information handling systems that are developing within the geosciences, GIS has not worked work well in most of global change research. This is not surprising. One would not expect that a genre of tools developed for management of detail-rich social/administrative environments would adapt well to systems where critical data are sparse, proxy data (satellite observations) are crushingly abundant, and dynamic understanding, commonly fluid dynamical understanding, is crucial.

Difficulties of GIS in the geoscience portion of global change research include:

1) *Epistemologically inappropriate tools*. Tools designed for flat solids adapt poorly to questions relating to movements of the gaseous and liquid fluid envelopes in three dimensional space. Conventional GIS software was designed for static analysis of solid, fixed-form geographical entities, and works less well for specifying the behavior and properties of entities, such as clouds and radiation fields, which vary continuously in time and space. The GIS approach tends to treat causality in terms of object-space relationships. The mainstream of scientific reasoning treats space as a parameter in object-object relationships. Many scientists are turned off by the object-space ideology implicit in much GIS work.

2) *Tools that are not appropriate for the users' software and hardware environments*. Much of the computer analysis in Earth System Science is done on computer code written by scientists. Scientific programmers, in general, like tight control over their software. Given a tradeoff between a nice graphical user interface and a set of callable routines that they can interwork into their own data structures, scientific programmers will consistently opt for the latter, especially if they understand the performance and the algorithms of the callable routine, and the GUI-based package uses proprietary, inadequately documented, and/or slow algorithms.

3) *Poor understanding, on the part of the GIS community of the spatio-temporal data streams that are currently in place and under development in global change research*. GISers tend to assume that data handling problems are mathematical and mechanical, e.g., problems needing resampling, reaggregation, or reprojection, and do not recognize that a large number of problems, such as intercalibration of satellite observations and achieving continuity in surface data sets where recording stations have been moved or been encompassed in urban heat islands, involve issues of substance as well as spatial transformations. Likewise, we do not appreciate sophisticated spatial data handling methods, such as 4D data assimilation methods used in near-term climate forecasting.

GIS probably fits in better on the biological and human dimensions of global change than the physical. Its application is often impaired, however, because the parametric and conceptual frameworks needed to support spatially explicit global change research have been slow to develop. How can you do quantitative work on the human dimensions of global change when the basic units of social accounting remain at the national scale, and when spatially disaggregated time series data are not available in digital form for even the most basic demographic and land use categorization schemes? It seems to me that work such as Tobler's Global Demography project are necessary cornerstones for building GIS into research on the human dimensions of global change, and I cannot understand why they are not better supported.

The handling of spatio-temporal information is a major component of global change research. While some in the GIS community have been guilty of arrogance and of overselling the value of GIS in the global change realm, I am convinced that the need for spatial analytic tools in global change research is immense. I think the GIS community could make useful contributions if practitioners would take the time to read the global change literature and direct their efforts to useful extensions of the highly-developed spatial-analytic framework already in place in the global change community rather than acting as though they had invented spatial reasoning. I hope this meeting will support the sort of dialogue needed to set this process in action.

Ashton Shortridge:

The challenge of global environmental change has generated a vast scope of issues for geography. Recording and modeling earth processes, both physical and human, on a global scale is a recent development crucial to understanding the issues inherent in global change but rife with complex problems. Overcoming these problems is critical for global change research.

It is widely recognized that the quality of data varies substantially across the face of the Earth. Spatial social and demographic data, for example, is routinely collected and available for much of North America and Western Europe. In the rest of the world, however, such data can be much more problematic. Often the accuracy, resolution, and/or precision is highly questionable.

Physical records suffer from similar liabilities; in some places, coverage is extensive and the accuracy of this data is fairly well known, while in others data varies greatly in reliability.

Methods of dealing with spatially variable data collection points have been developed; however, the challenge of viewing and utilizing data for which the accuracy varies over space remains relatively unexplored. The consequences for global change studies are, I believe, significant, since in a great many cases researchers must work with the information they have available, information which suffers from the difficulties identified above. My goal is to provide a better understanding of how to work with this data.

My current understanding of the issues involved with global data is not presently sufficient to analyze the problem. I have a great deal of work to do before I present a more concrete proposal. Over the next several weeks I will examine the current literature on this topic. I look forward to participating in the NCGIA I-15 specialist meeting on the implications of GIS for US Global Change Research. Global Change researchers from around the country will discuss the challenges they see to implementing GIS in their work. I intend to gain from the meeting a better understanding and tighter focus on my proposal thesis.

Ashbindu Singh:

Digital elevation and drainage basins datasets of continental land masses are being assembled at the US Geological Survey's EROS Data Center that will be broadly utilized by the scientific and resource management communities including global change, hydrologic modelling, resource monitoring and modelling applications. The primary collaborators are the USGS, NASA, UNEP, US AID, the Instituto Nacional de Estadistica Geografia e Informatica of Mexico, and the Japanese Ministry of Construction.

The datasets are assembled with a 30 arc-second cell size, approximately one kilometer resolution. Previously the best available global elevation dataset was ETOPO5, a dataset with a five-minute cell size, or approximately ten kilometers. Various data sources are used in the assembly. One primary data source is the Defense Mapping Agency's Digital Chart of the World (DCW). DCW is a global vector dataset of 1:1,000,000 scale map information. The DCW contours, spot heights, stream lines, and lake elevations are processed in a surface generation procedure to create the gridded dataset. Another primary data source is the 30 arc-second generalization of U.S. Defense Mapping Agency's Digital Terrain Elevation Data (DTED) that has recently become available. To cover areas where the DCW and DTED are both inadequate, map contours are being digitized and other isolated datasets are being acquired. The work on Africa, North America, and a part of Asia and the Pacific have been completed. South American dataset assembly is underway, however over half of South America is not covered by DCW or DTED, therefore extensive map digitizing is necessary. The data distribution goal is to make the data publicly available, free or for as low a cost as possible, on a variety of media including Internet file transfer.

Derivative datasets are also being produced from the elevation datasets. In addition to the traditional slope, aspect, and shaded-relief information, hydrologic information is also being extracted. Geographic information system techniques are used to process the elevation data to delineate stream lines and basin boundaries in a digital form. When integrated with other spatial digital information such as soils, land cover, and climate variables, the resultant databases can be used to assess, model, and predict land surface conditions such as erosion, land cover change, vegetation conditions, flood impact, and hydrological assessment.

Based on the experience gained so far, the following research areas are identified for use of GIS in global change research:

The map digitization for getting contour information in the digital form is very expensive
and time consuming, so research is required in improving automated capabilities more fully facilitating data input.

2. Since the dataset generation process is very time consuming in both analyst and computer time, more research is needed in developing optimum algorithms for the surface generation and optimization of procedures for orienting the hydrology.

3. Standardization in map projections is critical for the successful application of GIS in global change research. For example, in order to do drainage basin work properly one needs to use equal area projection and there is always degradation of the data set due to resampling for different projections.

The author is grateful to Susan K. Jenson of the EROS Data Center, Sioux Falls, South Dakota for providing valuable input to this paper.

Andrew R. Solow:

I am an applied statistician, with a background in spatial statistics. My research focuses on environmental and ecological statistics, including the use of Bayesian decision theory in environmental decisionmaking. As a statistician, my interests in the area of spatial data tend to be methodological.

Clearly, there is a growing recognition of the importance, even prevalance, of spatial issues and data in the environmental sciences. It also seems clear that the capability to process and display spatial data, as in a geographical information system, has outstripped the capability of analyzing such data. Actually, in some cases, analytical methodology already exists, but has simply not been introduced into the literature on spatial analysis. In other cases, however, there is a need to develop new methodology. It is also necessary to point out that the methods that are currently used to analyze spatial data are sometimes inefficient, if not incorrect.

One of the simplest problems in spatial analysis is to determine whether or not there has been a systematic change through time in a spatially distributed variable (such as surface temperature). The data on which this determination must be made are commonly irregularly distributed in space and time, correlated in space and time, and contaminated by measurement error. There is a need to develop and disseminate practical methods for dealing with these and other features of spatial data.

Spatial data can also be used to assess the impact of environmental changes on a particular landscape. For example, suppose that interest centers on assessing the proportion of a particular region that would be inundated by a given increase in sea level. One approach to this problem is, first, to estimate elevation everywhere within the region using observed elevations at a set of survey points and, second, to simulate the effect of sea level rise on the estimated landscape. A problem with this approach is that the estimated landscape is typically smoother than the true (but unknown) landscape. A better approach would be through simulation. Again, there is a real need to develop and disseminate methods for the efficient generation and use of spatial data.

Soroosh Sorooshian:

Like many other fields of science and engineering, the application of GIS as a tool in hydrologic sciences has seen an unprecedented increase in recent years. In this summary, I will focus my remarks on the role of GIS in two areas: (1) hydrologic modeling; and (2) water resources management.

Hydrologic modeling

Because hydrologic sciences is moving away from lumped models towards more spatially distributed approaches, GIS has been found to be a powerful tool in this endeavor. The capabilities offered by GIS in organizing, analyzing, and interpreting spatial data relevant to hydrologic processes are being exploited for the better understanding of the interactions among different hydrologic subprocesses. For example, streamflow modeling is an important area in hydrology because of the critical role it plays in flood forecasting. Surface runoff is a function of many interrelated factors that include, but are not limited to, climate, soil properties, land use, and topographic aspects of watersheds. The capabilities provided by GIS are an effective tool for relating many of these factors to surface runoff. For instance, the database containing the spatial heterogeneity of soil properties, vegetation cover, land use patterns, and topographic features (digital elevation data) can be easily superimposed and interfaced with the hydrologic inputs and outputs, i.e., precipitation and evapotranspiration, to generate runoff.

With the new emphasis on the role of the hydrologic cycle in climate systems, hydrologists are dealing with spatial scales (GCM grids) which are much larger than in the past. Application of GIS tools in this new research area is indispensable. In other aspects of hydrologic sciences such as groundwater, again, GIS tools have been most helpful in studies related to the movement of plumes and contaminants in aquifer systems.

Water resources management

Another area in which GIS technology is beneficial is water resources systems and management. In this context, various types of information, such as demography, irrigation requirements, land use development, etc. have been interfaced with hydrologic variables such as reservoir releases, mountain snowmelt, groundwater pumpage, and so forth, to assess various management scenarios. The clientele for these are decision makers at local, county, state, and regional offices.

General comments

While a good number of user-developed software are being introduced, the most commonly used commercial and public domain packages have been ARC/INFO and GRASS.

The one issue that concerns me the most is that, as the use of GIS tools becomes more widespread, the nonexpert user may fall for the "pretty pictures" displayed on the screen and lose sight of the credibility of the information and the underlying model used to generate it. This issue could be potentially critical in hydrology and water resources, where our understanding of a good number of processes is less than perfect. Therefore, the information generated by these models could provide misleading information to the decision makers. This concern spans over the entire range of GIS applications which I mentioned above. The question that remains then is: "How do we safeguard against imperfect knowledge behind the beautiful visualization display and generated information?"

Louis T. Steyaert:

As one result of ongoing global climate change research programs and associated Federal geographic data activities, a wide variety of multiresolution land surface data sets are now becoming increasingly available for developing, testing, validating, and applying environmental simulation models. Such modeling ranges from the more traditional use of an individual atmospheric, hydrologic, or ecologic model in focussed disciplinary research to more comprehensive integrative land-atmosphere interactions modeling in which all of these types of models may be linked across various time and space scales. In some cases, these advanced coupled modeling approaches, originating from within global change research programs, are now interfacing with Federal activities to develop enhanced operational atmospheric and hydrologic forecast models.

Digital cartographic mapping, space-based remote sensing technologies, and various types of observed and model assimilated hydrometeorological data are all contributing to these growing land surface data resources. Some of the new data sets for the conterminous United States include the recently released USDA STATSGO soils data base; multiresolution land cover characteristics data derived from 30m Landsat TM and multitemporal 1km AVHRR digital image-based products; and various categories of operational, near-surface hydrometeorological data originating from traditional surface weather and hydrologic observational networks, experimental digital rainfall estimates from NOAA's growing network of Doppler radars, extensive cloud cover and surface radiation budget data from the NOAA GOES system, and evolving sources of near-surface hydrometeorological data based on data assimilation techniques involving meteorological forecast models such as NOAA's ETA mesoscale model for North America.

Multidisciplinary, process-oriented field experiments such as those of the Global Energy and Water Cycle Experiment (GEWEX) are another source of multiresolution land data, especially land cover characteristics data developed from remote sensing technology. Multiresolution remote sensing products contribute to the understanding, mapping, and spatial extrapolation of multiscale land processes. Examples of key field experiments include the GEWEX Continental International Project (GCIP) in the Mississippi River Basin and the Boreal Ecosystem-Atmosphere Study (BOREAS) conducted in central Canada as part of the NASA-led International Satellite Land Surface Climatology Project (ISLSCP). One objective of GCIP and ISLSCP is to improve tools for making operational atmospheric, hydrologic, and water resource forecasts and assessments within the Federal government.

These multiresolution land surface data sets create many challenging opportunities for geographic information systems (GIS) technology as a tool for building and managing spatial data bases, analyzing and exploring spatial interrelationships, and displaying and visualizing model results. For example, multiresolution data are now available to investigate and understand complex interrelationships among topography, land cover, and soils from the scale of individual landscapes to the conterminous United States. Moreover, multisource data describing the temporal behavior of land cover characteristics (for example, vegetation seasonality from NDVI) and associated hydrometeorological parameters are becoming available for the first time. Understanding the interrelationships among dynamic and static properties of the land surface is a key science objective. Such understanding contributes to building better data bases and models. Thus, there is the dual need for GIS as a tool for land surface characterization research, as well as, environmental mapping. Some of the challenges are illustrated in the following discussion in terms of GIS's role in data accuracy, data development, and analysis.

Data accuracy and error analysis

GIS can help identify, analyze, and resolve data accuracy and error propagation problems. Land data sets are derived from a variety of sources including field surveys, surface observation networks, various types of satellites, and simulation models such as meteorological forecast models. In many cases, the quality and accuracy of these data are quite variable, and even unknown. Estimates of some data types are frequently available from multiple sources. The propagation of error through the analysis is of real concern in the intercomparison and overlay of spatial data with different levels of accuracy. In many models, spatial data such as vegetation class and soil properties are aggregated to grid cells on the basis of percentage composition or predominant class. Mismatches can occur. All of these examples are of interest to modelers and data base developers working with complex land cover characteristics and soils properties. Better GIS tools are needed to track, flag, and visualize minimum accuracy levels or inconsistencies.

GIS and the flexible land database approach

Environmental models require many types of land data including dynamic land cover characteristics that must be derived and tailored from existing data according to variable grid cell and polygon size requirements. Although most models operate on grid cells within some specified computational domain, the use of polygons as a basis for model analysis is growing, especially in those models dealing with precipitation-runoff and evapotranspiration processes in watersheds, or modeling based on an object oriented approach. Using coupled models, such as nested mesoscale models linked to an atmospheric GCM and providing data to various watershed and ecologic models, requires multiresolution land surface data for the entire set of land-atmosphere interactions models. The modeling process requires multiresolution tailored data for developing, initializing (boundary conditions), testing, validating, and intercomparing simulation models. There are many different types of modeling applications, for example those involving air, water, and land resource assessment.

A flexible land data base approach for multiple user requirements can help meet the tailored land data needs of individual modelers, even though many different types of applications are represented. In this approach, the land data base is populated with sufficiently detailed land cover characteristics, digital elevation model, soils data, and other land data to permit the flexible tailoring of data for a wide variety of applications. This concept was incorporated by the USGS EROS Data Center in developing a 1km AVHRR land cover characteristics database for the conterminous United States. This flexible database concept involving the use of GIS tools was recently demonstrated by the USGS as part of the test and evaluation of the 1km AVHRR land cover characteristics data by land-atmosphere interactions modelers. GIS tools were used to tailor land data to meet the specific modeling regional domain, grid cell size, land cover classification, and method of spatial data aggregation for each grid cell (for example, predominant class) of various atmospheric, hydrologic, and ecologic modelers. These GIS tools can be streamlined and supplemented to facilitate the tailoring of land surface data for models.

Environmental modelers have adopted two approaches for meeting tailored database needs. For example, some global change modelers have used GIS functionality to meet database needs. However, some modelers have incorporated "home grown" GIS functionality directly into their modeling system. In this case, a land data processing module is incorporated directly into the land surface component of the modeling system. More user-friendly GIS tools are needed.

Existing GIS is an integral part of the flexible database concept for tailoring land data to meet individualized applications requirements. However, the requirements for land data are becoming more complex. Remote sensing technology is providing the foundation for a growing number of multitemporal measurements of dynamic, biophysical land cover characteristics. The need for developing derivative products from remotely sensed data with GIS tools is expanding. Advanced GIS tools for land characterization research are needed to meet these needs.

Advanced data analysis

Several GIS tools for enhanced land characterization research are suggested to help understand multiscale interrelationships in land data and to develop improved land data products. These tools involve algorithms for interpolating and extrapolating weather data in complex terrain, portable color notebook PC with GIS and handheld GPS capabilities in the field, and capabilities to better handle hierarchical, temporal, and four-dimensional data structures.

Land surface characterization research. Land surface characterization represents both opportunities and challenges for GIS as a tool to analyze complex data interrelationships while focused on developing improved tailored data sets. For the first time, relatively detailed land data sets appropriate for continental- to global-scale analysis are being developed to meet the growing demands of environmental models. The STATSGO soils data and 1km AVHRR land cover characteristics databases permit detailed studies of terrain, soil, and land cover interrelationships throughout the conterminous United States. Equally important, the diurnal and seasonal dynamics of the landscape can be studied with various satellite-derived data sets (GOES, AVHRR, SSM/I) and available hydrometeorological data. As Landsat-derived products have become more uniformly available across the country, multiresolution landscape characterization becomes possible. These types of studies are of interest to many scientists and modelers. Knowledge gained from these studies helps build better models and data bases. GIS has a large role.

GIS can play an expanded role in the spatial interpolation and extrapolation of environmental data. For example, modelers have developed various algorithms designed to interpolate and extrapolate weather data in complex terrain. Because terrain interacts with atmospheric flow patterns, it is an important determinant of local weather and microclimate conditions. In fact, terrain is a major factor determining precipitation and potential solar insolation patterns that help to define microclimate, vegetation, and soils interrelationships. GIS tools are needed to extrapolate and interpolate surface weather data and to estimate potential solar radiation. Such tools will help scientists understand interrelationships between microclimate and land cover.

Candidate approaches for interpolating and extrapolating available surface weather data include thin plate-smoothing splines to interpolate precipitation according to elevation and aspect within a DEM; the PRISM model, which smoothes the terrain for an effective aspect to the prevailing rain-producing wind patterns; and various algorithms for extrapolating daily solar radiation, maximum and minimum temperatures, and precipitation from limited surface weather station data. Mesoscale models represent another promising approach for simulating seasonal weather patterns in complex terrain.

Portable GIS and GPS capabilities are needed to collect and analyze data in the field. Such a system is an essential tool for scientific research in the field for land characterization research, not just a means to validate data sets. A color notebook PC with GIS and GPS used to collect and interactively analyze data from automobiles and aircraft is also feasible to help understand the landscape structure. As remote sensing algorithms are increasingly used to regionally extrapolate vegetation parameters such as biomass, the role for GIS in the field will expand.

Hierarchical GIS. The coupled modeling approach uses nested grid domains for different types of models, and multiresolution data are needed to meet requirements for local, regional, continental, and global scale data. One of the major research themes is the "scaling up" of processes from local to global scales and the "scaling down" from global back to local scales. Much of the research is focused on understanding the multiscale behavior of such processes as evapotranspiration, net primary production, and precipitation-runoff. GIS can do much to support this research in terms of building multiresolution databases.

However, some spatial research issues on hierarchical scaling and generalization involve both raster and vector data structures. More research is needed on the scaling of topographic, soils, and land cover data at scales ranging from the local to the global level. This scaling involves generalizing data structures, as well as aggregating the thematic attributes in the case of soils and land cover data. More work needs to be done on generalizing stream networks and hydrologic boundaries from the watershed and basin to continental scales.

One of the main hydrologic research themes is the concept of the hydrologic response unit (HRU) for modeling precipitation-runoff processes. These HRU's are a function of the topography, land cover, and soils. Enhanced GIS tools are needed to support research on the development of HRU's and their hierarchical data structures.

Temporal GIS. Traditionally, analysts have treated the element of time in topographic, soils, land cover, and land use data as a relatively static concept, with typically a one-time change detection. Current GIS is generally well suited for conducting change detection studies on these types of static data sets. However, biophysical land cover characteristics and the associated hydrometeorological data are highly variable, with time scales ranging from hours to seasons. Expanded temporal GIS tools are needed to incorporate the time dimension of these data. Current GIS is simply not well suited to efficiently analyze multitemporal images and gridded data sets.

Four-dimensional GIS. New GIS tools are needed for enhanced three-dimensional and temporal analysis of landscapes, watersheds, large regions, continents, and the globe. In particular, concepts of a "4-D" GIS for regional analysis of near-surface hydrometeorological and land surface data need to be explored. In the preceding sections, several examples of multidimensional land data were cited, including operational data sets on surface meteorological and hydrological station reports, Doppler radar rainfall estimates for most of the conterminous United States, near-surface meteorological data based on mesoscale modeling and four-dimensional data assimilation, as well as routine satellite data from a wide variety of sensors. Better GIS tools are needed for diagnostic analysis of these time-space data fields. The ability to analyze simultaneously these types of data sets within the land surface layer (lowest 100 m of atmosphere), at the land surface, and within the soil moisture zone with terrain coordinates is essential. The ability to run and interactively analyze 1-dimensional offline simulation models using these data is desirable. Examples range from land surface parameterizations to various types of weather and climatic impact assessment models, for example physiologically-based crop forecast models driven by near-surface land data sets. Such a "4-D" GIS would serve the needs of the research and assessment communities.

User-friendly GIS

Perhaps the largest single impediment to the expanded use of GIS by the modeling community, and in some cases, by the remote sensing community, is the user friendliness issue. For many modelers, GIS appear overly complicated. More friendly user interfaces are needed to get more modelers involved with basic GIS capabilities.

References

Goodchild, M.F., B.O. Parks, and L.T. Steyaert, eds. (1993) *Environmental Modeling with GIS.* Oxford University Press, New York.

Goodchild, M.F., L.T. Steyaert, B.O. Parks, M.P. Crane, D.R. Maidment, C.A. Johnston, and S. Glendinning, editors. *GIS and Environmental Modeling: Progress and Research Issues*. GIS World, Fort Collins, in press.

Steyaert, L.T. (1993) A perspective on the state of environmental simulation modeling. In M.F. Goodchild, B.O. Parks, and L.T. Steyaert, editors, *Environmental Modeling with GIS.* Oxford University Press, New York, pp. 16-30.

Steyaert, L.T. Status of land data for environmental modeling and challenges for GIS in land characterization. In M.F. Goodchild and others, editors, *GIS and Environmental Modeling: Progress and Research Issues*. GIS World, Fort Collins.

Steyaert, L.T., T.R. Loveland, J.F. Brown, and B.O. Reed. Integration of environmental simulation models with satellite remote sensing and geographic information systems technologies: case studies. In *Pecora 12 Conference Proceedings*. ASPRS, Bethesda, in press.

Steyaert, L.T., and M.F. Goodchild (1994) Integrating GIS and environmental simulation models: a status review. In W. Michener, J. Brunt, and S. Stafford, editors, *Environmental Information Management and Analysis: Ecosystem to Global Scales*. Taylor and Francis, London, pp. 333-355.

Peter S. Thacher:

The purpose of the Global Change Research Program is to improve understanding of human-influenced and natural processes producing effects known as "Global Change". In the words of the 1988 NAS report, *Toward an Understanding of Global Change*, "We must dare to seek an understanding of the Earth as a single system of which we ourselves are an increasingly important part."

As human-induced effects that are distant in time and space become clear, greater integration of socio-economic data will be needed in order to identify human contributions. And the resulting knowledge must be translated into terms understandable and credible outside the scientific community so that better understanding can influence human actions both to reduce harmful effects (such as by reducing emissions of greenhouse or stratospheric ozone-depleting gases), while improving the prospects of meeting the needs of expanding populations sustainably, and to adjust to or mitigate unavoidable change (such as by better coastal planning to cope with sea-level rise). These examples highlight the differences in scales between current Global Change programs, and the relatively local actions that are needed.

Anthropogenic contributions to global change are not the result of "global" decisions, or even large-scale specific actions, such as weapons tests, or massive spills; more often it is the accumulation alongside natural change of many human actions (or inactions), local in scale, but widespread in practice. An obvious impediment is the difficulty of combining datasets with vastly different sources, scales and projections, particularly in a widely-distributed system where those working at finer scales rely on microcomputers and workstations.

GIS, remote-sensing and GPS are commonly used in research and observing programs under IGBP and other coopertive programs to improve understanding. But, no matter what spatial resolution is employed, remote sensing will always require ground truthing at finer scales than can be obtained from remote platforms, and to pin down human contributions and causal relationships integration of socio-economic data is required at scales appropriate to decision-making.

Cooperation between natural and social scientists can be furthered by ground-truthing, especially when it incorporates socio-economic inputs. This cooperation can speed delivery of practical applications to influence policies and decision-making that, in turn, can buttress support for continuing research at the global scale.

Most of the human actors driving global change are not scientists, and while many may be familiar with spreadsheets and static and dynamic modeling excercises, the results are normally presented in tabular or text form and lack spatial dimensions smaller than the nation state. In some parts of the world there are exceptions, as in marketing and census operations; usually the results are at national scales only. But most of the anthropogenic actions driving global change result from policies and decisions that are more local than national, even if they are widespread. And despite the availability of satellite images of natural resources and other terrestrial features for over 20 years, there are very few countries (virtually none in tropical latitudes) for which anything like wall-to-wall coverage is available.

Consequently, little documented baseline data exists for any period in time from which to measure past change. This calls for "backcasting" in both natural and social science to capture and convert earlier data as a basis for modelling and forecasting, as well as integrating socio-economic information at corresponding scales, including actions at the "project" level - past, present and planned - that have this potential.

Human dimensions of global change require finer spatial (as well as spectral and temporal) scales, particularly for describing land-use (as well as land-cover), than are yet publicly available; hopefully programs such as NASA's Mission to Planet Earth and commercial ventures will soon furnish finer scale products (with consequent difficulties for local analysts because of the size of datasets). For effective presentation outside the scientific community, these datasets will need to be integrated with socio-economic data at scales appropriate to human action; in the US this will call for something approaching Town Tax Assessors' maps at 1"=100' scale.

This initial specialist meeting for I-15 is an opportunity for practitioners who are well versed in socio-economic planning to be brought up to date on work underway in the other seven topical areas and to be engaged in defining needs that can increase the relevance and influence of Global Change research results on day-to-day decision-making.

Given uneven rates of population growth and energy use around the planet, a particular need is to facilitate the use of these tools in the "international development community", "from the top down", and at the same time to improve skills and capacities in all countries so that socio-economic progress can address contemporary problems and lay a basis for continued improvement "from the bottom up."

Another group that should be associated are those involved in current international agreements, such as on climate, biodiversity, desertification, marine pollution, and the like, where experience with these tools might be exploited.

Waldo Tobler:

Demographic information is usually provided on a national basis. But we know that countries are ephemeral phenomena. As an alternate scheme one might use ecological zones rather than nation states. But there is no agreement as to what these zones should be. By way of contrast global environmental studies using satellites as collection devices yield results indexed by latitude and longitude. Thus it makes sense to assemble the terrestrial arrangement of people in a comparable manner. This alternative is explored here, using latitude/longitude quadrilaterals as bins for population information. This data format also has considerable advantage for analytical studies.

The report is in three parts. Part I gives the motivation and several possible applications. Ways of achieving the objective include, among others, simple centroid sorts or interpolation. In Part II the results to date are described. The estimated 1994 population of 217 countries, subdivided into 19,032 polygons, are being assigned to latitude/longitude cells. The estimated number of people in these countries is 5,617,519,139, spread over 132,306,314 square kilometers of land. Part III describes needed extensions.

By reporting population in units of one tenth of a degree for the entire earth we have data which is two orders of magnitude finer than has previously been available.

The project has been funded by the California Space Institute, the Consortium for International Earth Science Information Network, the Environmental Systems Research Institute, and the National Center for Geographic Information and Analysis. Project staff include Uwe Deichmann, Jon Gottsegen, Kelly Malloy, and Waldo Tobler.

John Townshend:

Under version 0 of EOS-DIS a Pathfinder Program is being carried out, one of the main objectives of which is to gain understanding of the challenges and issues associated with data from the Earth Observing System. Several of the lessons learnt relate both directly and indirectly to GIS capabilities. From Justice and Townshend (1994) the main lessons learnt with respect to the generation of global data sets from the Advanced Very High Resolution Radiometer were given as follows:

1. Collecting global data does not of itself create useful global data sets.
2. Defining the required characteristics of a global data set is a complex and often contentious issue.
3. Globally comprehensive long term, well calibrated and characterized reflectance or radiance values of the sensor are the most important properties of remotely sensed data sets for global change research.

4. The user community is unlikely to be satisfied by a single product (even of basic radiance or reflectance values).
5. The consequences of changing any one component of the data processing segment or sensor/platform property cannot be reliably predicted.
6. A well designed data and information system is essential for the effective use of global data sets, but there is no consensus as to the design and functionality of many of the components of such an information system.
7. In the absence of well designed data sets, users take on the burden of creating them at the expense of their central mission of data use.
8. The usefulness of global data sets is greatly inhibited by a lack of validation of the basic data sets and derived higher level products.
9. Users are poorly equipped to use global data sets.
10. Efforts to integrate data from multiple sensor systems must be expanded.

What are the implications for the development of GIS capabilities? Perhaps the most far-reaching relates to item 10 in this list. Although in principle we can integrate data sets, in practice this is rarely done because a) different users cannot agree on a single format (e.g., the land oceans and atmospheric AVHRR Pathfinders all use different projections), b) reprojecting data is computationally demanding, c) the consequences of reprojecting and resampling of data are often unknown, d) for the land there are often inadequate topographic data to allow reliable coregistration especially in rugged areas, e) knowledge of the spatial location of data is often poor.

These issues imply the need for much better ancillary data and also the need for better tools for handling global data sets. The former point is very relevant to I-15, since we could define tools whose value might be limited because of the absence of appropriate ancillary data.

Strong arguments can be put forward for eliminating or at the very least delaying the geometric transformation and resampling of data sets as long as possible in the processing chain: the whole concept of representing data from a sphere on a flat surface is of course somewhat ludicrous when dealing with global data sets except for visualization. Specifically little attention has apparently been given to consequences of representation of global data sets within GCMs where not only are the global data represented on a flat surface but a one degree grid is used placing proportionately less emphasis on tropical areas.

It is impossible to over-emphasize the challenges to be faced during the EOS era in handling global data sets because of their extremely large volumes. The global 1km data set being derived from the AVHRR is already posing major problems for many users because of its very large size, but in reality it is small compared with those to be created by EOS.

Among other issues requiring attention are the problems of sensibly linking data sets with very different time and space resolutions, the linking of in situ observations with remotely sensed data, and the creation of adequate metadata information systems. For example users currently face significant obstacles in simply finding out what high spatial resolution data are available from the US, Europe, Japan and India and other locations.

Reference

Justice, C.O. and J.R.G. Townshend (1994) Data sets for global remote sensing: lessons learnt. *International Journal of Remote Sensing* 15(17): 3621-3639.

Ray Watts:

Four areas of GIS application were identified in the meeting announcement:

- storing, manipulating, and preprocessing data for models;
- integrating data from disparate sources;
- monitoring global change at various scales; and
- presenting results in a decision-making environment.

The last of these is the most difficult when it comes to motivating researchers; it does not surprise me that it quietly disappeared in the Steering Committee's translation into the 5 objectives of the initiative. "Think globally, act locally" is more than a bumper-sticker slogan - it is the way the world really works. Decisions about land resources, which are the primary resources that sustain human wellbeing, are mostly made at the local level by individual land owners, soil and water conservation districts, ranger districts, etc. If the USGCRP does not deliver information at this level or if the information does not meet decision makers' needs, then the program's relevance can rightly be questioned.

Can GIS technology address this information-delivery problem? Is research and development needed in order to make delivery more effective? The answer to both questions is definitely "yes." I urge workshop participants and the Steering Committee to keep information delivery as a central part of Initiative 15.

The needs of local decision makers are often not sophisticated, but they transcend normal GIS functions. With the possible exception of individual land owners, the most significant need is to be able to use GIS capabilities effectively in a group setting. Brenda Faber (CIESIN) and I have developed PC, DOS-based software - the Active Response GIS, or ARGIS - that combines three functions: (1) an electronic meeting environment (Group Systems), (2) GIS (IDRISI), and (3) a relational database (Paradox). The system is implemented on a portable cluster of laptop PCs.

The Arapahoe-Roosevelt National Forest has used ARGIS in revision of its 10-year Forest Plan. The most critical and successful system capability is the linkage of GIS data to the database containing information on public comments that were received in response to the draft Forest Plan. Any change that Forest Service staff makes (using the system's GIS tools) in management boundaries is immediately and permanently linked to relevant public comments, and the staff's rationale for making the change is recorded during the decision session. One result of applying ARGIS is enhanced accountability of the agency in addressing public comments.

The system's GIS capabilities can be used in multiple modes. A favored mode is to project GIS coverages onto a whiteboard, where members of the group can mark change polygons with markers; these polygons are then digitized by the facilitator. It is also possible for individuals to digitize polygons on their own workstations and then for the facilitator to combine the results. The latter mode is useful for identifying areas of consensus and areas of controversy.

Technical improvement of ARGIS is underway in a collaborative effort among ESRI, IBM Federal Systems Company, Ventana Corporation, and TERRA Lab (an interagency laboratory for regional global-change research). The version under development will work in a PC Windows environment using Group Systems for Windows and ArcView II. Early testing is being done on implementation over Internet, which would eliminate the need for decision makers to be in the same place at the same time.

What does all this have to do with Global Change research? Not only making research results accessible to decision makers, but, we believe, also fostering interdisciplinary research. The view that each discipline has of a landscape is unique; analysis of vulnerability of land resources to changing environmental or socioeconomic conditions is equally unique, discipline by discipline. Decisionmakers need information that minimizes disparate views and emphasizes common views; that is why there is so much current emphasis on integrated assessments. GIS has much to offer, if suitably enhanced, in terms of using a common tool on shared data among members of multiple disciplines; the goal should be to avoid "my GIS vs your GIS." The potential result is a unified perspective of the effects of changing environmental conditions at local, landscape, and regional scales. And that is what the program is intended to deliver.

Cort J. Willmott:

Climatic variability and change and their impacts can be assessed adequately only when the climate system and its variability are more fully understood. Atmospheric scientists have concerned themselves primarily with the atmospheric component of the climate system; that is, with atmospheric dynamics, physics and chemistry. Global climate models (GCMs) reflect this emphasis, although GCM representations of clouds and precipitation remain problematic. Land-surface (geographic), oceanic and cryospheric processes - and their roles in the climate system - are considerably less well represented within GCMs than atmospheric processes. Relatively little also is known about the interrelationships (including feedbacks) among climate change, environmental degradation, and the restructuring of human activities in response. Representations of climate, climate variability and change additionally exist within weather-station and satellite observations that have been made for decades. Future Geographic Information Systems (GIS) should be able to reliably and efficiently evaluate and compare all such sources of climatic information. Of even greater importance, future GIS should be able to simulate geographic dynamics (like GCMs simulate atmospheric dynamics) in order that they can be used for process-oriented investigations and for prognostication.

Several advances will be needed within future GIS if they are to make significant contributions to Global Change research, especially in the climate area. Seamless GIS analyses and comparisons of GCM-produced climate fields, satellite-observed fields and in-situ observations, in particular, will be required to assess global-change scenarios and prognostications. Geography (the terrestrial mosaic) and geographic dynamics also must be meaningfully coupled to climate, and climate variability and change. Several special challenges posed by climate and land- surface data and processes should be addressed.

1. All geo-spatial data should be encoded in spherical coordinates or coordinates that can be translated to spherical coordinates without loss of accuracy. All GIS analyses, in turn, should become intrinsically spherical. Translations of spherically referenced data to a plane and subsequent analyses in planar space virtually always introduce bias. Furthermore, it is often impossible to remove the bias once it is introduced.

2. New methods of evaluating the efficacy of geographic samples and sampling designs are needed. This is important because the extent to which a sample represents the full behavior of a variable is tantamount to the potential inference that can be made about that variable's behavior (cf., Willmott et al., 1994), even by the best analyses. Current statistical approaches underrepresent climatic/geographic theory; therefore, there is a need to rebuild many GIS methods to make full use of climatic/geographic theory. More common problems (such as sample-domain and domain-boundary dependence, as well as spatial discontinuities within the sampling domain) also need to be addressed. Here too, new approaches should be spherically georeferenced.

3. Models of spatial and temporal estimation within GIS increasingly need to embody geographic/climatological theory in addition to spatial statistics. We should increase the extent to which theory, rather than statistics, relates observations to one another within GIS. Interpolation algorithms, for instance, can be significantly improved when simple climatic theory informs the interpolator. Using anaverage environmental lapse rate and a DEM, for example, Willmott and Matsuura (1995) were able to cut air temperature interpolation errors from weather-station data nearly in half.

4. Methods of estimating spatial-estimation errors (e.g., associated with interpolation models) need to be significantly improved. We should be able to map error estimates and their likely reliability, as well as obtain estimates of the spatially and temporally integrated errors. Assessments should be

based on performance measures, rather than on the more commonly used fit statistics. Nonparametric assessments of confidence, as well as implicit and explicit methods of spatial cross validation, are promising. Visualization of performance (e.g., of error fields) also should be improved.

6. Future GIS increasingly should be viewed, evaluated and used as a prognostic tool. The extent to which future GIS embody theory about geographic dynamics will be proportional to their ability to contribute to global change research. Within a GIS context, we should be able to simulate geographic dynamics that we believe (theorize) may have shaped the modern world or will shape our future world. The geographical dynamics that guide land-surface change, for example, are fundamental to our understanding of how our world is likely to change over the twenty-first century. Future GIS additionally need to incorporate processes and models that may not be dominated by assumptions of strong and stable system equilibria. Invoking dynamic geographic models embedded within future GIS, for example, we should be able to examine the geographic and climatic implications of feedbacks (nonlinear or otherwise) or chaos among climate, ecosystem, and landscape dynamics. Research into nonlinear and complex systems, in general, represents an important direction for geographical and GIS research.

References

Willmott, C.J. and K. Matsuura (1995) Smart interpolation of average air temperature in the United States. *Journal of Applied Meteorology,* submitted in December 1994.

Willmott, C.J., S.M. Robeson, and J.J. Feddema (1994) Estimating continental and terrestrial precipitation averages from rain-gauge networks. *International Journal of Climatology* 14: 403-414.

Harumi Yanagimachi:

As one contribution for the initiative, Multiple Roles for GIS in US Global Change Research, I intend to introduce the commonly mentioned image of GIS in the field of climatological research especially in Japan.

1. *There is a gap between GIS potential and GIS user's needs.* When the time cross sections of climate are mainly discussed, GIS is especially effective in this type of discussion. In the case of discussion on the climatic change or variability, not only GIS but also statistical analysis systems are often applied to the time series data. Combinations of these means are not necessarily simple. Some researchers prefer programming by themselves to application of GIS.

So far as mapping is concerned, GIS now in practical use is excellent, and it really has lots of functions. However, it is not necessarily useful at peculiar needs. Though mapping is very important method especially for the climatological research, some series of calculations precede visualization, and complicated values are calculated frequently. Climatic secular change researches require the data that cover the long period. However, observation points usually change their location. The station which shifted slightly in its latitude, longitude or altitude is considered to be different or same point according to the purpose of research. Even if the shift of station is negligible, sometimes special procedures will be needed. We must also decide whether such a station should be included in the analysis by specific rule, or not.

Topography has affected the distribution of climatic elements. Accordingly, topographical characters should be taken into consideration, when interpolating of climatic element is processed. Topography is one of the major factors governing snow depth and precipitation. In this respect, altitude is also regarded as important.

GIS is utilized in so many fields. Needs are multiple. GIS activities should include more and more optional functions.

2. *On-line data availability should be enhanced.* Most of the World Wide Web and Gopher servers which include weather data provide the visualized maps of satellite imagery and weather forecasts. Such an information is very interesting for quick look. Moreover these are shown immediately. However, most of them are the objects of hobby or amusement. Useful and efficient data are sold as tapes or CD-ROMs. It takes some time to get data by off-line. If we need any atmospheric and climate data of Japan, we can obtain them from Japan Meteorological Agency as magnetic tapes. We can use tapes freely, but usually tapes must be copied by users themselves.

It is much desirable for us to get useful data via Internet to avoid the long delay before we can use data. To realize this, there are some difficulties now. To get big data through network, it might have sometimes troubles, and networks themselves might have to bear heavy loads.

3. *Adequate data formats decrease wasteful time.* After we obtain data, we have to recompile or edit them to adequate format which analytical software including GIS handles with. Preparations of data for research take much time. Many researchers deal with the same data and perform the same procedure. There are some GIS data formats. Data are frequently converted from one format to another. There might be the struggle for existence among GIS. Shortening of the preparation time is very urgent from both points of view of using GIS and supplying or sharing data.

4. *GIS for PC accelerates application of GIS.* When massive atmospheric and climate data in global scale are analyzed, research of these fields requires much computer power, such as main memory and data storage. Global scale climatic change analyses have been performed using mainframe computers or super computers, but these are changing to be calculated with workstations. We sometimes feel human resources that can administrate workstations are short-handed. However, most of PC's software is very useful and technically easy to deal with. PC's GIS is simpler and cheaper than in workstation's. Even visualization software for PC also has many

functions. Because personal GIS users feel much merit in PC, development of GIS for PC will increase GIS usage.