The "Grayware" Required to Deal with Global Change Issues

Abstract

It has become increasingly apparent that improving our understanding of the functioning of the Earth as a closely coupled and interactive system is a prerequisite to knowledgeable management of the planet's resources and to the preservation and enhancement of the global environment. Developing this understanding is indeed a tremendous scientific and institutional challenge. A primary objective of this paper is to underscore the need for the Nation's higher educational system to better prepare our future citizens, decisionmakers, and scientists to deal with global change issues.

A second major theme of this discussion is the role the mapping sciences can play in both detecting the signals and in helping to predict the impacts of global change. Specific examples of ongoing research are used to illustrate this point. Satellite observation of lake ice is being tested as a potential means for detecting regional climatic change, and coupling of ecosystem process models with GIS techniques is being used to predict the response of lakes located in northeastern Wisconsin to alternative climate change scenarios.

Background

It was with great pleasure that I participated last August in the ASPRS/ACSM/RT 92 Convention Plenary Session titled "Rising to the Challenge of Global Change: the Role of the Mapping Sciences." Among the nine speakers participating in the three plenary sessions conducted during the week, I was the only academician. Accordingly, my presentation (on which this paper is based) took a somewhat different view of the challenges faced by the mapping sciences in responding to the challenges of global change. This was a view not of global changes *per se*, nor of the hardware, software, or data required to understand global change problems. Rather, my focus was on the "grayware" requirements associated with global change. By "grayware" I mean both the intellectual perspectives and the academic infrastructure required to understand and rationally respond to global change problems. In this regard, I wish to make the following points in this paper:

- As traditionally configured, higher education in the United States is ill-equipped to provide the "environmental literacy," interdisciplinarity, and macroscopic perspective attendant to scholarly understanding of global change issues. Many parts of academia are in the process of determining how they can better respond to these issues.
- The mapping science community is currently faced simultaneously with tremendous challenge, opportunity, and obligation in advancing the understanding of global change. On the one hand, I am confident we have the tools to help ferret out the *signals* of global change in the interest of science. On the other, I believe we also have the tools to help predict the *impacts* of global change in the interest of rational policy development.
- Though we mapping scientists might currently be providing synoptic data about relatively large geographic areas, global change studies typically require yet a further expansion of both the spatial and temporal horizons within which most of us traditionally undertake our work.

Before amplifying upon each of the above topics, I wish to point out that I am *not* of the doom and gloom persuasion relative to global change. We must recognize that the supply of questions in this arena far exceeds that of answers. My colleague, Reid Bryson (who has been at the game of earth system science long before it has been referred to as such), has aptly pointed out that the *institutional structure of science often creates false impressions of how the Earth system actually works* (Bryson, 1992). We need be careful to avoid what Bryson refers to as "consensus science." When we are confronted with a problem of the magnitude of global warming and the seriousness of policy decisions required to respond to it, the public has a right to be assured that decisionmaking is founded on good science, not simply good fellowship. The mere fact that there is a preponderance of scientific *opinion* on a given issue does not minimize the requirement for convincing evidence. When the press reports that "the majority of scientists" believe that global warming results from the increase in carbon dioxide in the atmosphere, and only a minority disagree, in and of itself this does not confirm the validity of the global warming hypothesis. Consensus alone does not determine scientific validity; the *evidence* must. It is the objective accumulation of such evidence that the mapping sciences are all about in my estimation.[1]

The Academic Report Card

Having highlighted the need for "pure" science in addressing global change questions, let me also say that the days of denying the existence of global environmental problems should be long behind us. Other authors, including those contributing to this journal, have summarized the litany of pressing environmental problems currently faced by our global society. I make no attempt to reiterate them here. Rather, I wish to simply point out that the current reality dictates the need for pervasive environmental consciousness throughout the world and for effective ways to deal with problems that cannot be solved from the vantage point of a single discipline. How well are U.S. universities meeting these needs for each and every student? My contention is that there is substantial

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[1] One of the anonymous reviewers of the initially submitted version of this paper appropriately pointed out that in the social science research paradigm there is often no "objective accumulation" determining the direction of research. Instead, "socially determined accumulation" is the norm. These contrasting paradigms often impede interdisciplinary work between natural and social scientists.

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room for improvement in the basic environmental literacy our higher education system conveys, in the opportunities for interdisciplinary instruction and research it provides, and in the macroscopic perspective it nurtures in future scientists and decisionmakers.

Environmental Literacy

It is not uncommon these days for colleges and universities to have rather rigorous entrance or graduation requirements in mathematics, natural sciences, social sciences, humanities, English, foreign language, the arts, and ethnic studies. Though most schools require such a broad base of subjects, few ever show students how these subjects interrelate. Instead, it is generally assumed that the student will somehow do this integration in his/her own mind.

One of many potential outcomes from the above situation is the lack of understanding about the connectedness of our world and the value and need for environmental stewardship. Most colleges and universities do not require a science-based grounding in study of the environment, irrespective of a student's major field of study. (Note that I am not referring to courses that tend toward *advocacy* but, rather, scientific *synthesis*.)

Ironically, on many college and university campuses, environmental concepts tend to be everywhere and nowhere at the same time. As highlighted by Brough (1992), "Because environmental studies do not fit the mold of a conventional academic discipline, it is questioned—and sometimes dismissed—by the professional educational establishment... . Half a millennium of intellectual history dictates that a respectable academic discipline is one that splinters knowledge into smaller pieces. Environmental studies, in contrast, try to link the knowledge of many disciplines to help students grapple with increasingly complex problems. Universities have not embraced this approach."

David Orr (1990) has argued that no student should graduate from any educational institution without a basic comprehension of

- the laws of thermodynamics
- the basic principles of ecology
- carrying capacity
- energetics
- least-cost, end-use analysis
- how to live well in a place
- limits of technology
- appropriate scale
- sustainable agriculture and forestry
- steady-state economics
- environmental ethics

Brough states that U.S. colleges and universities graduate more than one million students each year. She further points out, and I believe most would concur, that, if our colleges and universities were to produce one million environmentally literate citizens each year, their professional decisions and personal actions could make a critical difference to the understanding and health of the planet. As it is, most of our young people—our future leaders—have little more then superficial knowledge about the earth as a system.

Interdisciplinarity

Most colleges and universities still approach earth science as if the world were a collection of separate systems. Teaching and research programs are typically organized along traditional disciplinary lines—such as atmospheric chemistry, botany, ecology, geology, geophysics, meteorology, oceanography, zoology—usually with only a modest degree of program interaction and/or conceptual integration. There is also usually very little linkage between the natural and social sciences.

While it is possible for university faculty members to cross the lines among disciplines, most university systems are not organized to encourage such behavior. In fact, there are many inherent disincentives for undertaking interdisciplinary teaching and research in most settings. First, interdisciplinary teaching and research normally take longer to organize because individuals from different disciplines must spend time learning to work together, defining common terms, and developing new concepts. Putting a group of specialists from four or five departments together is not inherently difficult. Developing new forms of collective thinking about environmental and resource problems is the issue. This takes time. For younger faculty members seeking publication and tenure, these "slow starts" in teaching and research can impede the progress of their academic careers. At the same time, interdisciplinary courses and publications are often perceived as being at the margin or fringe of what is expected by one's home department.

Indeed, the problem of forming an interdisciplinary team in a university often boils down to the following. It is difficult for a faculty member to satisfy both the demands of a traditional department and of an interdisciplinary team because these two organizations have fundamentally dissimilar goals and objectives. If one affiliates solely with an interdisciplinary team, reduced competency in one's original discipline can result. This dilemma is exacerbated by such decisions as how interdepartmental teaching and research are administered, how teaching effort is measured, how overhead is divided among units, how space is allocated, how "credit" for advising graduate students outside of one's home department is given, and how one's salary and promotion potential are affected by interdisciplinary effort in comparison to strictly departmental activity. The importance of such factors is particularly great in a time of shrinking university budgets.

The need for increased emphasis on interdisciplinary approaches to research was recently highlighted in a survey conducted by Sigma Xi. Sigma Xi is a scientific research society that has been in existence since 1886 and has over 100,000 members in North America. Entitling its initiative "A New Agenda for Science," this society undertook a survey of scientists in a variety of research settings to determine their impressions of the need for cross-disciplinary methods in modern research. Respondents to the survey identified "lack of interdisciplinary training" as one of the three most important issues facing the scientific community today. Likewise, almost three-fourths of the over 4000 survey respondents felt that government funded research is too "discipline specific" (Sigma Xi, 1988).

The point is, at least traditionally, that universities have had difficultly putting together and rewarding the types of interdisciplinary teams needed to pursue such inherently interdisciplinary topics as global change or Earth system science. The good news is that many institutions are attempting to do just that. For example, formal centers for global change have been established, or are under development, at such institutions as the Lamont-Doherty Geological Observatory, University of Maryland, Massachusetts Institute of Technology, University of Michigan, University of New Hampshire, Pennsylvania State University, University of California Santa Barbara, and Stanford University (Gibbons, 1992). Many other institutions with historical strength in interdisciplinary study of the environment are likewise placing increased emphasis on Earth system science.

At my own university, the University of Wisconsin-Madison, we established an interdisciplinary teaching and research unit to study the interrelations between people and the environment in 1970. This unit, the Institute for Environmental Studies, has a teaching staff of about 70 faculty with roots in 27 different departments and schools on our campus. Approximately 150 faculty, from 48 departments, participate in IES teaching, research, outreach, or student advising. In the main, this has been accomplished through "volunteer" faculty participation in the program. Having both chaired a graduate program and directed a research center in this context, I have first-hand knowledge of how interdisciplinary programs can and do work. However, I cannot overemphasize how the traditional structure and operation of most research universities in the U.S. often inhibit their response to such pressing interdisciplinary problems as global change.

F. Kenneth Hare (1970) aptly typified the large, structurally complex university when he noted that "We all know the conservative quality of such places, where nothing can easily be done for the first or last time. The status quo is defended in depth by the vested interests of a large number of able people."

Indications abound that the status quo is no longer serving either the modern university or society well. The media are replete with discussions about the need for higher education reform. Economics and demographics are two important forcing functions dictating this imperative. Beyond these is a much more fundamental need for modern higher education to meet the challenges of modern time. An important example of this need was underscored in a recent report of a meeting sponsored by the Board of Agriculture of the National Research Council. At this meeting, the heads of 52 scientific societies called on land-grant universities to move beyond their agricultural past and broaden their research agenda. Stressed in the report of this meeting was the fact that, when the land-grant universities were established (circa 1862), 75 percent of American workers made their living in agriculture. Now only about 2 percent of the population performs agricultural work. As articulated by one observer, "The United States [that] the land-grant universities were created to aid and assist no longer exists" (Wheeler, 1992).

Among the ways the representatives of the scientific societies suggested that land-grant universities could reshape their mission was to set up interdisciplinary research teams that would link faculty members in colleges of agriculture with those in schools of business, engineering, law, and medicine. But, university administrators participating in the meeting indicated that they face formidable barriers to setting up such programs. Reasons cited included the facts that ..."interdisciplinary research teams are slower to produce results...even though the results of interdisciplinary research might be more important to society." Beyond this, "Sometimes administrators must overcome outright hostility among researchers in different disciplines."

Macroscopic Perspective

Global change research is not only complicated by the general problems of undertaking interdisciplinary investigation, it is further complicated by the need to greatly expand both the spatial and temporal domains in which many scientists typically perform their work. For example, an atmospheric scientist or a physical oceanographer might work at regional to global scales on a regular basis. Similarly, the paleoclimatologist typically considers field observations in the geologic time scale. The problem is that many other disciplines central to global change research simply do not view the world over large areas and/or long time periods with any degree of regularity.

This problem was recently highlighted in a workshop, conducted by ecologists, that was aimed specifically at assessing potential inadequacies in ecological expertise in addressing global change questions. The workshop involved 23 prominent U.S. ecologists participating under the cosponsorship of the National Science Foundation and the Department of Energy. In the final report for the workshop (Brown and Roughgarden, 1990), three major inadequacies in ecological expertise were emphasized: the failure to consider humans as integral components of ecological systems; an insufficient understanding of how processes that operate at vastly different spatial and temporal scales combine with one another; and the lack of nationwide coordination in obtaining, analyzing, and disseminating basic data on organisms and the environment.

Note that the first inadequacy identified by the group is another expression of the historical separation of the natural and social sciences. In the main, ecological research emphasis has been placed on study sites that are undisturbed, or at least minimally disturbed, by humans. Likewise, humans are often treated as externalities to natural process models. As stated by Brown and Roughgarden (1990), "Today we know only roughly how humans interact with the environment"—even though humans not only participate in causing global environmental change, but they also suffer the consequences.

Complicating the understanding of the ecological role of humans is the influence of social, economic, cultural, technological, and political forces on their behavior (Stern *et al.*, 1992). Accordingly, improved understanding of the human dimensions of global change will be premised on increased research collaboration between ecologists (and natural scientists in general) and social scientists. In actuality, much *is* known about how humans interact with the environment (e.g., Thomas, 1956; Turner, 1990). The problem is that, without the synthesis of the natural and social sciences perspectives, the whole of our knowledge is ironically less than the sum of its parts.

Relative to the specific topic of spatial and temporal scale of inquiry, Brown and Roughgarden (1990) state:

> A review of the ecological experiments published from January 1980 to January 1987 by Karieva and Anderson (1988) found that 50% of all studies were done on plots less than 1 m in diameter, and 25% used plots less than 25 cm in diameter! Furthermore, most experiments were deliberately designed with homogeneous study sites to minimize spatial variation between experimental replicates, and were conducted over short periods to reduce the possibly confusing effects of seasonal or year-to-year variation. Indeed, a survey of the literature by Tilman (1989) showed that 40% of ecological experiments lasted less than one year (generally one field season) and only 7% lasted five or more years. In a few instances where studies have focused on the influence of scale *per se*, the answers to particular questions depended on the spatial and temporal scale used in the experiment (Wiens 1986).

My point is not to suggest that ecologists have been focusing on irrelevant scientific questions over the last several years. Neither is the point to contend that their scales of inquiry have been necessarily inappropriate for the various questions at hand. Rather, I wish to underscore that many ecologists would have great difficulty in "scaling up" their observations, models, and perspectives to a global, long-term dimension. And, the same can be said for most other fields of study dealing with global change questions.[2] Many disciplines having critical contributions to make to Earth system

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[2] A recent treatment of scale issues in geographic research may be found in "The Local-Global Continuum," Meyer *et al.*, in Abeler *et al.*, 1992, pp. 255–274.

science are simply mired in one, or both, of what Swanson and Sparks (1990) refer to as the "invisible place," and what Magnuson (1990) typifies as the "invisible present."

The "invisible place" refers to the concept that, without a sense of broad spatial perspective, the significance of detailed research results from a particular small site is not understood. The "invisible present" suggests that misleading conclusions can be drawn from short-term studies if there is no historical context in which to place these studies.

The Role of the Mapping Sciences in Global Change Research

I would be "preaching to the choir" if I were to emphasize the role that the mapping sciences play in broadening spatial perspectives. I need not reiterate for this readership how satellite remote sensing has profoundly influenced humankind's perception of the Earth as a system comprised of interrelated and delicately balanced parts. Instead, what I wish to emphasize here is the need for increased temporal perspective in our work, and the role modern mapping (e.g., GPS, satellite remote sensing, GIS) is playing and can play in helping a multitude of other disciplines to ferret out both the *signals* of global change and helping to predict the *impacts* of same into the future. In this regard, I believe that the only thing exceeding the opportunity for the mapping sciences to help assemble the evidence of global change in the interest of science, is the obligation to assist in predicting the impacts of such change in the interest of rational policy development at all levels of land management. Taking regional climate change as an example, a utopian goal would be to have the ability to forecast climate for a given area with the certainty and site specificity sufficient to integrate this information into the present land management decisionmaking process at the local level. Ideally, land management decisions could then be made in response to the anticipated climatic conditions; or decisions could be made with the aim of actually modifying these conditions.

Currently, we are far from the ideal world described above. Even with the aid of supercomputers, most general circulation models (GCMs) are constrained to forecasts which are very general in nature. For example, most of these models are presently only capable of supporting such forecasts as "On the whole, summers in the interior of North America in the next several decades will be drier and warmer." Such observations are certainly of general scientific value, but those charged with day-to-day resource management and planning need much more specific information if it is to have substantive influence on their decisionmaking process. For example, a model with more local "intelligence" might predict that in certain specific locations in a state precipitation during the growing season in the next ten years will be reduced by 30 to 50 percent (J.R. Anderson, unpublished data). At this level of specificity the implications of potential climate change take on new meaning. Immediately, questions surface such as, What will be the impact on the nature and geographic distribution of production agriculture? How will such changes influence the structure, pest tolerance, and productivity of our forests? What are the implications for our surface and groundwater resources in terms of both quantity and quality? What will be the influence on infrastructure planning and maintenance? What are the anticipated demographic responses to such changes? Can these changes be mitigated in some way?

Detecting the Signals

Before we can hope to provide answers to the above kinds of questions, we must first be able to reduce the scientific uncertainty about the direction and rate of change of such basic phenomena as average global temperature. But, as summarized by La Brecque (1989), "On every front, signals that could reveal a vector of change in global climate remain inextricably buried in background." It remains a question as to whether current warming is a long-term trend, or a continued manifestation of natural variability in the Earth's system. La Brecque characterizes this situation in historical context as follows:

> The warming that had begun slowly around 1880 was indisputable by the late 1930s. Some scientists declared that a long-anticipated climate change was at hand, and much more of the same was in store. Then, in about 1940, something odd happened. For some inexplicable reason, the half-century trend reversed itself in a large part of the Northern Hemisphere, and the world as a whole grew colder. By the 1970s, as a new generation of scientists struggled to find the cause, they anticipated even lower temperatures.
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> Suddenly, in the middle of that decade, these modern seers were confounded by yet another shift. From 1975 to the present, the global warming interrupted in 1940 has resumed, and to such an extent that the 1980s is unquestionably the warmest decade of the twentieth century. This time, though, there is a reluctance to prognosticate. With two abrupt temperature reversals fresh in collective memory, few investigators want to make bold assertions.

With the above reservations in mind, a variety of different kinds of climate-related records are currently under critical scientific scrutiny. Among these, the "best" are thought to be records of surface air temperature. These records date back to the middle of the nineteenth century and are the most extensive in terms of global coverage. They form the basis for the calculation of a global mean temperature, an expression of how the whole climate system is responding, irrespective of spatial variability within the system. Augmenting the land-oriented record are marine air temperature and sea surface temperature (SST) data.

One of the major problems with analyzing the global temperature record as a definitive indicator of climatic change is a series of discrepancies caused by changes in the conditions of temperature measurement over time. Among these changing conditions La Brecque (1989) notes the following:

- Prior to 1940, SST observations were made by collecting sea water in a bucket and placing a thermometer in the bucket on a ship's deck. Since about 1946, SST measurements have primarily been made by measuring the temperature of the cooling water coming into the ship's engine room. The net effect of these changes in measurement techniques is a negative bias in the bucket measurements (due to evaporative cooling) and a positive bias in intake thermometer readings (due to heat gain from the engine room). If this effect were not compensated in data analysis, a spurious warming trend of 0.5°C over the last 130 years might be assumed.
- From about 1850 to 1870 the buckets used to collect SST samples were made of wood rather than canvas. Wood, being a better insulator than canvas, would reduce the evaporative cooling associated with the measurements.
- Ground-based measurements are biased by a nineteenth-century change in the kind of screen used to protect thermometers from the wind and direct sunlight.
- The types of thermometers used have changed over time with virtually no overlap between types, so intercalibration of readings is problematic.
- In the past, thermometers were read every three hours and the eight daily readings were averaged to produce the average daily temperature. Now, the average daily value is produced by reading a 24-hour thermometer once a day for the daily maximum and minimum temperature and averaging those two numbers.

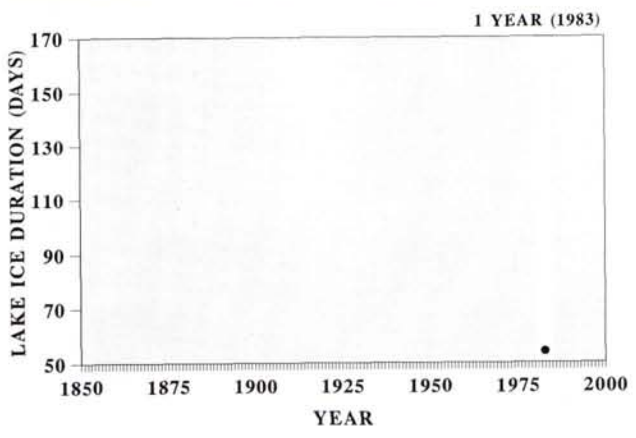

Figure 1. One-year ice duration record for Lake Mendota, Wisconsin. The single-year record only reveals the number of days the lake was frozen in the year of record (1983). (After Magnuson *et al.*, 1990).

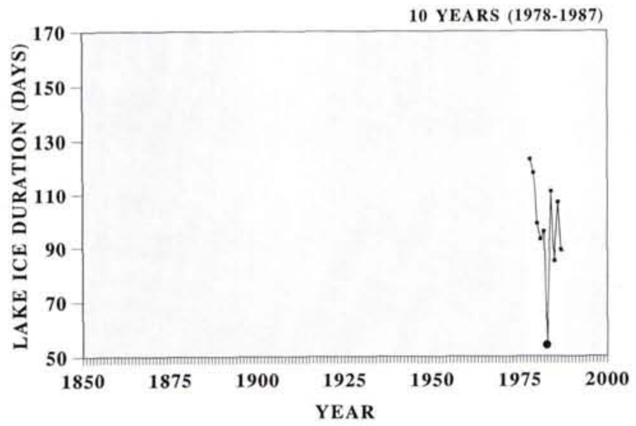

Figure 2. Ten-year ice duration record for Lake Mendota, Wisconsin. The ten-year sequence reveals the year-to-year variability of climate and the unusually short duration of ice cover in 1983. (After Magnuson et *al.*, 1990).

- The hour of day when the 24-hour thermometer is read has also changed over time from station to station, influencing the maximum and minimum and, therefore, the average daily temperature.
- Thermometers have been moved, often from centers of cities to outlying airports, producing a discontinuity in the records.
- The cities in which weather stations are traditionally located have increased in both area and population density over time, creating a spurious heating trend due to urban heat island effects.

Because of the problems inherent in deciphering global climate change from the surface temperature record, several other indicators of climate change have been under investigation. Among these are changes in precipitation (both rain and snow), precipitable water, sea level, permafrost temperatures, sea ice, and ice sheets. Of these, sea ice extent and ice sheet mass have already been subject to assessment utilizing satellite data. Below is presented another type of measurement which is amenable to remote sensing observation that may well hold potential as an indication of climatic change, namely monitoring the phenology of lake ice.

Lake Ice Monitoring Example

The topic of lake ice monitoring illustrates a concrete example of how mapping scientists, working with a range of other disciplinary specialists, can help document a potential signal of global climate change—one that is not observable in the temperature record. Beyond this, this particular effort illustrates the need to study an extended time series of data in order to detect the signal being sought after in the context of natural background variability. As suggested by Magnuson's (1990) "invisible present" concept, it is impossible to directly sense (in the short-term) gradual change as it occurs over decades, because these changes may be hidden in large year-to-year variations and time lags between cause and effect that are longer than a single year.

The rationale for monitoring the periodicity of lake ice formation and breakup as a climate change indicator has been suggested by previous researchers (Scott, 1964; McFadden, 1965; Maslanik and Barry, 1987). In short, lake ice provides a robust, integrative measure of climate in that the dates of freezing and thawing consolidate the experience of many months of winter weather—in contrast to the short-term variability of temperature. Also, the historical record of lake ice formation and breakup is considerably long, dating back to the nineteenth century (when local newspapers would print the dates of freezing and thawing). Currently, systematic records are kept by state and federal climatology offices.

To illustrate the nature of lake ice phenology and the concept of the "invisible present," I will draw heavily on the research of Robertson *et al.* (1992). In this work they focused on the ice cover record for Lake Mendota, located in Madison, Wisconsin. Lake Mendota has an area of about 3940 hectares, a mean depth of 12.4 metres, and a maximum depth of 25 metres. Its ice cover has been documented continuously since 1855. This record readily illustrates the need for time series analysis in the detection of potential climate change signals.

If data from only one year are analyzed, say 1983, the only information garnered is the number of days the lake was frozen (Figure 1). If the temporal window of analysis is broadened to ten years (e.g., 1978 through 1987), the large year-to-year variations become apparent (Figure 2). We can see that the range in lake ice duration spans from about 50 days to 120 days. In 1983, the lake was frozen for 40 days less than any of the other nine years.

If we now expand our horizon of analysis to 50 years (e.g., 1942 through 1991), the data reveal that the ice cover in 1983 was of unusually short duration (Figure 3). These data also suggest that the ice cover was relatively short in most other El Niño years.[3] The best explanation for the parallel occurrences of El Niño and the short ice-cover years at Lake Mendota is that both of these phenomena, previously perceived as merely local fluctuations, are associated with periodic shifts in the location of atmospheric circulation patterns that affect weather worldwide.

Perhaps the most important observations from Robertson's analysis come into view when the entire ice cover record for Lake Mendota is considered (Figure 4). It is in this view of the data that the warming trend at the end of the

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[3] El Niño years are those when the warm current that typically flows southward along the coasts of Peru and Ecuador in December, flows counter to its normal direction and is unusually warm and strong.

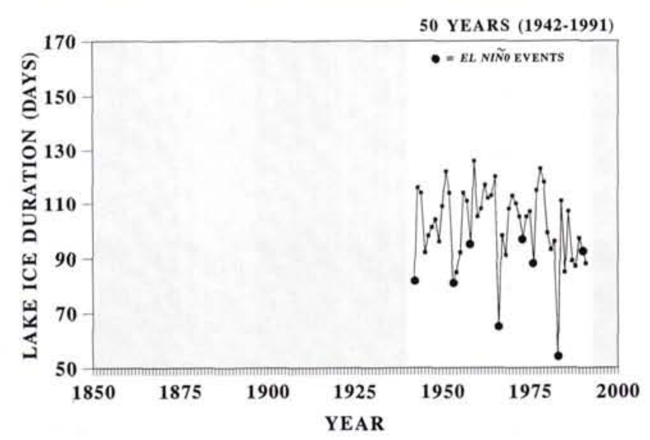

Figure 3. Fifty-year ice duration record for Lake Mendota, Wisconsin. The 50-year sequence highlights the apparent association of short duration ice years with El Niño cycles. (After Magnuson *et al.*, 1990).

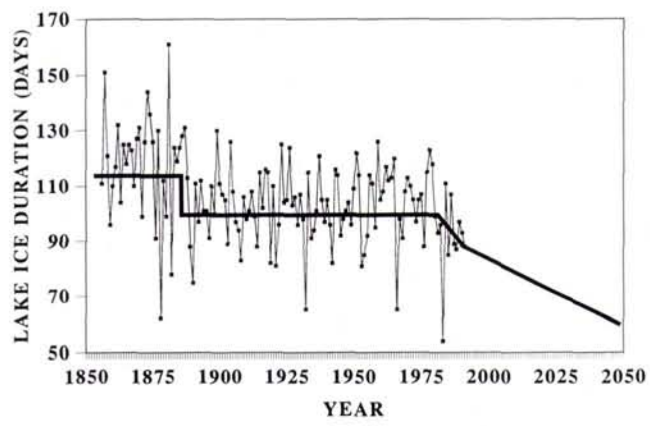

Figure 4. The complete 136-year record of ice duration for Lake Mendota, Wisconsin. The thick black line represents the mean ice cover duration, showing significant warming about 1890 and nearly constant values until about 1979. Since 1979 ice duration has continued to decrease. The extrapolation to 2050 is a generalized interpretation of Robertson's projection of ice cover under the assumption of global warming caused by a doubling of atmospheric CO_2. (After Magnuson *et al.*, 1990).

"little ice age" in the late 1880s becomes apparent for the first time. Also, from about 1900 to 1979, Lake Mendota was covered with ice on an average of about 100 days. Since 1979, that duration has decreased by 12 days (with virtually the entire change occurring in the date of thawing). Also shown in Figure 4 is Robertson's portrayal of the future duration of ice cover on Lake Mendota based on a hypothetical doubling of greenhouse gases in a global climate model.

Again, the intent of presenting Robertson's ice cover analysis is to illustrate the importance of long-term perception in uncovering the invisible present. Such long-term perception will have to become much more standard in science if we are to more fully understand the complex processes of global change.

A companion paper by Wynne and Lillesand (1993), also included in this Special Issue, describes how we have successfully used data from the Advanced Very High Resolution Radiometer (AVHRR) to discriminate the presence and extent of lake ice on the 45 lakes and reservoirs in the state of Wisconsin with a surface area greater than 1,000 hectares. This proof of concept study has resulted in our proposing that relevant portions of the entire AVHRR, GOES, and Landsat archive be analyzed for this purpose over a large latitudinal gradient. The importance of such an effort is that, if lake ice periodicity continues to hold up as a proxy for air temperature trends, it will circumvent many of the problems inherent in analyzing the temperature record.[4] In addition, this remotely sensed phenomenon would be particularly valuable in studying climate change in the high latitudes, where there is a relative paucity of meteorological stations, as well as where most GCMs predict that global warming due to an increase in atmospheric CO_2 will be the greatest (National Research Council, 1982; Manabe and Wetherald, 1986).

The three major limitations to our current use of AVHRR data for lake ice monitoring are spatial resolution, cloud cover, and the lack of a longer historical record. As we enter an era of more spaceborne synthetic aperture radar systems, and the other sensors in the Earth Observation System program, such limitations will be greatly mitigated. But, monitoring such phenomena as lake ice requires a commitment to data collection over large areas, on long time-scales, on a systematic basis. Regrettably, our historical operation of such systems as Landsat did not include such a commitment. Let us hope that we learn from our mistakes.

Predicting the Impacts

Predicting the long-term impacts of global change is an even more formidable task than ferreting out the signals of such changes. But, by coupling process models with GIS biophysical databases, we are rapidly developing the capability to display alternative future scenarios in a spatially explicit manner. When prospective changes are "put on a map" through the combination of modeling and GIS procedures they take on new meaning to decisionmakers. Once again, I wish to use a research program in which I am participating in order to illustrate this point.

Under the leadership of Prof. John J. Magnuson, an interdisciplinary team of scientists at our university is attempting to assemble the data, knowledge, and models needed to predict the potential impact of global climate change on the aquatic ecosystems of the Northern Highlands Lake District of northern Wisconsin. This work is being undertaken primarily under the rubric of the National Science Foundation's Long-Term Ecological Research (LTER) program. LTER comprises a network of individual sites spread throughout the continental U.S., Alaska, Puerto Rico, and Antarctica. The sites range from arctic and alpine tundra to tropical rain forests, deserts, and dry grasslands; from coastal wetlands, estuaries, and unspoiled wilderness to grazing lands and cornfields. The North Temperate Lake site in northern Wisconsin is one of the 18 sites in the LTER network. Many of the insights gained at this site have implications for similar

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[4] It should be noted that Schindler *et al.* (1990) have studied 20 years of data on the Experimental Lakes Area of northwestern Ontario, Canada. Over the period of study, air and lake temperatures have increased approximately 2°C and the length of the ice-free season has increased by three weeks.

northern lake districts of glacial origin, such as those in Canada, Scandinavia, and northern Asia.

Some of the specific scenarios Magnuson's group has suggested for the North Temperate Lake site represent significant, if not shocking, ecological changes relative to the current situation (Hill *et al.*, 1989). These scenarios also illustrate the complex and interactive nature of the processes operating in a lake region. For example, if a GCM scenario of a 5°C warming and 20 percent reduction in annual precipitation occurs in northern Wisconsin (a very plausible possibility) a series of interrelated events will likely transpire. Among these will be the following regional responses:

- The decrease in precipitation and increase in evapotranspiration will lower the water table, leading to drops in lake levels and loss of wetlands. Hence, the relative percentage of land, wetlands, and water may change significantly.
- Surface water and groundwater inflow to lakes will decrease, and some lakes will lose their surface connections by streams.
- A loss of species richness may result because the balance of invasions/extinctions will be tripped in favor of extinctions.
- Thermal regimes within lakes will shift toward warmer water temperatures, longer periods of summer stratification, and increased vertical stability due to larger temperature gradients across the thermocline.
- Aquatic productivity may increase due to longer growing seasons, increased sunlight, and warmer water temperatures.
- Species assemblages may undergo significant changes as thermal niche space expands or contracts for individual taxa, and as predatory and competitive interactions evolve into a new ecological equilibrium.
- Rates of nutrient input to lakes will change with land-cover types and because of altered percentages of water input by groundwater and precipitation.
- Internal nutrient cycling will be altered by warmer temperatures and by changes in dissolved oxygen levels, primary production, and decomposition of organic matter.
- Annual winterkill in some lakes may end as winters become less severe, leading to new species associations.
- Alternatively, dropping lake levels may increase the number of winterkill lakes. "Summerkill" may become a factor in some lakes if hypolimnetic dissolved oxygen concentrations in the summer drop below tolerance limits for coldwater fishes.
- Fire frequency will likely increase in a warmer, drier climate, with direct consequences to nutrient loading of the lake systems.

The above, partial list of potential changes illustrates the linkages and interactions among landscape, lake response, and disturbance processes to be dealt with in assembling a realistic impact scenario for the area under study. However, many of the modeling tasks to be done will be directly supported by remote sensing and/or GIS techniques. For example, a spatially explicit hydrologic model for the area is under development utilizing such basic information as topography, bathymetry, land cover, soils, groundwater flows, etc. Such tasks as evaluating the volumetric thermal niches of fishes are also readily amenable to spatial analytical techniques. Nutrient cycling in the forest canopies in the region is being studied through remote measurement of such factors as leaf area index and foliar and woody biomass. Demographic changes are being modeled with the aid of census data. Sonar data for fish surveys are being analyzed using digital image processing procedures. Digital reconstruction of the pre-settlement vegetation in the area is being undertaken based on the field notes and maps attendant to the original Public Land Survey for the area (circa 1983). The spatial variability of limnological parameters is being assessed on a regional basis using satellite data. The remotely sensed observations are being related to ground-based observations through GPS techniques. And yes, the phenology of lake ice in the area is being monitored via satellite data as well.

The point in my relating the interdisciplinary efforts aimed at predicting the impact of global climate change in northern Wisconsin is again only in the interest of providing a concrete example of the multifaceted role the mapping sciences can play in such an effort. The common geographic framework afforded by the GIS helps provide a common conceptual foundation upon which new questions can be asked and new hypotheses can be formulated. Long-term ground observations are helping us transcend the "invisible present;" and remote sensing data are providing a perspective beyond the "invisible place."

Conclusion

Scientists from single disciplines working alone are not equipped to solve problems of the complexity of global change. We can increasingly point to examples of interdisciplinary research that contribute to our understanding of human-environment interactions; nevertheless, these are still the exceptions to the rule. Instructionally, higher education is still not properly organized to educate the next generation of scientific and public policy leaders who must face the staggering problems associated with global change. As traditionally configured and operated, academe has not and will not adequately nurture the development of interdisciplinary science. One important consequence of this has been the relative isolation and insulation of the natural and social sciences. Within most disciplines, the emphasis has been on reduction rather than synthesis. Global change is dictating not only a more common outlook, but also one through which the world is viewed across broader spatial and temporal horizons. The mapping sciences have created many of the tools needed to provide this capability.

In fact, GIS technology holds the potential to provide much of the common ground—the basic conceptual glue—needed to undertake interdisciplinary Earth system science research. Similarly, satellite remote sensing, when combined with GIS and GPS might be thought of as a "macroscope." Just as the microscope changed the scientific view of the world, this macroscope holds the same potential. Reaching this potential dictates the development of new intellectual and institutional paradigms. In my opinion, aiding, if not leading, the development of these paradigms is simultaneously the tremendously important challenge, opportunity, and obligation of the mapping sciences.

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