Chapter Twenty One

Multiple Roles for GIS in Global Change Research

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21.1 BACKGROUND

The past ten years have seen a dramatic increase in support for research into the physical Earth system, and the effects of human-induced change, particularly in climate. Such research places heavy demands on geographic data, and on systems to handle those data, in order to calibrate, initialise, and verify models of the Earth system, and also to investigate the relationships that exist between various aspects of the physical system, and the human populations that both cause change and experience its effects.

It is widely believed that GIS and related technologies (remote sensing, GPS, image processing, high bandwidth communications) will play an increasingly important role in global change research (Goodchild *et al.*, 1993; Mounsey, 1988; Townshend, 1991). In particular, GIS is seen as a vehicle for collecting, manipulating, and pre-processing data for models; for integrating data from disparate sources with potentially different data models, spatial and temporal resolutions, and definitions; for monitoring global change at a range of scales; and for visual presentation of the results of modelling in a policy-supportive, decision-making environment. This chapter explores these potential multiple roles of GIS, in global change research and more broadly in environmental modelling and analysis. The emphasis throughout the chapter is on the role GIS can play in the science of global change research; in addition, but downplayed in the chapter, are its more general roles in creating and managing data in global databases such as the UN Environment Program's GRID. The discussion is based in part on the results of two specialist meetings conducted by the National Center for Geographic Information and Analysis (NCGIA) under its Research Initiative 15 (for the full meeting reports see Goodchild *et al.*, 1995, 1996).

21.2 INTRODUCTION

During the last decade there has been increased awareness of the potential for major changes in climate, deterioration of the stratospheric ozone layer, and decreasing biodiversity. At the same time, new political and economic transformations and structures are emerging. These phenomena are described as "global change" (Botkin, 1989; Committee on the Human Dimensions of Global Change, 1992; Price, 1989; Turner *et al.*, 1990) and can be classified as being of two basic types (Botkin, 1989; Turner *et al.*, 1990). In one sense the term applies where actions are global in extent or systemic, that is, at a spatial scale where perturbations in the system have consequences everywhere else, or reverberate throughout the system. Thus, for example, there is concern over "greenhouse" gases and other climate forcing agents that are manifested globally. The second meaning applies where there is cumulative global change. The loss of biological diversity at so many locations throughout the world is global in scale because its effects are world-wide, even though the causes are localised.

The international global change research program (IGBP, 1990; NRC, 1990) has grown out of the need for scientific assessments of both types of global change, and is ultimately intended to aid in policy decisions. Emphasis has focused largely on interactions between the Earth's biosphere, oceans, ice, and atmosphere. The research strategies that help to provide this scientific foundation were developed in the mid-1980s (ESSC, 1986, 1988; ICSU, 1986; NRC, 1986), and feature an advanced systems approach to scientific research based on: (1) data observation, collection, and documentation; (2) focused studies to understand the underlying processes; and (3) the development of quantitative Earth system models for diagnostic and prognostic analyses. Concepts such as Earth system science (ESSC, 1986), global geosphere-biosphere modelling (IGBP, 1990), and integrated and coupled systems modelling at multiple scales (NRC, 1990) have emerged, focusing broadly on the Earth system, but including subsystems such as atmosphere-ocean coupling. The US Global Change Research Program is one example of a national-level effort to implement this strategy (CES, 1989, 1990; CEES, 1991). GIS could play an important role in this research in two ways: (1) enhancement of models of Earth system phenomena operating at a variety of spatial and temporal scales across local, regional, and global landscapes, and (2) improvements in the capacity to assess the effects of global change on biophysical (ecological) systems on a range of spatial and temporal scales.

In addition to the biogeochemical process that drive the Earth system, changes in human land use, energy use, industrial processes, social values, and economic conditions are also increasingly being recognised as major forces in global change (Committee on the Human Dimensions of Global Change, 1992). The relationship of these activities and behaviours to global change is critical because they may systemically affect the physical systems that sustain the geosphere-biosphere. Thus additional research strategies that emphasise the human dimension in global change have recently emerged. The National Research Council's (NRC) Committee on Global Change (Committee on the Human Dimensions of Global Change, 1992) has emphasised that the development of a coherent and systematic assessment and understanding of global change phenomena requires better linkage between the environmental and human dimensions (social and economic). At present, several problems pose formidable challenges in addressing the human dimensions of global change, three of which are central to this initiative.

First, there are difficulties in collecting requisite socio-economic and demographic data. Those data that do exist often span a range of temporal and spatial scales, lack appropriate intercalibration, have incomplete coverages, are inadequately checked for error, and have unsuitable archiving and retrieval formats (Committee on the Human Dimensions of Global Change, 1992). Second, there remain serious problems in translating human activities and information across a range of scales (local, regional, national, or global). Human activities that drive and mitigate global change vary significantly by region or place (Feitelson, 1991; Turner *et al.*, 1990) but as in ecology, methods for explicit translation across disparate scales or levels of organisation are lacking. Feitelson (1991) noted that geographers have only recently begun to consider how activities at one geographic scale affect activities at other spatial scales, and proposed a conceptual framework for analysing how geographic scale affects environmental problem solving. For conceptually similar problems, ecologists have invoked hierarchy theory as a way of understanding complex, multi-scaled systems (Allen and Starr, 1982). Last, there is a dearth of ways of understanding the interactions of socio-economic systems and global change other than through logical analysis, which often requires a level of abstraction that makes their understanding obscure (Cole and Batty, 1992). Geographic visualisation could be used to gain insight into both data and models, though such visual "thinking" has been little explored.

Four broad themes emerge from this discussion to characterise the potential for GIS use in global change research. These are discussed below.

21.2.1 Use of GIS to support integrative modelling and spatial analysis

Scientifically based mathematical models for computer analysis, that is, environmental simulation, are fundamental to the development of reliable, quantitative assessment tools. One major purpose of these computer-based models is to simulate spatially distributed, time-dependent environmental processes realistically. But environmental simulation models are, at best, simplifications and inexact representations of real world environmental processes. The models are limited because basic physical processes are not well understood, and because complex feedback mechanisms and other interrelationships are not known. The sheer complexity of environmental processes (three-dimensional, dynamic, non-linear behaviour, with stochastic components, involving feedback loops across multiple time and space scales) necessarily leads to simplifying assumptions and approximations (e.g. Hall *et al.*, 1988).

Frequently, further simplification is needed to permit numerical simulations on digital computers. For example, the conversion of mathematical equations for numerical processing on a grid (discretisation) can lead to the parameterisation of small-scale complex processes that cannot be explicitly represented in the model because they operate at subgrid scales. There may be significant qualitative understanding of a particular process, but quantitative understanding may be limited. The ability to express the physical process as a set of detailed mathematical equations may not exist, or the equations may be too complicated to solve without simplifications.

In addition to incomplete knowledge, simplifications, and parameterisations of real world processes, other general themes emerge from a review of state-of-the-art modelling, and from efforts to link models with GIS. One is cross-disciplinary modelling, which is illustrated by the concept of modelling water and energy exchange processes within the soil-plant-atmosphere system, or ecosystem dynamics modelling with, for example, the environmentally and physiologically structured Forest-BGC model (Running and Coughlan, 1988). These models cross such disciplines as atmospheric science, hydrology, soil science, and plant physiology.

21.2.2 GIS-linked models and conceptual frameworks for hierarchical and aggregated structures

The requirements of global change research place significant emphasis on modelling at multiple time scales and across multiple spatial scales. NRC (1990) outlines a strategy for coupling models across time scales to account for feedbacks in land-atmosphere interactions. For example, the land surface parameterisations for water and energy exchange between the biosphere and atmosphere must adapt to climate-induced changes in vegetation characteristics that exert major influence on such exchange processes. Feedbacks may be further complicated by the existence of thresholds, and by hysteresis effects. Hay *et al.* (1993) discuss the use of nesting to model interactions between spatial scales, while Nemani *et al.* (1993), Burke *et al.* (1991), and King (1991) are concerned with the extrapolation of research results from local study areas to regional analysis. Hall *et al.* (1988) illustrate some of the problems in linking vegetation, atmosphere, climate, and remote sensing across a range of spatial and temporal scales. Spatial scaling involves significant research issues, such as how to parameterise (i.e., aggregate or integrate) water and energy fluxes from the plant leaf level to the regional level. In addition to scale problems, the parameterisation process is confounded by structuring processes which operate at different hierarchical levels (e.g., physiological, autecological, competitive, landscape). Finally, the interactions between levels are asymmetric in that larger, slower levels maintain constraints within which faster levels operate (Allen and Starr, 1982).

Complex terrain and heterogeneous landscape environments form another major theme in the use of physically based models of spatially distributed processes (Running *et al.*, 1989). Distributed parameter approaches are increasingly used instead of classic lump sum analysis as models become more sophisticated, allowing them to incorporate more realistic, physically based parameterisations of a wide variety of land surface characteristics data (King, 1991; Running *et al.*, 1989). Factors such as terrain and landscape variability are important considerations for land-atmosphere interactions (Carleton *et al.*, 1994; Pielke and Avissar, 1990).

Finally, environmental simulation modelling depends on the results of field experiments such as the First ISLSCP (International Satellite Land Surface Classification Project) Field Experiment (FIFE) (Hall *et al.*, 1988), an intensive study of interactions between land surface vegetation and the atmosphere, and the Boreal Ecosystem-Atmosphere Study (BOREAS; NASA, 1991). Such experiments are integral to the development and testing of models based on direct measurements and remote sensing data from various ground-based, aircraft, and satellite systems. In addition, focused research to understand processes and to develop remote-sensing driven algorithms for regional extrapolations will be supplemented by a range of simulation models under BOREAS (NASA, 1991).

These themes of environmental systems modelling suggest opportunities for the integration of GIS. For example, detailed consideration of landscape properties and spatially distributed processes at the land surface is fundamental to global climate and mesoscale models, watershed and water resource assessment models, ecosystem dynamics models that are physiologically based, and various types of ecological models involving landscape, population, and community development processes. The themes of multiple space and time scales are basic to coupled systems modelling, a highly cross-disciplinary modelling approach exemplified by the suite of models for land-atmosphere interactions research.

In addition to the issue of spatial processes operating at multiple time and space scales, GIS and environmental simulation models share converging interests in geographic data. The availability of geographic data from many sources, including land cover characteristics based on multitemporal satellite data, is growing rapidly. GIS by definition is a technology designed to capture, store, manipulate, analyse, and visualise diverse sets of geographically referenced data. In fact, advanced simulation models require a rich variety of multidisciplinary surface characteristics data of many types in order to investigate environmental processes that are functions of complex terrain and heterogeneous landscapes.

To illustrate, land surface characteristics data required by scientific research include land cover, land use, ecoregions, topography, soils, and other properties of the land surface to help understand environmental processes and to develop environmental simulation models (Loveland et al., 1991). These advanced land surface process models also require data on many other types of land surface characteristics, such as albedo, slope, aspect, leaf area index, potential solar insulation, canopy resistance, surface roughness, soils information on rooting depth and water holding capacity, and the morphological and physiological characteristics of vegetation. GIS along with remote sensing has a role in dealing with these complex data issues.

GIS can help meet these requirements and provide the flexibility for the development, validation, testing, and evaluation of innovative data sets that have distinct temporal components. There is the need to create derivative data sets from existing ones and GIS tools are also needed for flexible scaling, parameterisation and re-classification, creating variable grid cell resolutions, or aggregation and integration of spatial data. At the same time, methods are needed to preserve information across a range of scales or to quantify the loss of information with changing scales. Thus, this overall modelling environment seems suited for GIS as a tool to support integrative modelling, to conduct interactive spatial analysis across multiple scales for understanding processes, and to derive complex land surface properties for model input based on innovative thematic mapping of primary land surface characteristics data sets. By implementing a full range of spatial data models, GIS offers the ability to integrate data across a range of disciplines despite wide variation in their ways of conceptualising spatial processes and of representing spatial variation.

21.2.3 More efficient integration of models and GIS

Despite the above mentioned potential, a number of impediments stand in the way of more complete integration of GIS and global environmental modelling. GIS are generic tools, designed for a range of applications that extend well beyond environmental modelling, into data management for utilities, local governments, land agencies, marketing, and emergency response (Maguire *et al.*, 1991). While GIS support a wide range of data models, many of the fundamental primitives needed to support environmental modelling are missing, or must be added by the user (Goodchild, 1991). At present, environmental simulations must be carried out by a separate package linked to the GIS, and the ability to write the environmental model directly in the command language of the GIS is still some distance away. Nyerges (1993) provides a comprehensive discussion of these technical integration issues.

21.2.4 Visualisation of spatial patterns and interactions in global data

Effective use of GIS requires attention to several generic issues, many of which are also of concern to environmental modelers. The discretisation of space that is inherent in both fields forces the user to approximate true geographical distributions, and the effects of such approximations on the results of modelling are often unknown, or unevaluated. Space can be discretised in numerous ways—finite differences and finite elements are two of the examples well known to environmental modelers—and each has its own set of impacts on the results. Effective display of the results of modelling, particularly for use in policy formulation, requires attention to principles of cartographic design. Finally, spatial databases tend to be large, and effective environmental modelling may require careful attention to the efficiency of algorithms and storage techniques. Many of these generic issues are identified in the NCGIA research agenda (NCGIA, 1989, 1992) and are the subject of active research within the GIS community.

As this review demonstrates, and as the title of this initiative indicates, we view GIS as a tool that can play many roles in global change research. There is a need to identify those roles more clearly, and also to identify impediments that prevent GIS being used more broadly. We need to address the generic needs of global change research for spatial data handling tools, whether or not those needs will be met five or ten years from now by a technology we recognise as "GIS".

21.3 IMPEDIMENTS TO PROGRESS

With these issues in mind, the following sections address the problems that stand in the way of a greater role for GIS in global change research, and the research that needs to be conducted to address them. They address five major themes:

- 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, sampling methodologies, and completeness of coverage, and develop improved methods for analysis and visualisation 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 for dynamically linking human and physical databases within a GIS and for exploring the regional impacts of global change.
- To develop methods for detecting, characterising, and modelling change in transition zones, thereby addressing the problems that result from overly simplistic representations of spatial variation.

These themes span to varying degrees the concerns of the many disciplines that together constitute the global change research community. For the purposes of this chapter, the wide range of topics addressed by global change research is 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.

The following sections address major problem areas within this context.

21.3.1 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", specialise 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 analyse 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" (Goodchild, 1992), emphasising 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":

1. GIS as geographic information system, a class of software characterised 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, we can 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 visualisation 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 and complex 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, we face 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 harmonise approaches to data modelling, defined as the entities and relationships used to create digital representations of real geographic phenomena. The current variation in data modelling 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 modelling.
- The role of visualisation 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 modelling of uncertainty and error in geographic data; the particular problems of sampling, modelling, and visualising 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 a discussion of the multiple roles of GIS in global change research, 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 full range of viewpoints being expressed both within and outside the GIS community, and the research that needs to be done to move GIS forward.

21.3.2 Global change research communities

"What is this GIS anyway?" may be the question uppermost in the minds of many global change researchers, but it is quickly supplanted when one realises that the multiple roles of GIS in global change research extend well beyond the immediate needs of scientists for computerised 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 computerised 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 the US 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.

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, three major communities should be considered in examining the roles of GIS in global change research: scientists, policy-makers, and the general public. Each creates its own set of priorities for GIS, and its own set of impediments.

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; http://globe.fsl.noaa.gov) is conceived along these lines as a network of schoolchildren 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 organisation 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.

21.3.3 Data issues

Several issues associated with data arise in using GIS in support of global change research. 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 cataloguing. 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.

Third, issues arise over 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 are also useful for commercial and administrative purposes, and in many cases these tend to dictate access policies.

Fourth, there are 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. An important role in this arena is being played by the Open Geodata Interoperability Specification initiative (http://www.ogis.org).

21.3.4 Data models and process models

The term "model" is used in two very different contexts in environmental modelling. A process model is a representation of a real physical or social process whose action through time results in the transformation of the human or physical landscape. For example, processes of erosion by wind and flood modify the physical landscape; processes of migration modify the human landscape. A process model operates dynamically on individual geographic entities. Here we should distinguish between process models that define the dynamics of continuous fields, such as the Navier-Stokes equation, and must be rewritten in approximate, numerical form to operate on discrete entities; and models such as Newton's law of gravitation or individual-based models in ecology that operate directly on discrete entities.

A data model, on the other hand, is a representation of real geographic variation in the form of discrete entities, their attributes, and the relationships between them. Many distinct data models are implemented in GIS, ranging from the arrays of regularly spaced sample points of a digital elevation model (DEM) to the triangular mesh of the triangulated irregular network (TIN) model.

Under these definitions, there is clearly a complex and important relationship between data modelling and process modelling. In principle, the entities of a process model are defined by the need to achieve an accurate modelling of the process. In practice, the entities of a data model are often the outcome of much more complex issues of cost, accuracy, convenience, the need to serve multiple uses that are frequently unknown, and the availability of measuring instruments. An atmospheric process model, for example, might require a raster

representation of the atmospheric pressure field; the only available data will likely be a series of measurements at a sparse set of irregularly located weather stations. In such cases it is likely the data will be converted to the required model by a method of intelligent guesswork known as spatial interpolation, but the result will clearly not have the accuracy that might be expected by a user who was not aware of the data's history.

Such data model conflicts underlie much of the science of global change research, and yet their effects are very difficult to measure. The availability of data is often a factor in the design of process models, particularly in areas where the models are at best approximations, and distant from well-understood areas of physical or social theory. We rarely have a complete understanding of the loss of accuracy in modelling that results from use of data at the wrong level of geographic detail, or data that has been extensively resampled or transformed. Clearly the worlds of data modelling and process modelling are not separate, and yet practical reality often forces us to treat them as if they were.

21.3.5 Levels of specificity

Another key issue in data modelling can be summed up in the word specificity. While there may be agreement that data modelling requires the definition of entities and relationships, there is much greater variation in the degree to which those entities and relationships must be specified, and the constraints that affect specification.

One set of constraints is provided by the various models used by database management systems. The hierarchical model, for example, requires that all classes of entities be allocated to levels in a hierarchy; and that relationships exist only between entities at one level and those at the level immediately above or below. If these constraints are acceptable, then a database can be implemented using one or another of the hierarchical database management systems that are readily available. While the model seems most applicable to administrative systems, and has now been largely replaced by less constrained models, it has been found useful for geographic data when the collection of simple entities into more complex aggregates is important — for example, in the ability to model an airport at one scale as a point, and at a finer scale as a collection of runway, hangars, terminal, etc.

The most popular model for geographic data is the relational, and its implementation for geographic data is often termed georelational. Relationships are allowed between entities of the same class, or between entities in different classes, and this is often used to model the simple topological relationships of connectedness and adjacency that are important to the analysis of geographic data. But even georelational models impose constraints that may be awkward in geographic data modelling.

For many Earth system scientists, the important modelling frameworks are the ones implemented in the various statistical and mathematical packages, which are much more supportive of complex process modelling than GIS and database management systems. Matlab and S-Plus, for example, have their own recognised classes of entities and relationships, and impose their own constraints. Thus to an Earth system scientist, the task of data modelling may consist of a matching of entities and relationships to those classes supported by a common modelling package; whereas a GIS specialist may be more concerned with matching to the constraints of the georelational model. The entity types supported by a modelling or statistical package will likely include simple tables of data, and arrays of raster cells, but not the full range of geographic data types implemented in the more advanced GIS, with their support for such geographic functions as projection change and resampling, and with implementations of data model concepts like planar enforcement and dynamic segmentation. Choices and constraints may also be driven by the nature of data — a field whose primary data comes mostly from remote sensing will naturally tend to think in terms of rasters of cells, rather than vector data, and to the attributes of a cell as averages over the cell's area rather than samples at the cell's centre.

The georelational model imposes one level of constraints on data modelling. Further constraints are imposed by the practice of giving certain application-specific interpretations to certain elements of data models. For example, many GIS implement the relational model in specific ways, recognising polygons, points, or nodes as special types within the broad constraints of the relational model.

This issue of specificity, or the imposition of constraints on data modelling, contributes substantially to the difficulty of integrating data across domains. For example, the data modelling constraints faced by an oceanographer using Matlab are very different from those of a GIS specialist using ARC/INFO. One might usefully try to identify the union of the two sets, or their intersection, in a directed effort at rationalisation.

21.3.6 Generalisations of GIS data models

It is widely accepted that GIS data models have been developed to support an industry whose primary metaphor is the map — that is, that GIS databases are perceived as containers of maps, and that the task of data modelling is in effect one of finding ways of representing the contents of maps in digital form. Maps have certain characteristics, and these have been largely inherited by GIS. Thus maps are static, so GIS databases have few mechanisms for representing temporal change; they are flat, so GIS databases support a wide range of map projections in order to allow the curved surface of the Earth to be represented as if it were flat; they are two-dimensional, so there are few GIS capabilities for volumetric modelling; they are precise, so GIS databases rarely attempt to capture the inherent uncertainty associated with maps, but almost never shown on them; and they present what appears to be a uniform level of knowledge about the mapped area.

There are many possible extensions to this basic GIS data model, with varying degrees of relevance to global change research. The five points made above lead directly to five generalisations:

- temporal GIS, to support spatio-temporal data and dynamic modelling (Langran, 1992);
- spherical GIS, avoiding the use of map projections by storing all data in spherical (or spheroidal) coordinates; computing distances and areas and carrying out all analysis procedures on the sphere; and using the projection for display (Goodchild and Yang, 1992; Raskin, 1994; White *et al.*, 1992);
- 3D GIS, to support modelling in all three spatial dimensions (Turner, 1992);
- support for modelling the fuzziness and uncertainty present in data; propagating it through GIS operations; and computing confidence limits on all GIS results (Heuvelink and Burrough, 1993);
- methods of analysis that allow for variable quality of data.

The spherical data models are clearly of relevance to global change research, but their benefits need to be assessed against the costs of converting from more familiar representations such as the latitude/longitude grid. Methods of spatial interpolation, which are widely used in global change research to resample data and to create approximations to continuous fields from point samples, are particularly sensitive to the problems that arise in using simple latitude/longitude grids in polar regions and across the International Date Line. On the other hand, the benefits of consistent global schemes may be outweighed by the costs of converting from less ideal but more familiar schemes.

21.3.7 The data modelling continuum

The literature contains several discussions of the various stages that lie between reality and a digital database: from reality to its measurement in the form of a spatial data model, to the additional constraints imposed by a digital data model, to a data structure, to the database itself. For example, the sharp change in temperature that occurs along a boundary between two bodies of water might be first modelled as a curved line (perhaps by being drawn as such on a map); the curved line would then be represented in digital form as a polyline, or a set of straight-line connections between points; the polyline would be represented in a GIS database as an arc; and the arc would be represented as a collection of bits. Modelling and approximation occurs at each of these four stages except perhaps the last. The polyline, for example, may be no better than a crude approximation to the continuous curve, which is itself only an approximation to what is actually a zone of temperature change. It is important to recognise that approximation and data modelling occur even before the use of digital technology.

21.3.8 The data life cycle

Related to the previous concept of a data modelling continuum is the data life cycle, which is conceived as the series of transformations that occur to data as it passes from field measurement to eventual storage in an archive. In a typical instance, this life cycle may include measurement, interpretation, collation, resampling, digitising, projection change, format change, analysis, use in process modelling, visualisation, exchange with other researchers, repetition of various stages, and archiving. The data model may change many times, with consequent change in accuracy. Moreover, data quality is more than simply accuracy, since it must include the interpretation placed on the data by the user. If data pass from one user to another, that interpretation can change without any parallel change in the data, for example if documentation is lost or misinterpreted. In this sense, data quality can be defined as a measure of the difference between the contents of the data, and the real phenomena that the data are understood to represent — and can rise and fall many times during the life cycle, particularly in applications that involve many actors in many different fields. It is very easy, for example, for data collected by a soil scientist, processed by a cartographer, analysed by a geographer, and used for modelling by an atmospheric scientist, to be understood by the various players in very different ways.

21.3.9 Information management

Recent advances in digital communication technology, as represented by the Internet, and applications such as the World Wide Web (WWW), have created a situation in which there is clearly an abundance of digital data available for global change research, but few tools exist to discover suitable information or assess its fitness for use. Much effort is now going into development of better tools for information management, in the form of digital libraries, search engines, standards for data description, and standards for data exchange.

Several recent developments in geographic information management are of relevance to global change research and GIS. While the Federal Geographic Data Committee's Content Standard for Geospatial Metadata (http://www.fgdc.gov/Metadata/metahome.html) has attracted much attention since its publication in 1994, the effort required to document a data set using it is very high, particularly for owners of data who may have little familiarity with GIS or cartography. If the purpose of metadata is to support information discovery, search, browse, and determination of fitness for use, then much less elaborate standards may be adequate, at least to establish that a given data set is potentially valuable. At that point the potential user may want to access a full FGDC record, but if the owner of the data has not been willing to make the effort to document the data fully, other mechanisms such as a phone or e-mail conversation may be just as useful, and more attractive to the owner. Scientists appear reluctant to document data without a clear anticipation that it will be used by others. However, it may be that funding agencies will begin to require documentation as a condition for successful termination of a project. Otherwise, documentation to standards like FGDC may have the character of an unfunded burden.

An owner of data may be willing to provide an initial contribution of metadata to a data catalogue. But if the data are later modified, or deleted, are there suitable mechanisms for ensuring that the catalogue reflects this? Users of the WWW are acutely aware of the problems caused by "broken" URLs (Universal Resource Locators) and similar issues. Although it might be possible to provide facilities for checking automatically whether a data set has been modified, owners may not be willing to accept this level of intrusion.

Another issue associated with distributed information management that is already affecting the global change research community concerns the use of bandwidth. The communication rates of the Internet are limited, and easily made inadequate by fairly small geographic data sets. Research is needed to develop and implement methods that reflect more intelligent use of bandwidth, including progressive transmission (sending first a coarse version of the data, followed by increasingly detailed versions) and the use of special coarse versions for browse. While methods already exist for certain types of raster images, there is a need to extend them to cover all types of geographic data.

A final information management issue of major importance to global change research is interoperability. Today, transfer of data from one system to another frequently requires that the user invoke some procedure for format conversion. While such procedures may not be complex, they present a considerable impediment to data sharing and the research it supports. In principle, the need for conversion should not involve the user, any more than it does in the automatic conversion of formats that is now widely implemented in word processors — the user of Microsoft Word, for example, will probably not need to know the format of a document received from someone else, although conversion still needs to occur. Achievement of interoperability between the software packages used to support global change research should be a major research objective.

Reasonable goals for interoperability research might include the following:

- interoperability between representations of imagery tied to the Earth's surface — this might include recognition of a common description language that can be read automatically, and used to perform necessary operations such as resampling to a common projection; interoperability between band-sequential and band-interleaved data; interoperability between different representations of spectral response, including different integer word lengths;
- interoperability between data sets based on irregularly spaced point samples, allowing automatic interpolation to a raster, or resampling to another set of sample points;
- interoperability between any data model representations of continuous fields over the Earth's surface.

21.4 CONCLUSION

Several themes from this discussion are of sufficient generality to warrant revisiting in this concluding section. Data models lie at the heart of GIS, because they determine the ways in which real geographic phenomena can be represented in digital form, and limit the processing and modelling that can be applied to them. GIS has inherited its data models from an array of sources, through processes of legacy, metaphor, and commercial interest, and there is a pressing need for greater recognition of the role of data models, better terminology, and a more comprehensive perspective.

A second strong theme is 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.

The discussion 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; too many methods of spatial analysis are limited to a plane, and are not readily adapted to the globe. A survey of existing techniques for spatial analysis on the sphere has been published as an NCGIA technical report (Raskin, 1994). In August 1995 NCGIA began a 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. The current status of the work can be reviewed at http://www.geog.ucsb.edu/~raskin.

With funding from ESRI (Environmental Systems Research Institute) and CIESIN (Consortium for International Earth Science Information Network), NCGIA 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 was 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. The work is documented in an NCGIA Technical Report (Tobler *et al.*, 1995).

Another general issue is 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 (World Meteorological Organisation). Other debates are occurring in the context of the Internet, and its implications for intellectual property rights and the international market for data. Efforts such as the US Department of State-led Earthmap (http://www.gnet.org/earthmap), the Japanese Millionth Map, and the international community's Core Data are attempting 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 *et al.*, 1995). Other efforts, such as the Alexandria Digital Library (ADL) project (http://alexandria.ucsb.edu) are seeking general solutions to the problems of finding geographic data on the Internet.

While much of the discussion of this chapter has been motivated by the specific context of global change research, similar concerns arise in considering the potential roles of GIS in any area of science. Global change research is particularly complex, involving many disciplines, and of great public interest, so there are good reasons for suggesting that it might form a useful model for the scientific uses of GIS generally.

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